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Brackish groundwater as drinking water source

A literature review for a proposed water resource for Dunea

Bridging Science to Practice

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Summary / Samenvatting

Dunea, one of the ten drinking water companies in the Netherlands and operating in the coastal zone, is investigating the use of brackish groundwater for (1) an alternative and/or supplementary source for drinking water and (2) enlargement of their strategic freshwater reserve by the 'Freshkeeper effect'. In this review, a selection of brackish water reverse osmosis (BWRO) installations operating on a comparable feed water quality with respect to the Dunea case are analysed in detail, together with four Dutch BWRO applications. Out of 100 screened articles 12 articles were found that described (multiple) BWRO plants located all around the world, clearly indicating that BWRO is proven technology. Compared to existing BWRO systems described in the selected articles and scientific reports, the salinity in the feed of the Dunea case is rather high, although far lower than seawater. Precipitation of calcite and of iron and manganese (hydr)oxides is a potential risk for brackish water treatment by Dunea. However, with a recovery of ≤50%, a solid operation with use of only simple anti-scalants to prevent calcite scaling seems viable as long as the water is kept anaerobic during treatment to prevent iron and manganese precipitation. Ammonium removal from the permeate might be required based on the current Dutch drinking water quality standards. As anoxic brackish groundwater in the coastal zone of The Netherlands may contain high concentrations of methane gas (which passes through RO membranes), methane removal from the produced permeate by aeration might be required. Even though there are some practical challenges to be addressed, BWRO application for drinking water production seems a viable route for Dunea.

Dunea, het waterbedrijf van Den Haag en omstreken, verkent de winning van brak grondwater (1) als alternatieve en/of aanvullende bron voor drinkwater en (2) als mogelijkheid om de strategische zoetwatervoorraad in de duinen te vergroten ('Freshkeeper effect'). In dit rapport wordt een overzicht gegeven van ervaringen in Nederland en internationaal met ontzilting van brak grondwater door middel van omgekeerde osmose (brackish water reverse osmosis; BWRO). Uit 100 (wetenschappelijke) artikelen zijn 12 artikelen geselecteerd die (meerdere) BWRO toepassingen beschrijven in verschillende delen van de wereld. De geselecteerde studies hebben een BWRO voedingswater met een vergelijkbare kwaliteit als het verwachtte voedingswater bij Dunea. Aanvullend zijn vier Nederlandse BWRO toepassingen in detail geanalyseerd. Uit deze screening blijkt duidelijk dat BWRO het predicaat 'bewezen technologie' verdiend. In vergelijking met de BWRO installaties uit de geselecteerde artikelen en overige wetenschappelijke rapporten is het zoutgehalte in het voedingswater bij Dunea relatief hoog, hoewel het zoutgehalte nog steeds aanzienlijk lager is dan typische zeewaterconcentraties. Neerslagvorming door oververzadiging van kalk (calciumcarbonaat) en van ijzer- en mangaan(hydr)oxiden is een potentieel operationeel risico. Desalniettemin, uitgaande van een recovery van ≤50% en eventueel gebruik van niet-specifieke anti-scalants, lijkt een solide bedrijfsvoering goed haalbaar. Voorwaarde is wel dat het water anaeroob blijft gedurende de behandeling zodat ijzer- en mangaanneerslag wordt voorkomen. Hiermee is goede ervaring in de beschreven Nederlandse toepassingen. Het kan nodig te zijn om ammonium uit het permeaat te verwijderen om aan de Nederlandse drinkwater kwaliteitseisen te voldoen. Brak grondwater in de Nederlandse kustzone kan hoge concentraties methaan bevatten, dat niet verwijderd worden door RO membranen. Methaanverwijdering uit het geproduceerde permeaat door beluchting is daarom mogelijk vereist. Ook met deze praktische uitdagingen in het achterhoofd, lijkt de toepassing van BWRO voor de productie van drinkwater een kansrijke route voor Dunea.

Contents

1 Introduction

The increasing world population, urbanization, industrialisation, and sea level rise and changing weather patterns by climate change are heavily impacting drinking water supply and demand, particularly in coastal zones. To ensure water availability, drinking water companies start to look for additional and/or alternative sources to suit their needs. One of these alternative water sources which is increasingly being exploited is brackish groundwater, available in aquifers. According to market studies (for instance [1]) and literature, desalination of this brackish water using reverse osmosis membrane technology (BWRO) is now in a mature phase of technological development[2]. One major advantage of using brackish groundwater instead of seawater for drinking water production are the lower operational costs of desalination, due to its lower salinity. The second major advantage of brackish groundwater is the limited potential for fouling (generally anaerobic water). The third major advantage is that anthropogenic pollution is generally not present in (deeper) brackish water aquifers allowing for straightforward and reliable drinking water production [3]. Today, 69% of all desalination installations in the world use reverse osmosis (RO) as core desalination technique (see Figure 1-1) [4]. 21% of these RO installations are fed with brackish groundwater globally, but this can vary significantly per country. In the United States for example, approximately 72% of all municipal desalination plants is fed with brackish groundwater [5].

Dunea, one of the ten drinking water companies in the Netherlands and operating in the coastal zone, assesses the use of deep brackish groundwater for 1) an alternative and/or supplementary source for drinking water and 2) enlargement of their strategic freshwater reserve by the 'Freshkeeper effect'. In this review, a selection of BWRO installations operating on a comparable feed water quality with respect to the Dunea case are analysed in detail. For these selected BWRO installations, we collected and analysed the available supporting information, i.e. on the hydro-geological setting, well design and –configuration, BWRO feed water quality, required pre-treatment steps for BWRO, RO membrane type, anti-scalant use, recovery applied (%), concentrate management, BWRO product water quality, prevention of well clogging, RO membrane fouling prevention methods, BWRO energy consumption and the BWRO business case (CAPEX, OPEX and drinking water production costs). Dunea's intention is to learn as much as possible from the available cases, in order to wisely implement this knowledge in their own design. Therefore, based on the available literature and Dutch case studies, an answer will be given to the following question:

''To what extent is BWRO proven technology and what lessons can be learned from relevant case studies described in literature?''

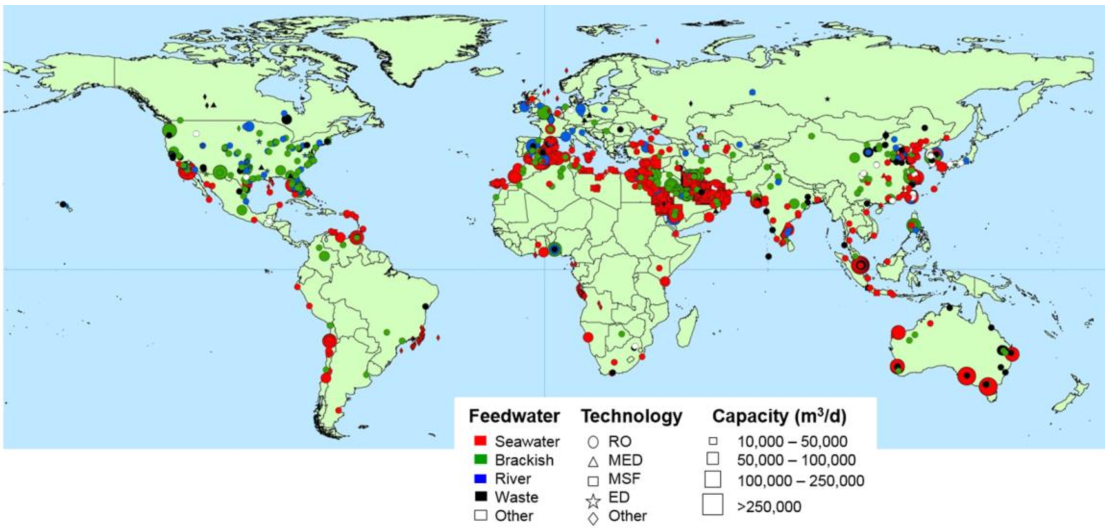


Figure 1-1: Worldwide application of desalination technologies, among which BWRO is indicated with green circles [4]

2 Methods

2.1 Literature review

The literature study was performed in the period of 29-7-2019 till 2-8-2019 using the SCOPUS database. Using 'brackish groundwater desalination reverse osmosis' as search request, the 100 most recent articles were screened for resemblance with the expected feed water quality of the Dunea case (see Appendix I – Memo Dunea). The final and most critical criteria for selection of an article was the assessment whether most of the mentioned feed water quality parameters fell between the minimum and maximum concentrations listed in Appendix I – Memo Dunea. Those articles describing BWRO plants fed with comparable brackish water as present in the Dutch coastal zone (Meijendel) are expected to have practical value and/or relevance for Dunea. The step-wise screening procedure used consisted of:

1. article title judgement
2. abstract judgement
3. quick-scan for availability of feed water quality data
4. assessment whether feed water quality parameters resembled the expected water quality of Dunea

When all four criteria were positively met, the article was analysed completely and relevant data was extracted. The 100 most recent articles were selected for the study to increase the chance of getting recent economic evaluations and process parameters, since these are known to become less relevant with increasing age. In total 12 articles were found that met the criteria described above, some of them describing multiple brackish water reverse osmosis (BWRO) plants. Several papers with additional information regarding the specific test cases mentioned by these 12 papers were used as well, together with several papers and conference proceedings describing the Dutch example cases.

No extensive search for information described in scientific reports from outside of the Netherlands was performed, which is known to (also) include relevant information. Especially in the United States, the development and application of BWRO systems are well documented throughout the years [5].

2.2 Use of Dutch experiences on BWRO

Use of brackish water as a drinking water resource was explored by Brabant Water and Vitens between 2007 and 2012, and later by Oasen. Between 2014-2017, BWRO in combination with aquifer storage and recovery (ASR) was studied at a greenhouse at approximately 10 km from the nearest Dunea well field.

The obtained experience with BWRO application in the Netherlands is reported generally in scientific reports, not in peer reviewed papers. As they are extremely relevant for this review, these reports were added to the review.

2.3 Set-up of the report

Within this report, information from the selected scientific articles and scientific reports is clustered in several ways to get an easily assessable overview of the data and an overview of the conclusions drawn. For an overview of the information gathered from all the selected articles and Dutch scientific reports underlying the hereinafter showed graphs, the reader is referred to Appendix II – Overview table. Chapter 1 introduces the research, addresses the focus points and states the main research question. Chapter 2 describes the methods used to conduct this literature research. Chapter 3 shows the results from the literature study (page 9), including the Geohydrology of BWRO locations (page 9), Water quality BWRO feed water (page 12), Clogging of brackish water extraction wells (page 13), Brackish groundwater pre-treatment (page 15), Scaling prevention measures for BWRO installations (page 17), BWRO membranes and permeate water quality adjustments (page 19), Concentrate management and environmental impact (page 21) and a BWRO economical evaluation (page 22). The Dutch reference cases of BWRO application are described on page 24 till page 33. The conclusions of this research are presented in Chapter 4 and the bibliography can be found in Chapter 5.

3 Results

3.1 Current state of desalination (globally)

The current state of desalination and brine production on a global scale has been reviewed in 2019 [4]. Within this study, it is shown that reverse osmosis (RO) is applied in 13446 out of total 15906 cases of operational water desalination facilities (see Figure 3-1). This large contribution (84,5%) of RO-based desalination facilities is expected to increase further in the future judging from the trends in installed capacity per year and the number of publications per year on the different desalination technologies. Of all operational desalination plants, 5960 out of 15906 (37,5%) use brackish water as feed for desalination (see Figure 3-2), which in drinking water production terms is called brackish water reverse osmosis (BWRO). A slightly lower number of desalination plants (5328 out of 15906; 33,5%) is fed with sea water, which in drinking water production terms is called sea water reverse osmosis (SWRO). The major difference between BWRO and SWRO is that the osmotic pressure of the feed water is higher for SWRO systems in general, making SWRO a more energy-intensive process. Sea water is abundantly available in coastal areas, while brackish (ground)water is generally available in coastal zones, both in river deltas and coastal aquifers.

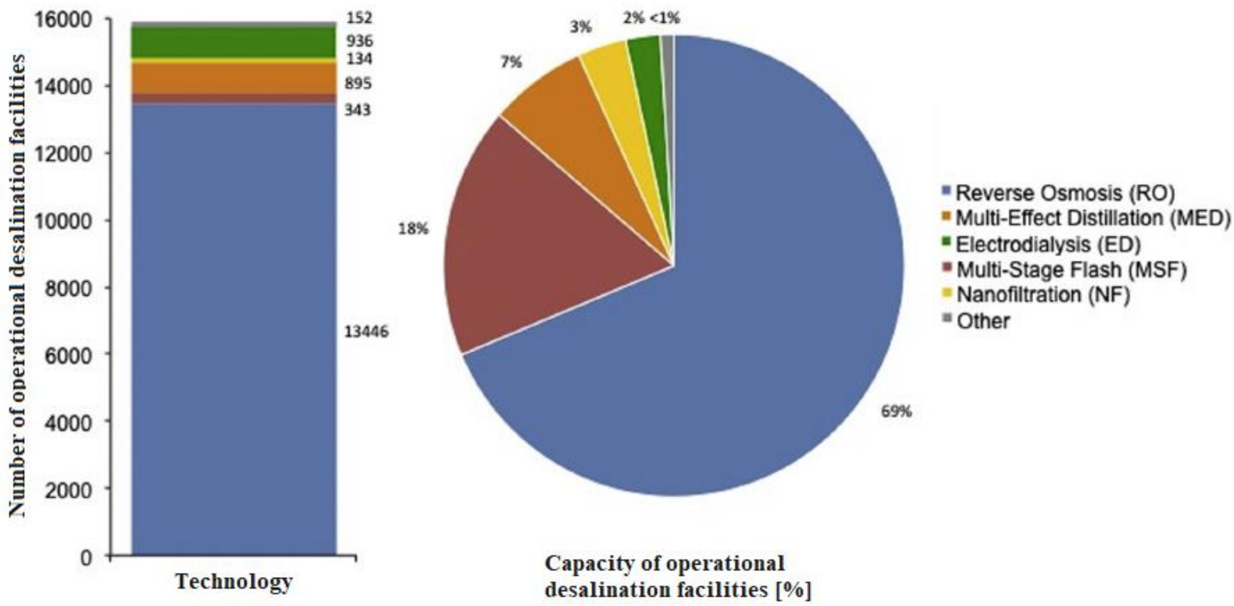


Figure 3-1: Number and capacity of operational desalination facilities by desalination technology [4]

Reverse osmosis of brackish groundwater (BWRO) is increasingly applied for the production of drinking, industrial or irrigation water in an economically feasible way [3]. According to these authors, BWRO and SWRO systems are considered as two of the most promising solutions for the worldwide water scarcity. Especially in coastal areas of Europe (e.g. Denmark) and Mediterranean countries, overexploitation of available aquifers can result in salinization of abstraction wells [6], [7]. Abstraction of brackish water (as feed water for BWRO) at the boundary between salt and fresh aquifers can have important co-benefits like preventing salinization of wells, as demonstrated for example in Israel where BWRO is applied to prevent salinization of a coastal aquifer [8] and in the coastal zone of The Netherlands [9]. In the following sections, various aspects relevant for BWRO applications are discussed and the relevance towards the Dunea case is given.

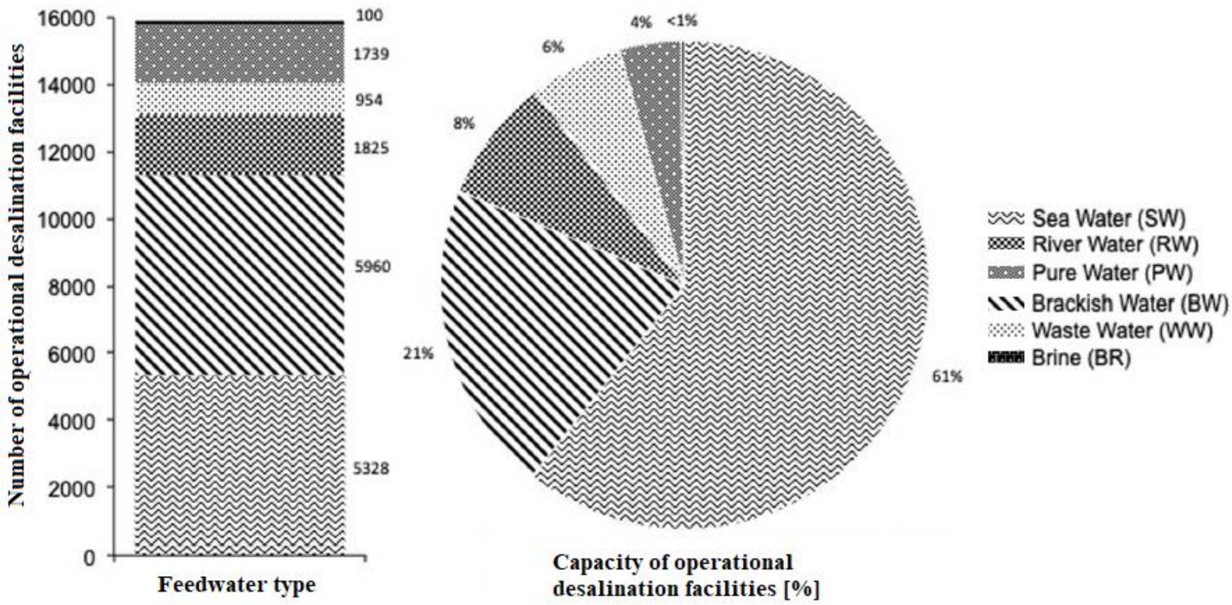
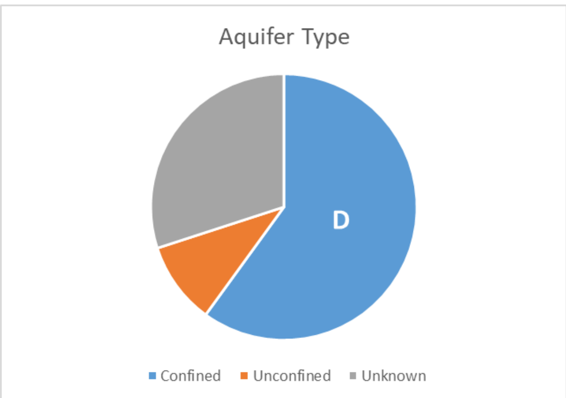


Figure 3-2: Number and capacity of operational desalination facilities by feed water type [4]

3.2 International BWRO case studies

3.2.1 Geohydrology of BWRO locations

Within the selected articles and scientific publications, 10 sites reported information on the source aquifer for BWRO (see Table 3-1). The local geohydrological characteristics of these sites were compared with the geohydrology of the Dutch coastal zone relevant to Dunea (Meijendel area). Like the Dunea area, most of the reported cases abstract from confined sand aquifers, of which the bulk consists of young, unconsolidated, coastal sands (Figure 3-3). Only one site reports application in the very same Peize-Waalre Formation. Most sites are situated less than 100 km from the coastline, but also more than 5 km from the coastline. The Dunea area (0,5 – 5 km; average ~2 km) is relatively close to the coastline. This is underlined by the relatively high salinity of the target aquifer: to date, most BWRO cases which describe the geology of the aquifer involved are targeting slightly brackish aquifers. Three of the studies mention active salinization of the target aquifer. Little information is found on well types and depth of well screens.



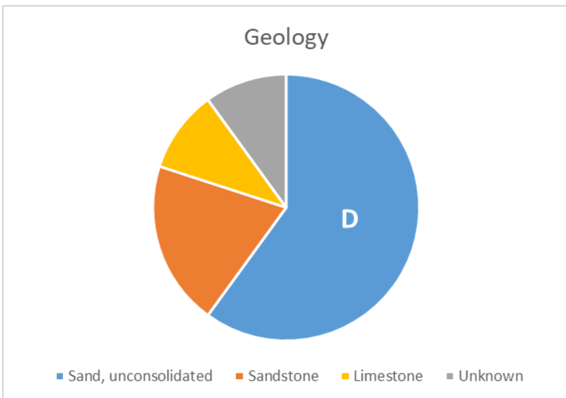


Figure 3-3: Overview of aquifer type and geology of target aquifers for brackish water abstraction (n = 10). D = Dunea.

Table 3-1: Overview of selected studies providing geohydrological information on BWRO application locations

Reference	Country	Location	Approximate distance to coast [km]	Capacity [m3 / day]	Aquifer name / formation	Aquifer number + unconfined / confined	Aquifer salinity (TDS/EGV/Cl)	Type sediment
[10]	Jordan	Zarqa desert	120	136364	Zarqa aquifer /		Investigated: TDS = 0,948 - 2,288 g/L EC = 1568-3500 µS/cm Zarqa basin: TDS = 1,632-3,072 g/L EC = 3070-4720 µS/cm Cl = 0,593-1,610 g/L	$CaCO_3$, $MgCO_3$ ($CaSO_4$ at some locations)
[8]	Israel	Granot	8	52900			At start -> after 10 years TDS = 1,497 -> 1,832 g/L Cl = 0,685 -> 0,803 g/L	SiO_2
Dunea	Netherlands	Meijendel	2	36000[1]	/ Peize-Waalre Formation	3: Confined	EC = 12787 µS/cm Cl = 4,897 g/L	
[11], [12]	Egypt	El Gouna town	1	9500	Coastal aquifer: Quarternary / Pliocene	Confined	Brackish groundwater: TDS = 5-15 g/L Red Sea water + concentrate: TDS 42-44 g/L	Interchange of coarse alluvial fan deposits with finer grained stream/beach deposits, and shallow marine sandy muds and siltstones with carbonates. $CaSO_4$ and $CaCO_3$.
[15]	Algeria	In Salah / Oued Rjem		3500	Albian aquifer /		EC = 2940 - 3140 µS/cm Cl = 0,495 g/L	Sandstone, sparingly $CaCO_3$ and $CaSO_4$
[6], [17]	Netherlands	Zevenbergen	65	1200	/ Maassluis	2b: Confined	EC = 1380 µS/cm Cl = 0,311 g/L	
[6], [18]	Netherlands	Noordburgum	19	1200	Enschede / Harderwijk	1b: Confined by clay layers in aquifer 1a	EC = 2420 µS/cm Cl = 0,650 g/L	Coarse sand - gravel
[19]	Netherlands	Ridderkerk	35	600	Fluvial /	3: Confined	TDS = 0,981 g/L Cl =0,380 g/L	Alternation of fine sands and poorly developed impermeable clay layers
[13], [14]	Spain	Alicante / San Vicente del Raspeig	7	450	Quarternary	1: Unconfined	EC = 6000-8010 µS/cm Cl = 1,267-1,655 g/L	Silts and sands, with a low presence of clays, overlying an impervious loam. Imbedded $CaSO_4$ layers are frequently found
[16]	Netherlands	ASRRO Westland	3	200	/ Peize-Waalre Formation	Confined		
[20]	Brazil	Sao Paulo	56	4	Guarani aquifer / Botucatu Formation	Confined by the Serra Geral Formation (600	TDS = 1,059 - 1,321 g/L EC = 1702 - 1842 µS/cm Cl = 0,085 - 0,098 g/L	Sandstone

[1] The capacity mentioned for the Dunea Meijendel case is based on current best estimates. Efforts are made to see whether this capacity can be achieved, including pilot research

					meters of basalt-rock)		

3.2.2 Water quality BWRO feed water

As the feed water quality was part of the article selection procedure for this study, all selected papers show most water quality parameters within the range of concentrations present in individual wells present in the Meijendel dune area. Figure 3-4 shows the chloride concentrations of the described BWRO sites found within the selected studies including the (expected) concentration in the Dunea case (highlighted as orange bar, orange area gives the range between the minimum and maximum concentration found in the different wells in the Meijendel-area). Chloride, which is perhaps the most common parameter used to describe the salinity of a specific water, show that the expected Dunea feed water is more saline compared to most cases within this study. With increasing feed water salinity in (BW)RO installations the maximum achievable recovery generally decreases and a higher pressure (= more energy) is needed for the desalination process. However, this figure is a clear indication that **application of BWRO on comparable feed water salinities has been implemented already at several places in the world**. Note that little information could be extracted from the selected articles on oxygen concentrations in the feed water, hindering direct assessment of the (an)aerobic nature of these feed waters. More detailed information of the water quality in the selected studies can be found in Appendix II – Overview table.

Compared to existing BWRO systems described in the selected articles and scientific reports, the salinity in the Dunea case is rather high, although far lower than seawater.

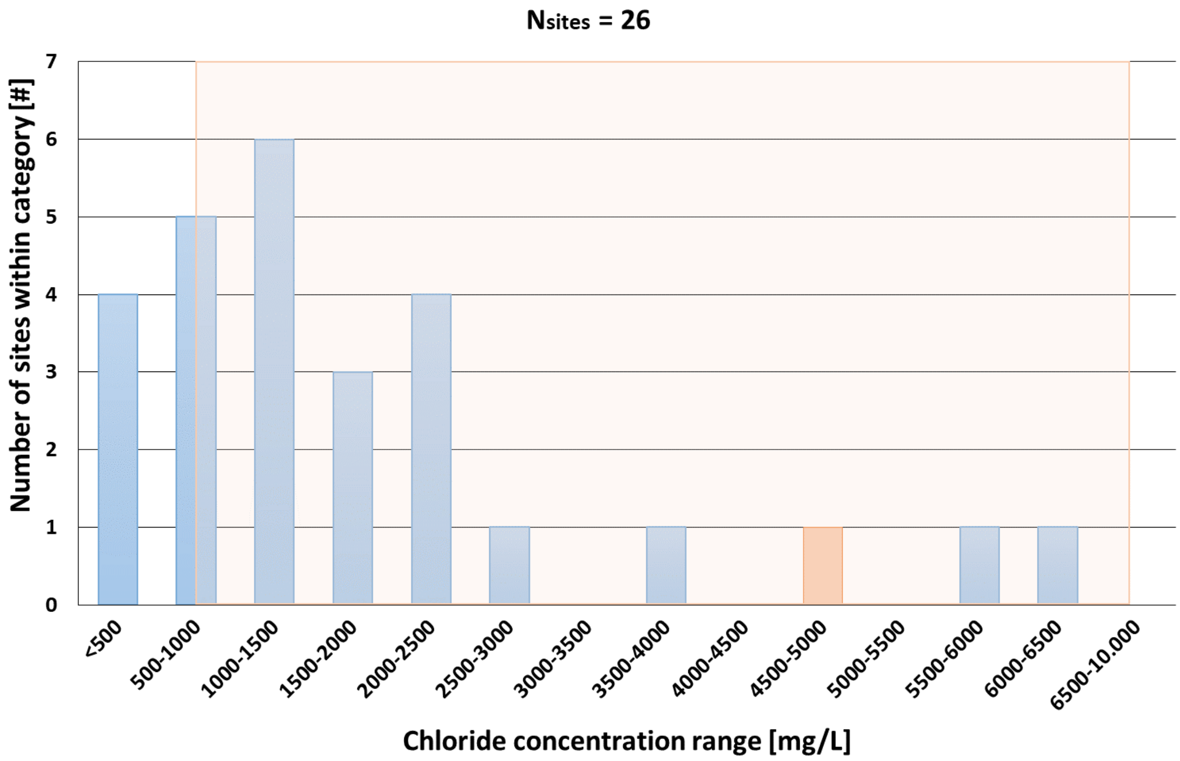


Figure 3-4: Overview of chloride concentrations found in the described BWRO sites within the selected studies including Dunea's estimated concentration range. The orange bar is indicative for the (expected) average Meijendel concentration whereas the orange area indicate the minimum (left boundary) and the maximum (right boundary) concentration found in one of the individual Meijendel wells.

3.2.3 Clogging of brackish water extraction wells

Clogging is an operational risk for water extraction wells. In general, water well clogging can be handled in operations, either through preventive measures (e.g., specialized well design or adjustment of well operation) or curative measures, in particular well rehabilitation (i.e., mechanical and/or chemical cleaning of the well screen, gravel pack, and/or well bore). Clogging usually is a gradual process, however in specific cases, water well clogging can be relatively fast, persistent and difficult to manage, leading to high operational costs and risk of interruption of the water production.

No data on water well clogging was found in the literature reviewed for this report. However, there is a lot of experience, both practical and scientific, in occurrence and mitigation of clogging of water extraction wells in the Netherlands (see for example the handbooks [21] and [22]). While this information stems from experience and research on *fresh*water extraction wells, some can be learned from this on clogging risks of brackish water extraction wells. In addition, there is to be learned from practical (but anecdotic) experience with brackish water extraction in the Netherlands, by the greenhouse industry, by Tata Steel in IJmuiden, and by water supply companies Vitens (well field Noardburgum) and Brabant Water (pilot Zevenbergen).

In general, three types of water well clogging are distinguished:

1. Chemical clogging, i.e. formation of chemical precipitates on the water well's filter screen and/or in the gravel pack. Mixing of different (chemical) groundwater types is the cause of chemical well clogging. While calcite precipitation has been reported in some cases, the most common form of chemical well clogging is formation of iron(hydr)oxide precipitates, resulting from mixing of oxic and anoxic, but iron-rich water types. This mixing occurs within the well and, to a lesser extent, within the gravel pack, hence the formation of precipitates at or near the filter screen.

2. Mechanical or particle clogging, i.e. the blockage of soil pores at the well bore by straining of (naturally occurring) soil particles. Particle clogging is the dominant cause for clogging of water wells extracting from anoxic (mostly confined) aquifers. Particle clogging can be mitigated by regularly switching on and off the water well (i.e., the shock from switching on and off the well is thought to unleash the blocked particles).

3. Biological clogging, i.e. the formation of biomass on the water well's filter screen. Biological clogging often occurs in combination with chemical clogging, e.g. from biomass (slimes) produced by iron oxidizing bacteria.

All brackish groundwater extractions in the Netherlands, including the pilot planned by Dunea, extract (brackish) anoxic groundwater from deep and/or (semi)confined aquifers. No mixing of water types occurs, and so particle clogging is the only form of clogging that would be expected. To the best of our knowledge, no severe clogging issues have been reported for brackish groundwater extractions by the greenhouse industry in the Netherlands. There are tens of (small) brackish groundwater extractions in Westland, some of them operating for more than 15 years. However, it should be noted that these extractions do not run constantly, but only during times when farmers are short of harvested rainwater. Intermittent operation helps to prevent particle clogging.

At their facility in IJmuiden, Tata Steel has been extracting brackish groundwater for several decades, using wooden (teak) water wells. Water is extracted between approximately 130 and 180 meters depth and used for cooling. The Tata water extraction wells have been operating without known problems between late 1960s and early 2000, until clogging issues started to occur in some of the wells from 2005 onwards ([23]). The exact cause for clogging has not been determined, however, the most likely cause was thought to be inflow of oxic groundwater from leakages higher up in the well casing (i.e. aging of the old teak wells), subsequent formation of iron(hydr)oxides when water types mixed, and settlement of these particles during standstill of the wells. Iron(hydr)oxides were indeed found in abstracted water from some of the wells, forming an operational risk for the cooling installations (Tata Steel, personal communications).

The only longer term experience with brackish groundwater extraction for drinking water in the Netherlands is at the Noardburgum well field of Vitens (Freshkeeper pilot, see section 3.3.1) and in the Zevenbergen pilot of Brabant Water (section 3.3.2) [6]. In both pilots, brackish water extraction has been running almost constantly for two (2009-2011, Noardburgum) and almost four consecutive years (2009-2013, Zevenbergen). No clogging issues have been reported for the extraction wells, despite the fact that in both pilots the wells were operated 24/7 at constant discharge (50 m3/h) to ensure a constant feed of brackish groundwater to the RO installations (i.e. water wells were not switch on/off regularly to prevent possible particle clogging). At Zevenbergen, soil particles were present in elevated concentrations in the extracted brackish water in the first weeks of the pilots, after which concentrations dropped to normal, low levels. These elevated concentrations did not cause problems for the extraction well, but did result in fast clogging of the cartridge filters, which had to be replaced regularly in those first weeks. It is thought that the temporarily elevated concentrations were the result of clay particles dispersed from the sediments during drilling of the brackish water extraction well using freshwater (a change in the SAR ration after infiltrating freshwater into a saline aquifer can induce clay peptisation / dispersal; SAR = Sodium Adsorption Ratio, i.e. ratio between Na^+ and [Ca^{2+} + Mg^{2+}] in the pore water).

In 2014, a follow-up pilot was initiated by Vitens, and a second Freshkeeper well was drilled (Freshkeeper well: both fresh and brackish groundwater are extracted within one well, but with two separate filter screens). The extracted brackish water is not used, but disposed of directly in the underlying aquifer (i.e. the brackish water filter screen serves merely to protect the freshwater filter screen from inflow (upconing) of brackish water). This extraction well has been in operation for 6 years now, without any clogging problems reported. Since 2018, the Freshkeeper well constructed in 2009 has been put in operation again as well, and as such, at present two brackish water (Freshkeeper) extraction wells are in operation at well field Noardburgum.

In summary, from long-term experiences with freshwater extraction wells and anecdotic experiences with brackish water extraction wells, the following can be learned about clogging risks for the brackish water extraction well planned by Dunea:

- The planned extraction well will extract water from a semi-confined, anoxic aquifer. Particle clogging is the dominant cause for clogging of water wells extracting from anoxic aquifers;
- To our knowledge, other brackish groundwater extractions in the Netherlands have not experienced any clogging problems. The experience (greenhouse horticulture, Tata, Vitens, Brabant Water), however, is anecdotic;
- Particle clogging can be mitigated by regularly switching on and off the water well, but this is not feasible in the Dunea pilot as the BWRO requires a constant inflow of feed water;
- In the first weeks after well construction, particle concentrations in the extracted water may be relativeky high. This is due to dispersal of clay particles during drilling of the brackish water extraction well using freshwater. At Zevenbergen, these elevated concentrations did not cause problems for the extraction well, but did result in fast clogging of the cartridge filters, which had to be replaced regularly in the first weeks of the pilots.
- Chemical clogging of the water extraction well is <u>not</u> considered a risk for the extraction well. It is crucial, however, to prevent the inflow (leakage) of oxygen into the system, as iron(hydr)oxide precipitates will form, which may foul the cartridges and membranes. Prevention of oxygen leakage is standard procedure for anoxic BWRO, and was not at all a problem in the Noardburgum and Zevenbergen pilots.

3.2.4 Brackish groundwater pre-treatment

Of the selected case studies, fourteen cases mentioned pre-treatment of the brackish groundwater prior to feeding the BWRO installation [6], [8], [26]–[29], [10], [13], [14], [17]–[19], [24], [25]. In Figure 3-5 an overview of these fourteen cases with respect to the type of pre-treatment applied is shown. Six out of fourteen studies use (self-cleaning) cartridge filters as only pre-treatment step prior to feeding the BWRO installation, having final mesh sizes between 10µm and 1 µm. These cartridge filters have low area-requirement and are relatively easily replaced if needed, possibly explaining their frequent use in small-scale BWRO systems but also in large-scale BWRO systems (52.900 m^3/day,[8]).

Generally speaking, since brackish water typically originates from (deep) aquifers, the abstracted water does not contain oxygen (i.e. the water is anaerobic). This means that iron and manganese are present in their soluble form, Fe^{2+} and Mn^{2+}/Mn^{3+}. If, during pre-treatment after abstraction, the water is subjected to oxygen, iron and manganese will (partly) oxidize to form insoluble iron and manganese (hydr)oxides (Fe^{3+} and Mn^{4+}). This can cause severe clogging within present pre-treatment filters or even within the RO membrane system itself. Within the selected articles, no information was found about the oxygen concentration in the abstracted brackish water. Since the expected average feed concentration in the Meijendel area contains 8 mg/L of iron in, presumably, anaerobic water, it is therefore of extreme importance to keep the water anaerobic all the way from abstraction, pre-treatment, BWRO treatment and concentrate transport up until the very moment of concentrate treatment/disposal. Under continuous operation, when the complete system is pressurized, one would not expect introduction of oxygen in the system. However, during for example initial start-up, replacement of cartridge filters, vacuums originating from bad design of pumps and/or by dosing of anti-scalant or cleaning chemicals, oxygen can emerge in the system. Adequate dosing of bisulphite in the oxygen-rich parts of the installation before re-start is a way to prevent any unwanted oxidation to occur.

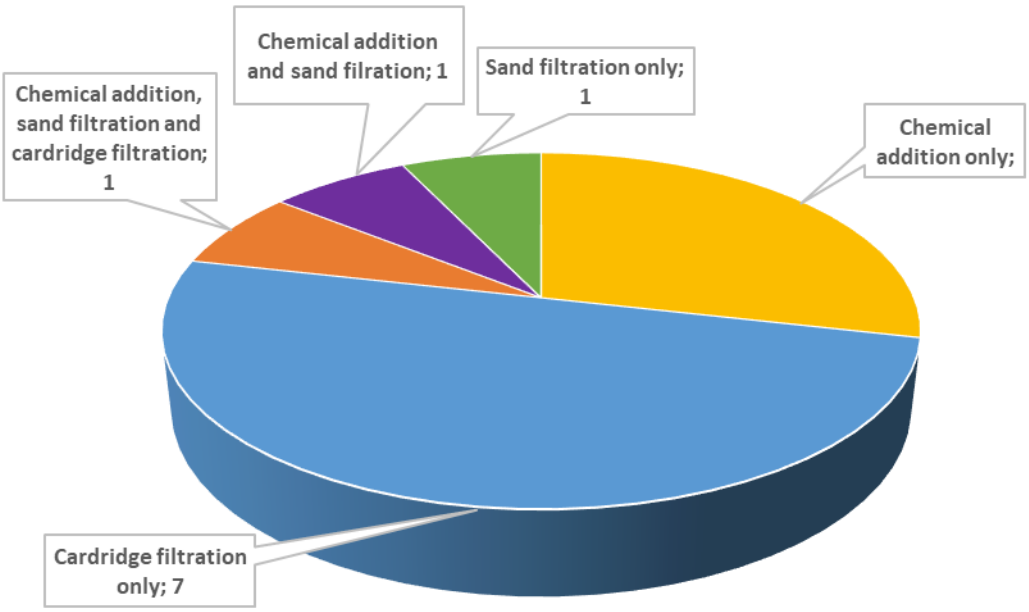


Figure 3-5: Application of different pre-treatment technologies for BWRO systems in cases where pre-treatment was described (n = 14).

Chemicals added in the pre-treatment step described in the selected articles include anti-scalant, chlorine and sodium-meta bisulphite [10], [13], [14], [24], [25]. Anti-scalant increases the solubility of salts, which would otherwise precipitate within the RO membrane system or in the concentrate transport line due to the increase in concentration. Dosing of chlorine is used to prevent biological fouling in downstream processes by inactivating bacteria, but due to its oxidizing nature it can also oxidize dissolved iron and manganese which will form iron- and manganese(hydr)oxides. Therefore, particle removal technologies like rapid sand filtration or cartridge filters are applied post chlorine dosing, to prevent clogging of the RO membrane system. As free chlorine is known to be able to damage the structure of (thin film composite) RO membranes, it is important to remove any unreacted free chlorine. For free chlorine removal and/or for complete removal of oxygen from the feed water, bisulphite dosing can be applied. This species is easily oxidized by both free chlorine and oxygen, removing these species from the feed water.

The studies which do not mention a pre-treatment for BWRO are not necessarily incomplete: it could be that no pre-treatment is necessary. The core function of cartridge filters and sand filters is the removal of suspended solids from the feed water, preventing clogging of the RO membrane feed spacers. Aquifers can act as natural sand filters by themselves and therefore produce particle-low water which is directly suitable for BWRO application. This is largely dependent on properly dimensioning the abstraction well (diameter and pumping rate in harmony with aquifer composition) [22]. Commercially available RO membranes have feedwater requirements in terms of Nephelometric Turbidity Unit (NTU) and Silt Density Index (SDI) parameters (see for instance [25]).

3.2.5 Scaling prevention measures for BWRO installations

By applying BWRO, solute concentrations of the concentrate stream will be higher compared to the feed stream. This may lead to precipitation within the BWRO process or, after a certain induction time, within the produced concentrate stream. This precipitation is generally unwanted and scaling prevention measures like anti-scalant addition or pH modification are applied to mitigate these problems. Alternatively, the recovery of the BWRO system, which is the ratio of the amount of product water over the amount of feed water, can be decreased. Since the feed water quality of the selected studies are similar to the range in Dunea feed water composition (see Appendix I – Memo Dunea), scaling prevention measures applied in these cases are quite relevant. Figure 3-6 shows the bicarbonate, calcium, and silica concentrations found within these studies including the (expected) concentration in the Dunea case (highlighted as orange bar, orange area gives the range between the minimum and maximum concentration found in the different wells in the Meijendel-area). In addition, the reported recoveries of all selected articles and scientific reports are shown. Bicarbonate, calcium and silica concentrations are often involved in the consideration to apply anti-scalant and/or pH modification. It can be concluded that the average concentration of these parameters in the Dunea case is generally in the middle to higher range compared to the other studies, while the range of concentrations present in the individual Dunea wells match the average values in the selected studies particularly well. For more detailed information about the type and dosing of anti-scalant and pH correction applied in the various, see Appendix II – Overview table.

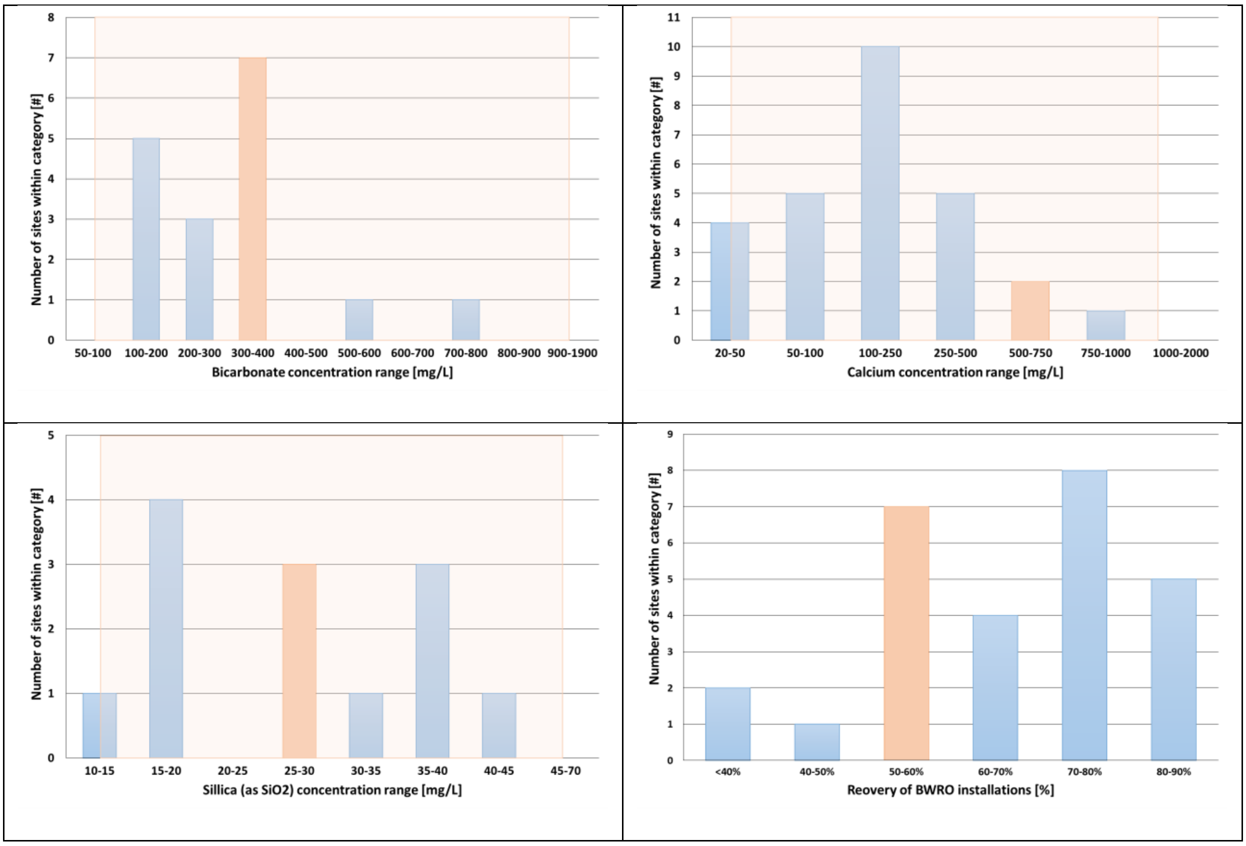


Figure 3-6: Overview of bicarbonate, calcium, silica concentrations found in the selected studies including Dunea's estimated concentration range. The orange bar is indicative for the (expected) average Dunea concentration whereas the orange area indicate the minimum (left boundary) and the maximum (right boundary) concentration found in one of the individual Dunea wells. Recoveries are shown in the bottom right panel.

Since the similarity between Dunea's case and the selected studies is high (as discussed above), the application of scaling prevention measures in the studies coupled with their respective recoveries are indicative for Dunea as well. Figure 3-7 shows that BWRO systems having a recovery >50% usually use anti-scalants, possibly supplemented by pH modification (blue section). BWRO systems having a recovery ≤50% might need anti-scalant and/or pH modification as well (orange/yellow), but there are examples of anti-scalant-free and pH modification-free BWRO installations which are the Dutch cases (green section). However, the feed water of the Dutch cases which are situated further away from the sea contains less salt compared to the average water quality from the Meijendel wells.

Recently, the performance of 8 commercially available anti-scalants was tested on a wide range of feed water qualities [30]. Next to these practical studies, theoretical considerations based on specific calculation software can aid in answering the question whether the average Meijendel feed water can be treated at 50% recovery without the use of anti-scalant or pH modification. In Appendix IV – Genesys Membrane Master 4 prediction BWRO Meijendel, the result of the Genesys anti-scalant calculation tool for Dunea's expected water quality is given. According to this calculation, addition of 4.58 mg/L Genesys LF anti-scalant will prevent oversaturation of calcium carbonate and manganese during BWRO operation. Note that as aluminium, barium and strontium feed concentrations were not available, (scaling of) these ions were not accounted for in this calculation. A pH modification from 7.3 to 5.5 would be required to sufficiently lower the saturation indexes of the above mentioned components and that for this calculation iron supersaturation is not considered given the BWRO feed water is (supposed to be) kept anaerobic at all times. Note that Genesys LF anti-scalant, according to the safety data sheet, contains 20-50 weight% of phosphonic acid (H_3PO_3) [31], which can be assumed to be a phosphate precursor.

Based on the calculated average water quality expected and the anti-scalant software calculation result using this water quality, precipitation of calcite, iron and manganese is a risk for brackish water treatment by Dunea. However, with a recovery of ≤ 50%, a solid operation with use of only simple anti-scalants seems viable as long as the water is kept anaerobic during treatment to prevent iron precipitation.

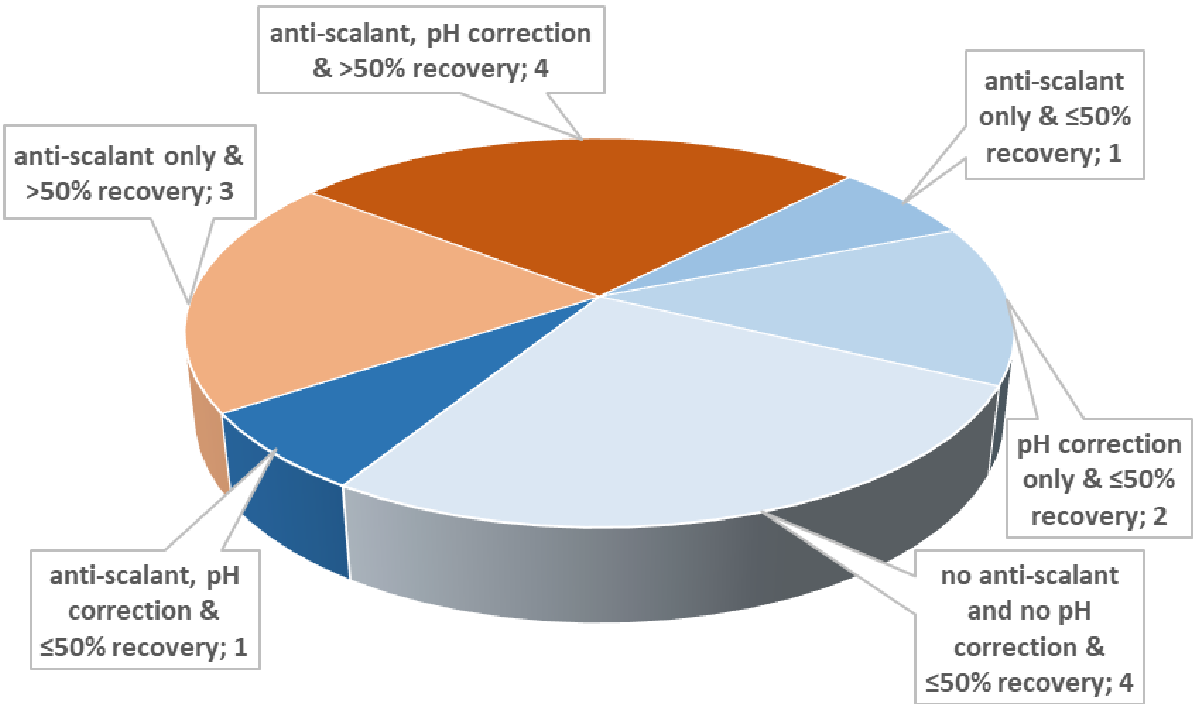


Figure 3-7: Application of scaling prevention measures in 15 BWRO sites described in the selected papers

3.2.6 BWRO membranes and permeate water quality adjustments

The type of RO membrane applied has a large influence on energy consumption, permeate water quality, fouling potential and investment costs of any BWRO installation. As shown in Figure 3-8, from the selected studies which specified the type of RO membrane embedded in the system, DOW FILMTEC membranes were most often used. All Dutch cases used DOW FILMTEC RO membranes. Koch membranes were mentioned in two studies of which one study described 6 BWRO plants and a Hydranautics RO membrane model was used in one of the selected studies. More detailed information of the types of membranes applied can be found in Appendix II – Overview table. Calculations using reverse osmosis membrane software of well-known RO membrane suppliers can aid in answering the question which membrane is the optimal choice in terms of economics, durability and permeate water quality. Results of such a software calculation are shown in Appendix III – DOW WAVE prediction BWRO performance Meijendel, using DOW FILMTEC XLE-440 membrane modules. From these calculations it can be concluded that the Stiff and Davis saturation index will be positive, meaning precipitation is likely to occur and pH correction and/or anti-scalant dosing might be required in the Dunea case (as already mentioned in section 3.2.5).

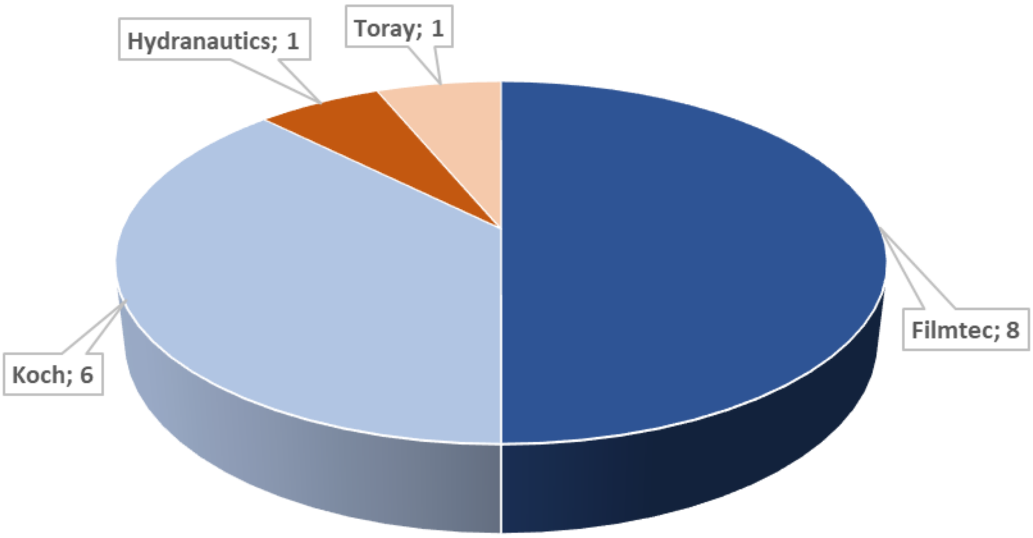


Figure 3-8: Application of RO modules of commercial suppliers in 16 BWRO case studies

Permeate quality depends on multiple factors including feed water composition, membrane type, membrane age, temperature, flux, and membrane cleaning procedure (chemicals and frequency). It is therefore difficult to predict permeate water quality and only few articles provide information about this. In Israel at a large scale BWRO installation (52.900 m^3/day intake) equipped with DOW FILMTEC BWRO and sea water reverse osmosis (SWRO) membranes, permeate concentrations of TDS, chloride and boron were <20 ppm, <10 ppm and <0.2 ppm respectively, meeting the Israeli Water Authority and Israeli Ministry of Health regulations [8]. Recently, a model for boron permeation was published for large scale sea water reverse osmosis (SWRO) membrane application in Spain [32]. The anticipated permeate water quality for BWRO application on feed water of Dunea's coastal dunes (Meijendel) is shown in Table 3-2, based on calculations by the WAVE program (see Appendix III – DOW WAVE prediction BWRO performance Meijendel). Ammonium, sodium and chloride are present in the permeate in relevant concentrations with respect to the water quality parameters listed in the Dutch legalisation called the Drinkwaterbesluit. Drinking water company Oasen uses cat-ion exchange to remove the residual ammonium from the permeate prior to remineralisation and aeration. The membranes used in the calculation were the DOW Filmtec XLE-440, since they could also be used in the Membrane Master 4 program for anti-scalant dosing projection (see

Appendix IV – Genesys Membrane Master 4 prediction BWRO Meijendel). These membranes have based on the specs listed in the WAVE program a NaCl rejection of 99.0% at 2000 mg/L NaCl. As the Meijendel feed water contains twice this NaCl concentration, it is not strange that calculated rejections of Na^+ and Cl^- were slightly lower at 97,9% and 98,1%, respectively. Note that Table 3-2 contains only the components relevant for scaling in RO systems, except for barium, strontium and boron as feed water concentrations were unknown. Other parameters, which are relevant in drinking water production like arsenic and chromium, are not calculated and therefore no qualitative data on these is available. For arsenic, based on an average feed concentration of 3.5 µg/L, a maximum feed concentration of 7.6 µg/L, a retention of 99% and a recovery of 50%, the concentrate arsenic concentration is expected to be on average 7 µg/L and maximum 16 µg/L.

As deep brackish groundwater in the coastal zone of The Netherlands may contain high concentrations of CH_4 which passes RO membranes, CH_4 removal by aeration upon desalination might be required. Data of CH_4 concentrations in brackish ground water are however scarce. All foreign cases in the selected articles that describe post-treatment of BWRO permeate, mention pH modification / remineralisation (and chlorination [10]) as applied post-treatment prior to use for drinking water or mixing with raw brackish groundwater for use as irrigation water.

Table 3-2: Calculated concentrate and permeate composition based on the expected average feed water composition in Dunea's case using DOW WAVE software. All concentrations are rounded to whole numbers, except for concentrations <1. Used membrane type is DOW Filmtec XLE-440, recovery 50%, flux 24.4 L/m²h, feed water type 'well water SDI<3', design temperature feed water 10°C.

Parameter	Unit	Feed	Concentrate	Permeate
NH_4^+	mg/L	4	8	0,2
K^+	mg/L	61	121	1
Na^+	mg/L	2427	4804	50
Mg^{2+}	mg/L	274	545	3
Ca^{2+}	mg/L	525	1044	6
CO_3^{2-}	mg/L	1	6	0
HCO_3^-	mg/L	309	606	4
NO_3^-	mg/L	1	1	0,1
Cl^-	mg/L	4897	9701	92
F^-	mg/L	0,03	0,05	0
SO_4^{2-}	mg/L	619	1233	4
SiO_2	mg/L	25	50	0,3
CO_2	mg/L	16	18	16
TDS	mg/L	9144	18121	160
pH	-	7,3	7,5	5,6

3.2.7 Concentrate management and environmental impact

None of the foreign cases which describe BWRO concentrate management methods provide details about the regulatory trajectory of approval of the selected method. Figure 3-9 provides an overview of the number of times a certain concentrate management method is applied based on the selected articles and scientific reports that provided this information. Concentrate disposal by deep well injection is used most frequently, with concentrate volumes ranging between 18,5 to 5000 m^3/day and distances to sea ranging between 19 and 970 km. Second most frequently applied method is disposal at sea, with concentrate volumes ranging between 3480 to 8464 m^3/day and distances to sea ranging between 1 and 59 km. Disposal in surface water is sometimes possible when brackish feed water is of good quality (relatively low salinity), recovery of the BWRO installation is low and surface discharge regulations are not very strict. The use of evaporation ponds is generally only possible in a warm, dry climate where area availability is not an issue. There are no examples of concentrate being transferred via the sewer system to the municipal waste water treatment plant.

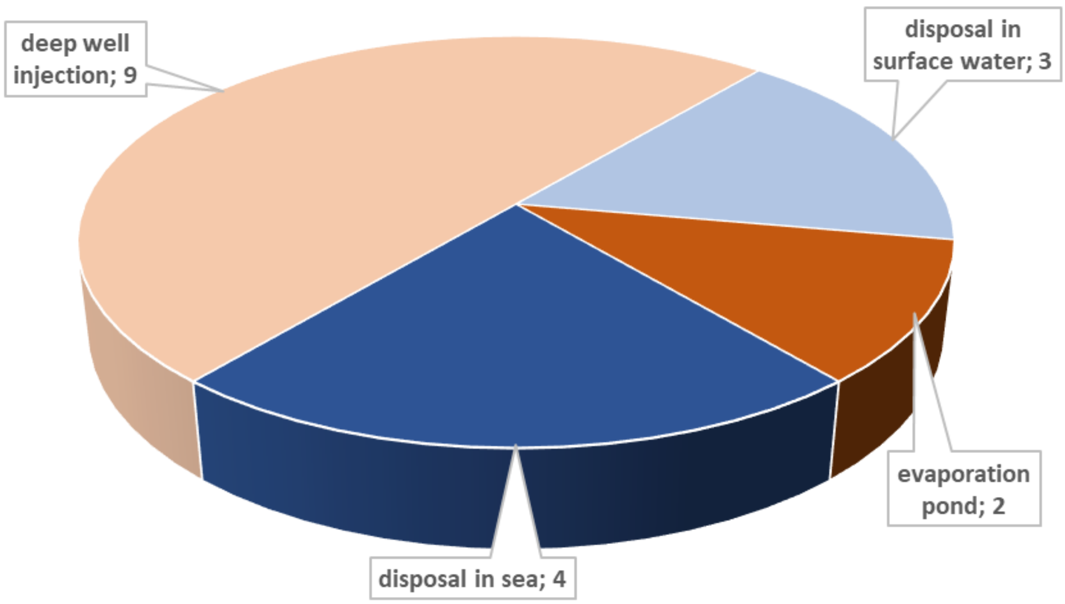


Figure 3-9: Overview of applied concentrate management methods used in the selected cases of the literature study

BWRO concentrate streams can contain, apart from the feed water components in higher concentrations, various chemicals which are added to the stream during the BWRO process, including anti-scalants, acids and bases for pH modification, bisulphite and cleaning agents for in-place RO membrane cleaning (CIP). Anti-scalants can contain phosphorous, which makes them unwanted to dispose of in nature. Several phosphorous-free, biodegradable anti-scalants are tested for their performance in RO processes [33], [34]. Typical chemicals used for membrane cleaning mentioned in the selected articles include ethylene-diamine-tetra-acetic acid (EDTA),citric acid, ammonia, sodium hydroxide and sodium dodecyl sulphate. These are mainly used to achieve extreme pH value's at which mineral deposits on RO membrane surfaces are either dissolved or converted into water-soluble components which are removed from the system. Usually, the volume of this stream is small compared to the produced volume of concentrate and therefore, after mixing with the concentrate, the effect on the combined residual stream is limited and therefore both streams can be disposed together.

3.2.8 BWRO economical evaluation

When considering the costs of BWRO plants, one should consider that prices vary significantly with BWRO plant location, age, installed capacity and feed water composition (especially salinity). Figure 3-10 shows the building year and the intake capacities of already built BWRO installations described in the selected papers. The largest part of already built BWRO installations considered here were built before 2000 and all cases are smaller in terms of capacity compared to Dunea's intended plans; a larger capacity generally leads to lower specific costs. Only considering BWRO installations built since 2009 and where economic information is available, three Palestinian installations of 1200-1440 m^3 intake per day capacity produce drinking water at 0,24 – 0,31 €/m^3 [35]. A study describing 6 slightly older BWRO installations built in the period 2004 – 2008 and having a permeate production capacity ranging from 4546 m^3/day up to 68.191 m^3/day, mentions specific costs between 0,26 and 0,57 €/m^3 [36]. Of the hereinafter mentioned four Dutch cases, specific costs range between 0,21 and 0,96 €/m^3 (see paragraph 3.3). Dunea's intended permeate producing capacity lies, considering all infiltration areas separately, between 2750 (Solleveld) and 18.000 (Meijendel) m^3/day. Probably the most relevant cases for Dunea are the Dutch cases, separately described in paragraph 3.3, as they were recently built and operated in the Netherlands. An overview of all relevant economic data found in the selected articles and scientific reports is given in Table 3-3.

BWRO has been applied since the '80s. The capacity of the proposed abstraction by Dunea is one order of magnitude larger compared to most of the case studies considered in this review.

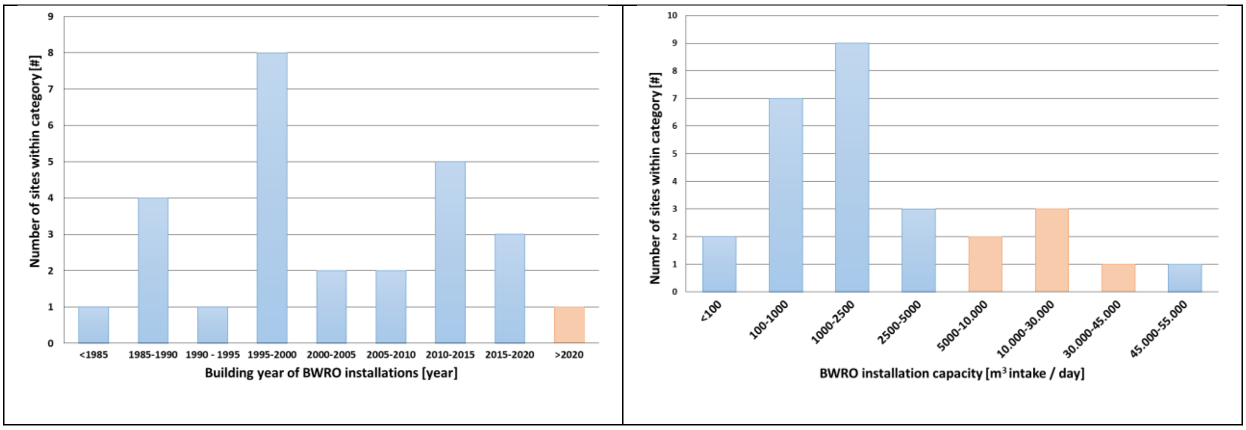


Figure 3-10: Overview of the building year and capacity of the BWRO installations described in the selected articles. Dunea's planned abstraction capacities in Solleveld, Berkheide and Meijendel amount 5500, 22.000 and 36.000 m^3/day, respectively

Table 3-3: Overview of economics of BWRO systems. For the conversion from dollar to euro, an exchange rate of 0,91 € per $ was used.

Country	Capacity	CAPEX	OPEX	Specific costs	Energy consumption	Remark	References
Unit	m^3 intake / day	k€	k€ / year	€ / m^3	kWh / m^3	–	–
Jordan	136.364	95755	4143	0,26	0,83	Extrapolated pilot study	[10]
United States	3785 – 56781	2217 – 94287	528 - 7478	0,26 – 0,58	n.a.	Seven BWRO installations in Texas	[36]
Algerian	3500	114	90,9	–	0,13	Membrane replacement-, electrical- and chemical cost only	[15]
Palestine	1200 – 1920	n.a.	n.a.	0,25 – 0,65	0,75 – 2	Six small BWRO installations in Palestine	[35]
Netherlands	1200	n.a.	n.a.	0,47	0,58	Dutch example case Zevenbergen. Specific costs include abstraction and RO treatment	[17], [37]
Netherlands	1200	350	20,9	0,21	0,63	Dutch example case Noardburgum. Specific costs permeate production only. CAPEX/OPEX include well construction, RO installation and pumping energy only	[6], [18], [38]
Netherlands	600	66,4	37,9	0,35	0,45	Dutch example case Ridderkerk. No pre- or posttreatment cost considered	[19]
Spain	600	n.a.	n.a.	0,37	1,4 – 1,7	Based on 11 years BWRO experience. Membrane replacement cost comparison	[26]–[28]
Spain	450	360	45,5	0,30	1.5 kWh (/m^3?) for abstraction, 1 kWh/m^3 for RO passage and 0.08 kWh/m^3 for post-RO transport	Energy consumption contains well abstraction, RO treatment and distribution	[13], [14], [25]

3.3 Dutch cases

BWRO is frequently applied by greenhouse horticulture in the Netherlands (e.g., Westland, Noordoostpolder, Wieringermeer, Haarlemmermeer). These systems have been running for over ten years, however, (practical) experiences are poorly documented. Within this section, four Dutch, well-documented example cases of BWRO application will be discussed in more detail; Noardburgum (Vitens), Zevenbergen (Brabant Water), Ridderkerk (Oasen) and 's-Gravenzande (Prominent Tomatoes). The first two example cases (Noardburgum and Zevenbergen) mentioned are pure drinking water production oriented, the third (Ridderkerk) is slightly more driven towards a test-case of an innovative abstraction and injection well design (but having a drinking water company as partner in the project) and finally the 's-Gravenzande case is an example of BWRO application in horticulture / industry. Figure 3-11 shows the approximate location of these four locations on the map of the Netherlands, together with the depth at which a chloride concentration of 1000 mg/L is reached with respect to mean sea level (MSL) (adapted from [39]).

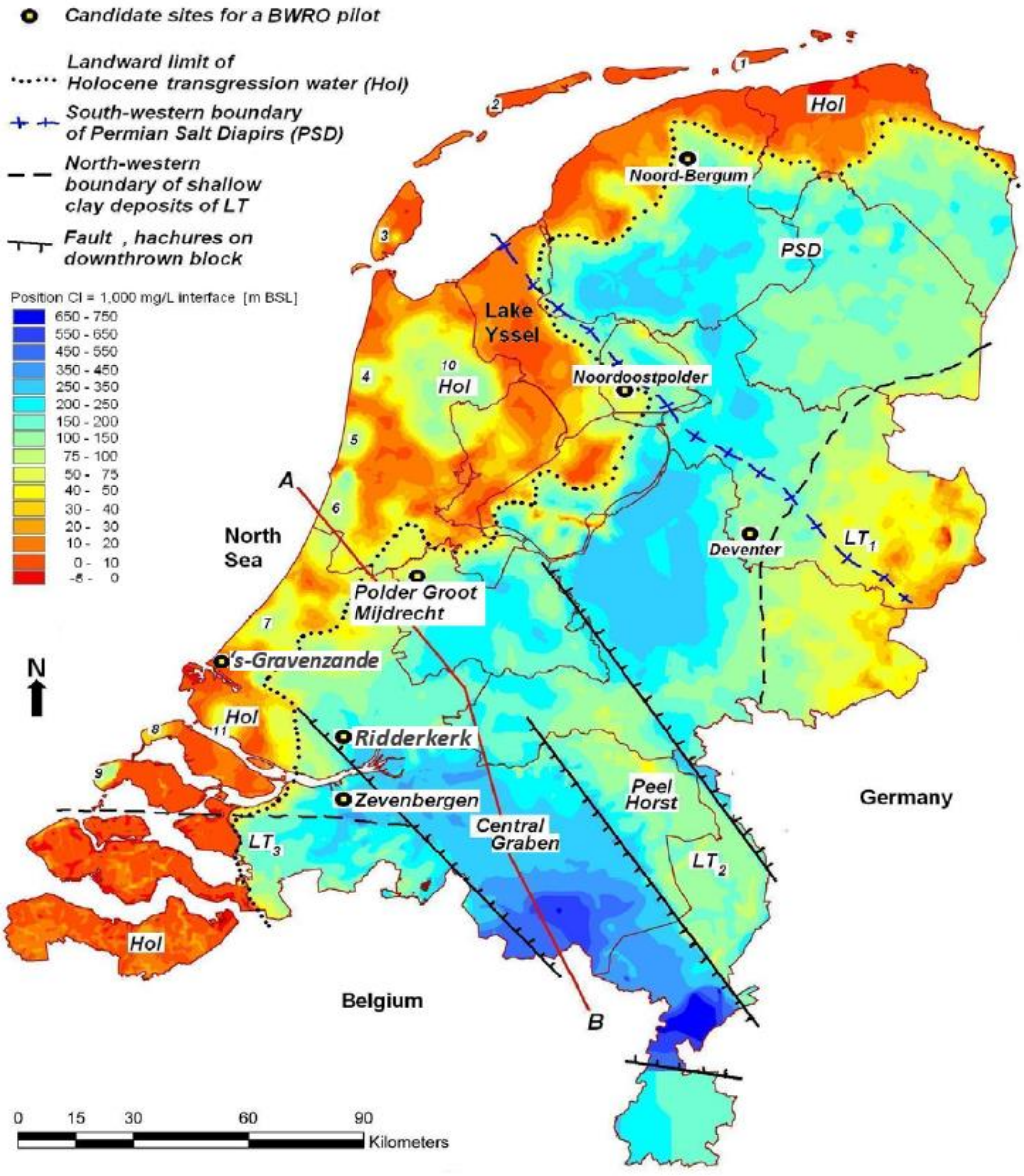


Figure 3-11: Approximate position of the Noardburgum, Zevenbergen, Ridderkerk and 's-Gravenhage BWRO (pilot) plants [39]

3.3.1 Noardburgum (Vitens)

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 [40]. In 1993, drinking water company (later becoming) Vitens had to close the northern well field of production location Noardburgum (see Figure 3-12), because of salinization of the freshwater abstraction wells due to up-coning of the underlying brackish groundwater. This production stop led to the necessity to develop new well fields in areas less vulnerable to salinization.

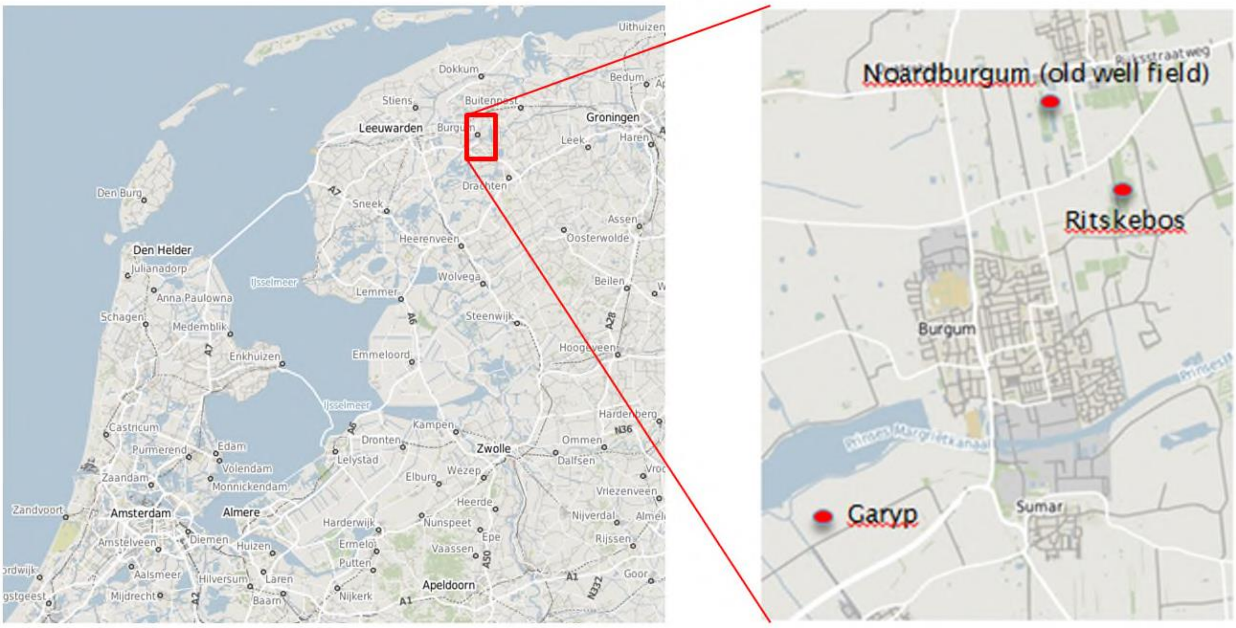


Figure 3-12: Well fields Noardburgum (abandoned in 1994), Ritskebos and Garyp, in the northern part of the Netherlands

In 2002, the Freshkeeper concept was developed [41]. Seven years later, Vitens started a pilot study (1200 m^3 intake / day) in the old well fields of Noardburgum to see whether this concept, simultaneous abstraction of brackish- and fresh water, would prevent the Noardburgum well field from further salinization [18]. The freshwater was distributed directly to the nearby drinking water production plant; the abstracted brackish water was desalinated after which the fresh permeate was distributed to the production plant, while the BRWO concentrate was disposed of by deep well injection into an underlying brackish aquifer. The pilot was successful: a down-coning of the brackish-fresh water interface was observed, meaning that salt concentrations within the production aquifer decreased over time [38], [39]. In 2014, a follow-up Freshkeeper pilot was initiated at Noardburgum (again: 1200 m^3 intake / day), which aim was both design optimisation and operation optimisation: maximizing the freshwater recovery while minimizing saltwater interception. This pilot rendered important insights in the aquifer's response to different pumping regimes and (changing) spatial distribution of the brackish-fresh water interface at variable distances from the abstraction and injection well [40]. In this pilot the abstracted brackish water was however directly injected in an underlying brackish aquifer, without the application of BWRO.

Since April 2018, both Freshkeeper wells installed for the two pilots are operational, abstracting in total one million m^3/year of freshwater which is fed to the drinking water production plant. The brackish water abstracted from both wells is not treated with RO, but directly injected into an underlying (more saline) aquifer. BWRO is thus not applied mainly because the discussion on concentrate disposal by deep-well injection in the Netherlands is still ongoing, and there are no clear (national) policies yet.

The geohydrology, hydrochemistry and well design of the Noardburgum site is described in Appendix V – Noardburgum site description (Table 6-3, Figure 6-3, Figure 6-4 and Figure 6-5) [39], [42]. Abstracted brackish water (510 – 1800 mg/L Cl) was, during the first pilot, treated with a DOW FILMTEC LE-440i RO membrane installation operating at 50% recovery. The recovery of 50% allowed for anti-scalant free and pH modification-free treatment of the brackish groundwater, a prerequisite for legal deep well injection in the underlying more saline layer for these pilots. Chemical composition of the RO feed water, permeate and concentrate is presented in Table 3.5.

During and after BWRO treatment, the feed and concentrate streams were kept anaerobic, preventing the formation of iron(hydr)oxides which could clog the RO membranes and/or the injection well [37]. Membrane scaling and injection well clogging due to mineral precipitation were not a problem at the Noardburgum site, even though some minerals were over-saturated in the concentrate stream (including calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), siderite ($FeCO_3$), hydroxyapatite ($Ca_5(PO_4)_4(OH)$), quartz (SiO_2), rhodochrosite ($MnCO_3$) and vivianite ($Fe_3(PO_4)_2{\cdot}8H_2O$)). Possible explanations for the absence of precipitation of carbonates (calcite, dolomite, siderite) were the geochemistry of the aquifer and the very high Fe^{2+} concentrations of the Noardburgum concentrate (78.5 mg/l). Compared to Zevenbergen (section 3.3.2), the Noardburgum disposal aquifer was finer textured, and while calcite contents were very high at Zevenbergen (18 weight%), the Noardburgum disposal aquifer was nearly free of calcite (0 weight%). Both the presence of calcite and the finer texture are beneficial for carbonate precipitation, as they provide potential nucleation sites [43]. The high iron(II) levels at Noardburgum may also explain why calcite precipitation did not occur. In lab experiments with "synthetic" solutions mimicking the Noardburgum concentrate, with and without Fe^{2+} present, calcite precipitates did not form in presence of Fe^{2+}, but precipitation occur in solutions free of Fe2+ [39]). Herzog et al. [[44]] drew similar conclusions in a study on magnetic water treatment: Fe2+ inhibits calcite precipitation.

The overall chemical composition of the BWRO concentrate stream produced in Noardburgum fits the natural chemical environment of the disposal aquifer, with only a slight increase observed in iron concentration which, from environmental viewpoint, was considered irrelevant [39]. For deep well injection for drinking water purposes, clear policy is yet to be defined in the Netherlands. Nowadays, the stand-still principle is applied, meaning that BWRO concentrate injection should not lead to an increase in selected water quality parameters (which include organic micro-pollutants, metals, nutrients and halogens) [45].

In Table 3-4, the available economic relevant parameters of the Noardburgum pilot installation are shown. It must be noted that the specific costs (in €/m^3 produced permeate) were calculated based on a depreciation period of 20 years and a rough estimate of the CAPEX and OPEX of the wells and BWRO installation, so permeate production costs only (so excluding costs of post-treatment of drinking water production from permeate, drinking water distribution and concentrate disposal, among others).

Table 3-4: Overview of economic parameters available from the Noardburgum pilot test

Capacity	CAPEX	OPEX	Specific costs	Energy consumption	Recovery	References
m^3 intake / day	k€	k€ / year	€ / m^3	kWh / m^3	%	–
1200	350	20,9	0,21	0,63	50	[6], [18], [38]

3.3.2 Zevenbergen (Brabant Water)

At Zevenbergen, the pilot plant consisted of a single brackish water abstraction well, meaning that no fresh water is abstracted. Figure 3-13 shows the setup of the Zevenbergen installation, including the chloride profile at the start of the pilot in the different aquifers [39]. The abstracted brackish groundwater is treated with a RO installation equipped with DOW FILMTEC LE-440i membranes, having a total capacity of 1200 m^3 intake water per day and operating at 50% recovery. The concentrate stream is disposed in a separate aquifer composed of unconsolidated, medium grained, marine sands of late Tertiary and early Pleistocene age with intercalated clay or loam layers. It contains many reactive minerals as can be derived from the high concentrations of carbonates, bulk organic matter (BOM), phosphate, trace elements and pyrite. Further details on the aquifer composition at the Zevenbergen site can be found in Appendix VI – Zevenbergen site description, Figure 6-6. Chemical composition of the RO feed water, permeate and concentrate is presented in Table 3.5.

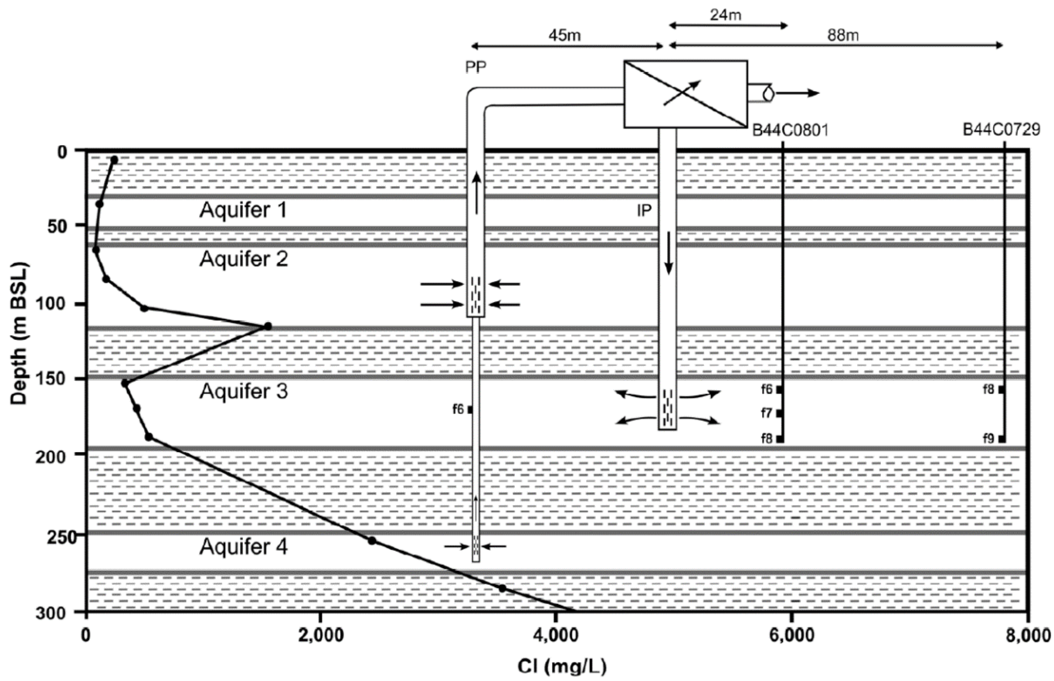


Figure 3-13: Setup of the BWRO pilot Zevenbergen (Brabant Water), including pumping (PP), injection (IP) and observation wells. The RO feed water was a mixture of water abstracted from aquifer 2 (49.2 $m^3\,hr^{-1}$) and aquifer 4 (0,8 $m^3\,hr^{-1}$), to ensure overall chloride concentration would be >300 mg/L throughout the pilot experiment. The RO installation operated at 50% recovery, rendering 25 $m^3\,hr^{-1}$ of permeate water and an equal amount of concentrate. BWRO concentrate was disposed by deep well injection into aquifer 3.

The relatively low recovery of 50% was maintained to prevent severe mineral supersaturation of the concentrate, which could cause scaling of the membranes and/or clogging of the injection well and aquifer due to mineral precipitation. Anti-scalants (e.g., polyphosphates) or pH modifications, which are often used to prevent membrane scaling, were not used in this BWRO pilot. This was an important prerequisite for approval of the injection permits issued for the pilot. The BWRO concentrate at Zevenbergen contained high levels of bicarbonate, calcium, strontium, lithium and boron. Boron was present in both the concentrate (1240 µg/L) and permeate (268 µg/L), as it is known that the un-dissociated form of boric acid (H_3BO_3) can pass RO membranes unlike many other dissolved species. Note that the world health organization (WHO) standard for boron in drinking water is 500 µg/L, which is in the same order of magnitude compared to the permeate concentration found in Zevenbergen [46], [47]. The macro parameters chloride, sulphate, calcium, iron, silica and (natural) dissolved organic carbon (DOC) concentration exceeded the levels of the native groundwater, yet levels in the concentrate were not worrying from an environmental point of view. As mentioned, boron, lithium and strontium levels were high in the concentrate, but all fell within the ranges found in the disposal aquifer.

Table 3-5: Chemical composition of feed water ("voeding"), permeate ("permeaat") and concentrate ("concentraat") of the Noardburgum and Zevenbergen BWRO pilots. Data from [6], used with permission.

		Noardburgum			Zevenbergen		
		voeding	permeaat	concentraat	voeding	permeaat	concentraat
pH		6.8	5.2	7.0	7.3	5.5	7.5
EC	[mS/m]	253	2.92	473	136	1.47	256
CH4	[mg/L]	15.0	14.7	15.7	1.0	n.d.	1.4
Cl	[mg/L]	691	4.4	1409	321	1.8	583
Br	[mg/L]	2.9	<0.1	5.5	0.6	n.d.	1.8
F	[mg/L]	0.06	<0.05	0.12	0.16	<0.05	0.27
HCO3	[mg/L]	344	<10	671	386	7.8	752
SO4	[mg SO4/l]	<2.0	<2.0	<2.0	4.0	0.1	7.8
tot-PO4	[mg P/L]	0.16	<0.02	0.28	0.10	0.006	0.20
TOC	[mg/L]	4.5	<0.5	9.6	4.0	0.8	7.8
Na	[mg/L]	90.4	4.4	174	167	2.4	328
K	[mg/L]	3.5	0.36	6.5	6.3	0.1	12.4
NH4	[mg N/L]	0.9	0.2	1.4	0.9	0.8	1.7
Ca	[mg/L]	375	0.83	754	128	0.14	259
Mg	[mg/L]	32	<0.1	61	12.0	0.14	24.2
Sr	[ug/L]	1237	<2	2516	997	1.0	2106
Ba	[ug/L]	261	<1	533	1.7	0.03	2.9
Fe	[mg/L]	39.5	0.077	78	1.6	0.002	3.4
Mn	[mg/L]	0.85	<0.005	1.7	0.04	<0.001	0.09
Si	[mg Si/L]	15.8	<0.5	30.0	11.2	0.12	19.9
As	[ug/L]	<0.1	<0.1	<1.0	1.3	n.d.	2.0
B	[ug/L]	n.d.	n.d.	n.d.	726	268	1239
Ni	[ug/L]	<1.0	<1.0	<1.0	1.4	n.d.	2.6

n.d. = niet bepaald

The injected concentrate strongly interacted with the disposal aquifer, which resulted in a complex pattern of water quality changes, including precipitation of calcite and siderite, dissolution of minerals rich in magnesium and strontium, and sorption of phosphate, silica, arsenic and nickel from the injected solution. In comparison with the native groundwater, injection had no negative effects on the water quality of the disposal aquifer at Zevenbergen, i.e. was in line with constraints set within the Water Framework Directive. However, the injection pressure required increased with approximately 10% within one year [39], which is an indication of well clogging. The equal end levels of bicarbonate at the first and second observation well indicated that all precipitates formed in between the injection well and the first observation well at 24 m distance. An estimated 35 tons of $CaCO_3$ must have been deposited there during the first year of injection, explaining the observed increase in required injection pressure. Both the presence of calcite and the fine texture within the disposal aquifer are beneficial for carbonate precipitation, as they provide potential nucleation sites [43]. This would also explain why precipitation at Zevenbergen occurred in the disposal aquifer, and not during the RO treatment. Also, this provides a warning for the operation of RO's and injection wells: once the first precipitates have formed, they may catalyse and thus accelerate further precipitation, leading to scaling and/or clogging. In a later stage of the pilot, CO_2 (weak acid) was dosed to the concentrate. This effectively stopped calcite precipitation in the disposal aquifer. As such, a recovery of 50% can be technically possible for BWRO installation operation, but, depending on both physical and chemical soil composition and feed water composition, measures should be taken to prevent mineral precipitation in the disposal aquifer. Well regeneration was performed using HCl, often applied for wells clogged with carbonates [48].

In Table 3-6, the available economic relevant parameters of the Zevenbergen pilot installation are shown. It must be noted that the specific costs (in €/m^3 produced permeate) were calculated based on abstraction and BWRO treatment only (post-treatment and distribution costs not included, among others). Note that, upon request and agreed confidentiality, supporting information on the numbers mentioned is available at Brabant Water (Stephan van den Wetering) within a Royal Haskoning DHV report about the Zevenbergen pilot.

Table 3-6: Overview of economic parameters available from the Zevenbergen pilot test

Capacity	CAPEX	OPEX	Specific costs	Energy consumption	Recovery	References
m^3 intake / day	k€ / year	k€ / year	€ / m^3	kWh / m^3	%	–
1200	n.a.	n.a.	0,47	0,58	50	[17], [37]

3.3.3 PURO Ridderkerk (Oasen)

In Ridderkerk, an innovative brackish water abstraction and infiltration well design was tested, called the PURO technology [19]. As shown in Figure 3-14, this well design incorporates the BWRO installation into the well, allowing for direct concentrate disposal at an underlying aquifer and abstraction of permeate water.

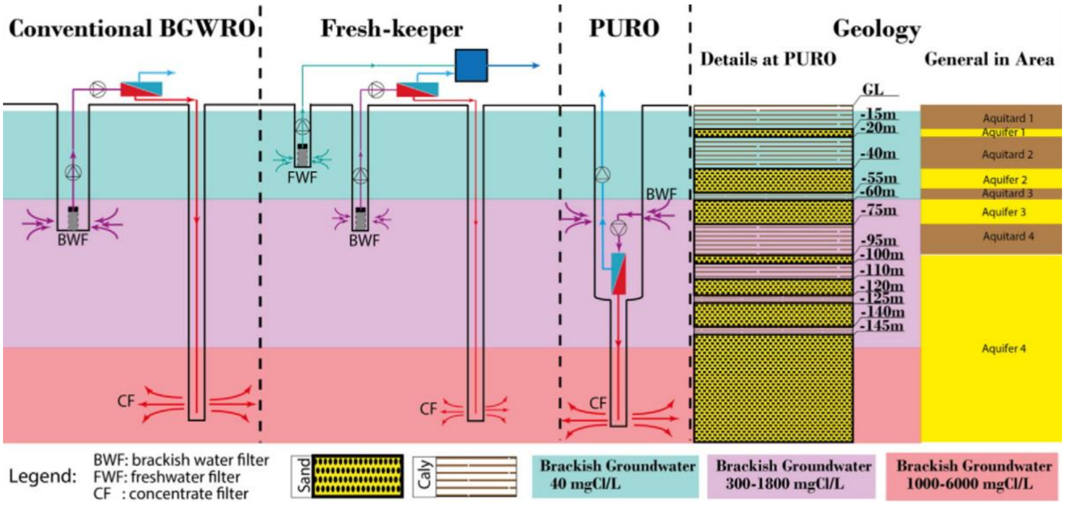


Figure 3-14: Treatment of brackish groundwater with reverse osmosis happens with conventional BWRO methods in The Netherlands (left), Fresh-keeper (middle-left) and PURO (middle-right). The hydrogeology at PURO location in details and in surrounding is shown (right).

The hydrogeological setting at which the PURO system was installed in Ridderkerk is shown in Figure 3-15. The hydrogeology at the PURO site exists of a semi-impermeable layer of clay and peat to a depth of 15 m Below Surface Level (BSL). Underneath is a sandy aquifer, which contains freshwater, to a depth of 26 m BSL which is separated by a major semi-impermeable layer of clay (26–40 m BSL) from the second aquifer. At greater depths, down to about 100 m BSL, an alteration of (fine) sands and poorly developed impermeable clay layers are found. The boundary between fresh and brackish water is found at the second aquifer (about 60– 70 m BSL) around which the intake of the RO unit is located. The injection filter of the concentrate is located at a depth of 175–200 m BSL.

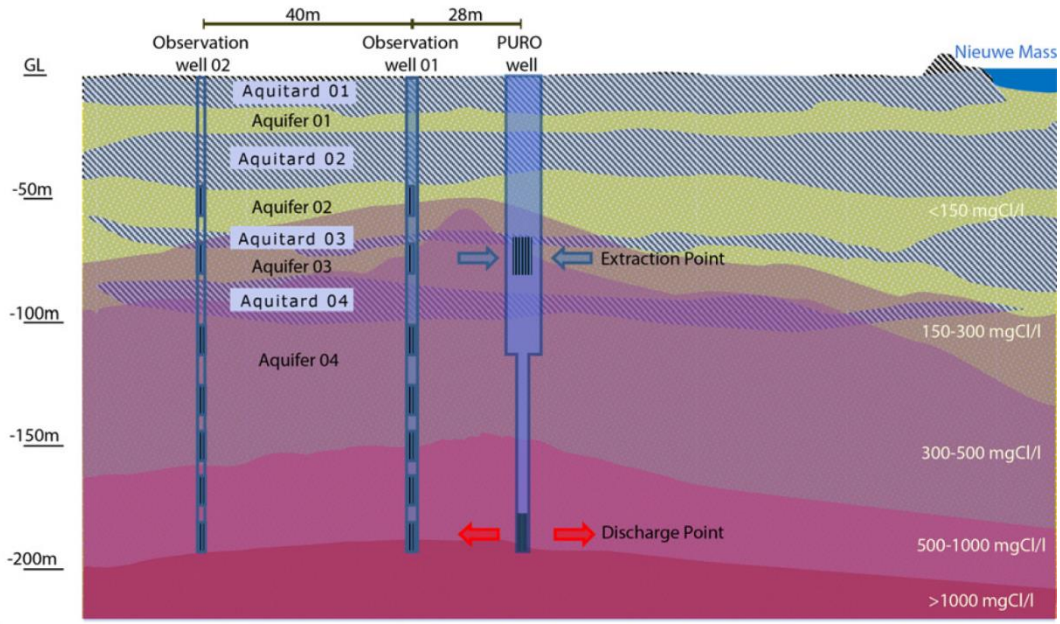


Figure 3-15: Simplified hydrogeology around the PURO pilot and location of observation wells in the pilot.

The PURO installation was equipped with 16 inch modules containing DOW FILMTEC LE-440i membrane elements, having a total capacity of 600 m^3 intake water per day and operating at 50% recovery. No anti-scalant and/or pH modification was applied, to allow for deep well injection of the produced concentrate. The main advantage of the PURO design is a calculated and argued energy saving of 39% compared to conventional BWRO. This is achieved by using the hydrostatic pressure on the brackish feedwater, such that the high pressure required for RO treatment can be easily achieved using a less powerful pump. Main disadvantage of PURO is that operation and maintenance costs of PURO installations are higher compared to conventional BWRO, since the actual RO installation is not readily accessible. This was also one of the main lessons learned from the pilot. The calculated costs for a conventional BWRO system is shown in Table 3-7.

Table 3-7: Overview of economic parameters for a conventional BWRO installation in the Ridderkerk pilot test [19]

Capacity	CAPEX	OPEX	Specific costs	Energy consumption	Recovery	References
m^3 intake / day	k€	k€ / year	€ / m^3	kWh / m^3	%	–
600	66,4	37,9	0,35	0,45	50	[19]

3.3.4 Brackish water abstraction below fresh water storage in ’s Gravenzande, Westland

An innovative ASR solution [9], [16], [49]–[52], combined with a Freshkeeper and RO, is used at this site to maximize the recovery of injected freshwater surpluses (see Figure 3-16). Multiple partially penetrating wells (MPPW) allow for deep injection and shallow abstraction, postponing the salinization during recovery to attain higher recovery efficiencies. By simultaneously abstracting upper fresh and lower brackish groundwater, salinization of the fresh water well is prevented even longer. The abstracted brackish water is used as additional and reliable freshwater source after desalination. This site therefore shows very strong parallels with the proposed set-up of brackish water abstraction in Dunea’s well fields, while lying within only 10 km of the Solleveld well field.

The Westland ASR system is installed to inject the rainwater surplus of 270,000 m^2 of greenhouse roof in a local shallow aquifer (23 to 37 m-below sea level (m-BSL). Rainwater can be pre-treated and injected with a total rate of 40 m^3/h, and recovered with a total maximum rate of 50 m^3/h. Deep brackish water can be recovered at the base of the aquifer for RO-treatment with ~ 5 m^3/h.

The results at the demo site indicate that ASR-RO is technically viable and beneficial. A high level of control on the freshwater – brackish water interface was attained and additional freshwater could be produced by abstracting the brackish water and subsequently treating this with RO. This created a high-quality freshwater stream and a waste stream with a quality similar to the native groundwater in a deeper, more saline aquifer.

The biggest operational threat (besides the common operational threats using normal brackish water RO) during ASR-RO in a sand aquifer is clogging of RO-membranes and potentially also of the saline water re-injection well(s). This is caused by mobilization of clay particles (during freshening of brackish zones) and formation of Fe-colloids, both in the infiltration stage. Abstraction of brackish water in deeper sections of the aquifer to prevent firm admixing of injected freshwater and regular flushing of the RO-membranes are viable methods to overcome these operational threats.

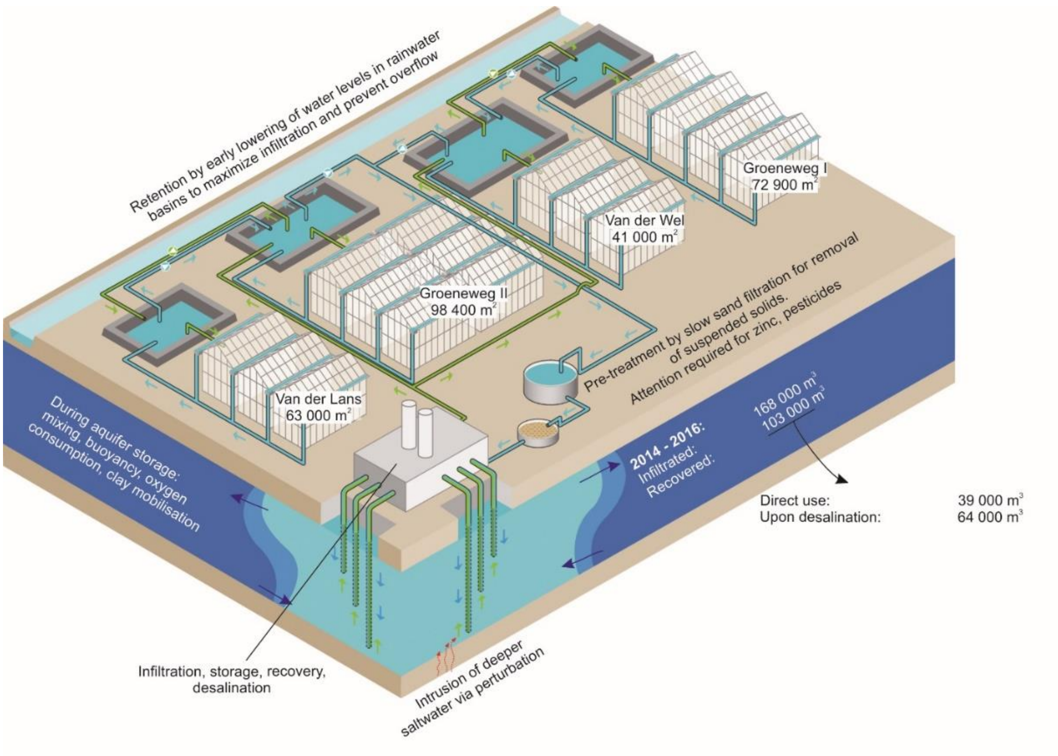


Figure 3-16: Set-up of the Westland combined ASR and RO scheme

4 Conclusions

Based on the literature research conducted, it is safe to say that BWRO is a widely applied technology throughout the world at least since the '80s. BWRO plants having capacities between 50 and 52.900 m^3 intake / day have been build and up to 11 years of stable operation of BWRO systems on comparable feed water composition expected from Meijendel have been reported. BWRO application on a large scale like the proposed Meijendel case is already in place and operational in, for instance, the Israeli Granot BWRO plants. Given the close proximity of Meijendel to the North Sea, Meijendel's expected salinity of the abstracted brackish water is among the highest compared to the cases described in literature, but still far below sea water salinity levels. On the contrary, the projected recovery at which the BWRO installation in Meijendel will operate is among the lowest of the cases described in literature. Suppliers of membranes and/or anti-scalants have software tools available capable of designing, comparing and predicting BWRO installation design performance and required anti-scalant application or pH modification. Most cases described in literature apply a pre-treatment step before the BWRO installation of which cartridge filtration is most frequently mentioned in this study. Application of any pre-treatment step focussed on suspended solids removal is highly recommended since it acts as an early warning system in case of unexpected feed water alterations and (BW)RO membranes are not suitable for high suspended solids containing feed water operation. Concentrate streams (together with membrane cleaning products) are, in most cases, either infiltrated in an underlying more saline aquifer or disposed of in the nearest salt water body.

BWRO is frequently applied by greenhouse horticulturalists in the Netherlands (e.g., Westland, Noordoostpolder, Wieringermeer, Haarlemmermeer). These systems have been running for over ten years, (practical) experiences however are poorly documented. In the Netherlands, four BWRO example cases have been reported in detail, of which three are drinking water related: Noardburgum (Friesland, Vitens), Zevenbergen (Noord-Brabant, Brabant Water), Ridderkerk (Zuid-Holland, Oasen). The 's Gravenzande (Zuid-Holland, Prominent Tomatoes) case is one of the few well-documented horticultural applications of BWRO. These Dutch cases mainly show that stable BWRO operation for over one year can be achieved at several locations in the Netherlands, including 's Gravenzande which is located at 10 km distance of the Solleveld well field. In 's Gravenzande, Zevenbergen and Noardburgum proof of principle of the Freshkeeper concept is provided. In addition, these cases show that at BWRO capacities one order of magnitude lower compared to Dunea's intentions, brackish water is abstracted from aquifers and readily converted by BWRO into ultrapure water for less than €1,00 per 1000L.

Therefore, answering the main research question, the conclusion can be drawn that BWRO does deserve to be called 'proven technology'. Much can be learned / deducted from available example cases described in literature, but one has to keep in mind that factors including feed water composition, concentrate management method and the type of final application of the produced ultrapure water make each BWRO unique for both its specific challenges and its specific solutions.

Based on the calculations made in this report which apply specifically to the average feed water quality of the Meijendel area, scaling by precipitation of calcite, iron and manganese is a risk for brackish water treatment by Dunea. However, with a recovery of ≤ 50%, a solid operation with use of only simple anti-scalants seems viable as long as the water is kept anaerobic during treatment to prevent iron precipitation. With respect to the calculated BWRO permeate composition, ion exchange is advised for trace ammonium removal. As deep brackish groundwater in the coastal zone of The Netherlands may contain high concentrations of methane which is not completely rejected by RO membranes, CH_4 removal from the produced permeate by aeration might be required. When combining ASR and BWRO in a sandy aquifer, there is a risk of mobilization of clay particles (during freshening of brackish zones) and formation of Fe-colloids, both in the infiltration stage. This may lead to clogging of the abstraction wells and of the RO-membranes.

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6 Appendix

6.1 Appendix I – Memo Dunea

BESTEMD VOOR: Dunea
BETREFT: Brakwaterkwalitieit Meijendel - Berkheide
VAN: Koen Zuurbier
DATUM: 9 augustus 2019

Aanleiding

Binnen COASTAR wordt gemodelleerd aan een grootschalige winning van brakwater onder de zoetwaterlens van Dunea, teneinde drinkwater beschikbaar te maken na ontzilting via omgekeerde osmose en ter bescherming/vergroting van de zoetwaterlens. Om een inschatting te maken van de samenstelling van het voedingswater voor omgekeerde osmose en het concentraat (de waterstroom met daarin de verwijderde zouten) is de samenstelling van het brakke water onderzocht.

Brongegevens

De samenstelling van het brakke water is in het verleden in het gebied bemeten, maar de resultaten zijn beperkt gearchiveerd. Zo zijn ze niet aanwezig in het DINOLoket. Wel is door KIWA (thans: KWR) de rapportage *SWE 93.001: Hydrochemie en hydrologie van duinen en aangrenzende polders tussen Katwijk en Kijkduin* beschikbaar. Hierin zijn historische metingen vastgelegd en geïnterpreteerd.

Aanpak

Algemene brakwaterkwaliteit Meijendel - Berkheide

Door de initiatiefnemers worden onttrekkingsbronnen voorgesteld in de brakke zone onder de zoetwater lens. Beoogd wordt om een chlorideconcentratie van maximaal zo'n 7.500 mg/l onttrekken zodat naar omgekeerde osmose met 50% recovery een concentraat met een chlorideconcentratie van 15.000 mg/l ontstaat. Dit is vergelijkbaar met zeewater voor de kust van dit duingebied. Daarom is uit de database:

1. Een selectie gemaakt van metingen binnen het gebied waar brakwaterwinning wordt beoogd (Meijendel-Berkheide)
2. Een selectie gemaakt van metingen met een chlorideconcentratie van 1000 – 10.000 mg/l.

Hieruit zijn 62 metingen overgebleven, waarbij niet bij iedere meting de volledige samenstelling is gemeten. Hiermee is een inschatting gemaakt van de kwaliteit van het brakwater in het hele gebied.

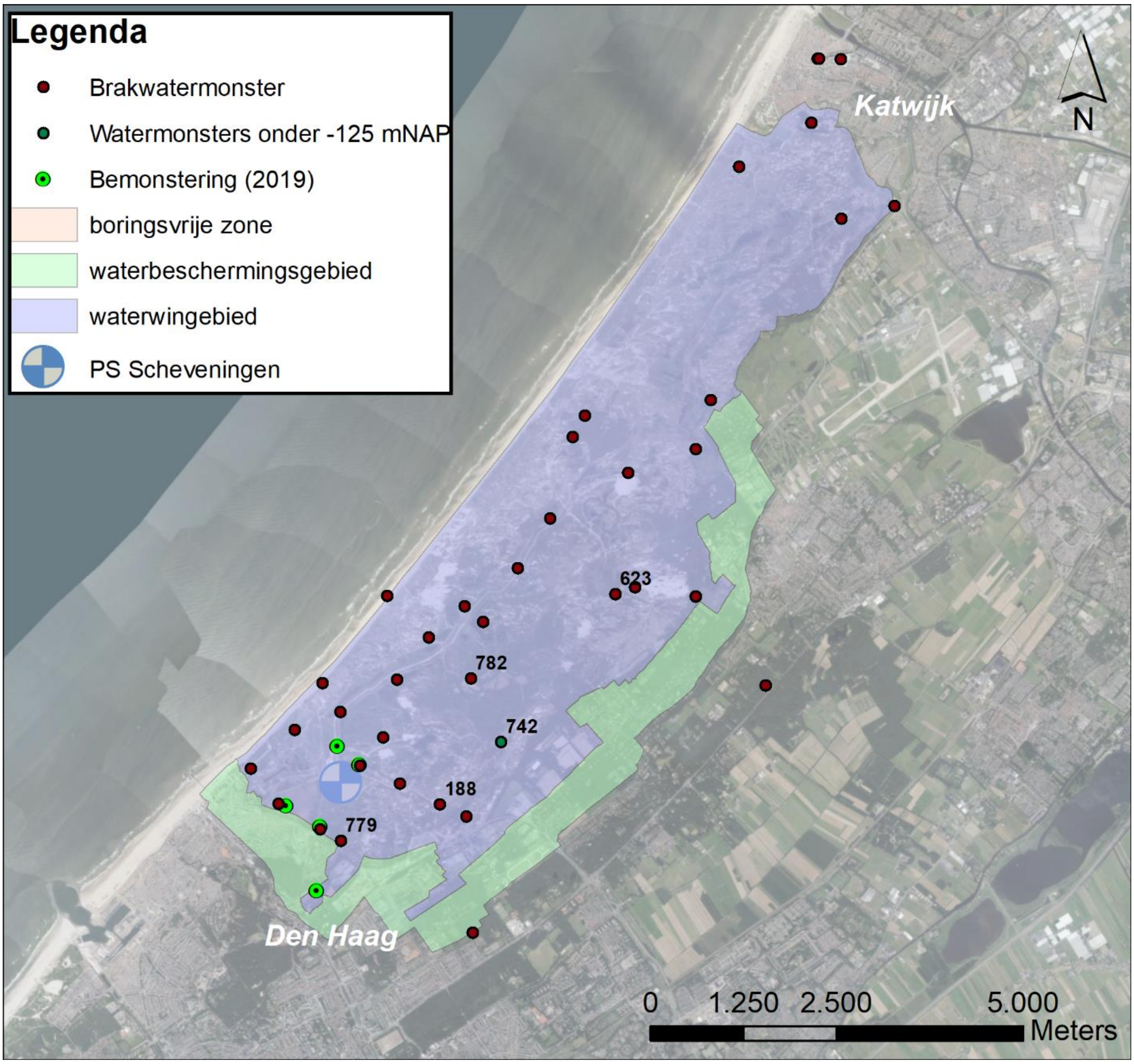
Specifieke kwaliteit brakwater op pilotlocatie

Vervolgens zijn in de omgeving van de mogelijke pilotlocaties (Klein Zwitserland, Harstenbroek, Pompstation Scheveningen) extra monsters genomen en geanalyseerd. De kwaliteit ter plaatse van het pompstation (peilbuizen WME-WPHO-F7 en WME-WPHO-F8: filters op -85 en -97 mNAP) wordt hier belicht omdat dit de voorkeurslocatie is voor de pilot.

Specifieke kwaliteit grondwater doelpakket lozing concentraat pilot
Uit de dataset met monsters is een selectie gemaakt van de filters met een diepte beneden -125 mNAP. Dit zijn filters die in het doelpakket staan van de concentraatlozing (Formatie van Maassluis).

Resultaten algemene kwaliteit brakwater Meijendel - Berkheide
In Tabel 6-1 is de gemiddelde, minimale, en maximale concentratie en de mediaan op basis van alle metingen weergegeven. Dit is een gemiddelde van alle waarnemingen van brakwatermonsters, onafhankelijk van hun locatie. Het geeft daarmee een grof beeld, maar wel beïnvloed door historisch gekozen locaties en filterdiepte. Gezien de spreiding van de monsterpunten (Figuur 17) is dit acceptabel.

Gezien de grote spreiding van het beoogde puttenveld voor brakwaterwinning over de gebieden Meijendel/Berkheide, zal de gemiddelde concentratie de beste inschatting bieden van het voedingswater van de brakwater RO. Een correlatie met Cl zou ingezet kunnen worden om de samenstelling van het brakke water bij verschillende Cl-concentraties te voorspellen, maar is alleen aanwezig voor Na en SO_4 (Figuur 18).



Figuur 17: Locaties monsterpunten ten behoeve analyses brakwater

Tabel 6-1: gemiddelde van gemeten waarden in het brakke water Meijendel-Berkheide

Parameter	Eenheid	Aantal metingen	Gemiddeld	Min	Max	Mediaan	PS_Scheveningen
							(n=2)
EGlab	µS/cm	60	12787	3070	23400	12320	12045
TDS (calc)	mg/l	60	8180	1960	15000	7880	
pH	lab	56	7.3	6.6	8.4	7.3	7.6
Na	mg/l	62	2427	240	6100	2177	2416
K	mg/l	57	61	12	240	54	31
Ca	mg/l	62	525	34	1768	496	218
Mg	mg/l	62	274	19	737	263	73
Fe	mg/l	57	8	0	40	6.5	4.7
Mn	mg/l	55	0.9	0.0	3.3	0.7	0.5
NH4	mg/l	55	4.3	0	27	3.1	3.2
SiO2	mg/l	45	25	12	66	24	21
Cl	mg/l	62	4897	1030	9808	4625	4175
SO4	mg/l	58	619	14	1322	622	596
HCO3	mg/l	62	332	60	1829	284	301
NO3	mg/l	50	0.7	0.0	9.7	0.4	<4.9
PO4-o	mg/l	23	1.5	0.4	3.8	1.5	0.1
Al	µg/l	11	2.0	0.0	5.0	2.0	1.5
As	µg/l	11	3.5	0.0	7.6	4.3	4.7
Cu	µg/l	11	0	0	0.8	0	<3
F	µg/l	22	26	0	260	50	<1
Ni	µg/l	11	4.8	2.0	7.0	5.0	<2
Zn	µg/l	11	11	4.0	22	9.0	<5

Resultaten Monstername Pompstation Scheveningen

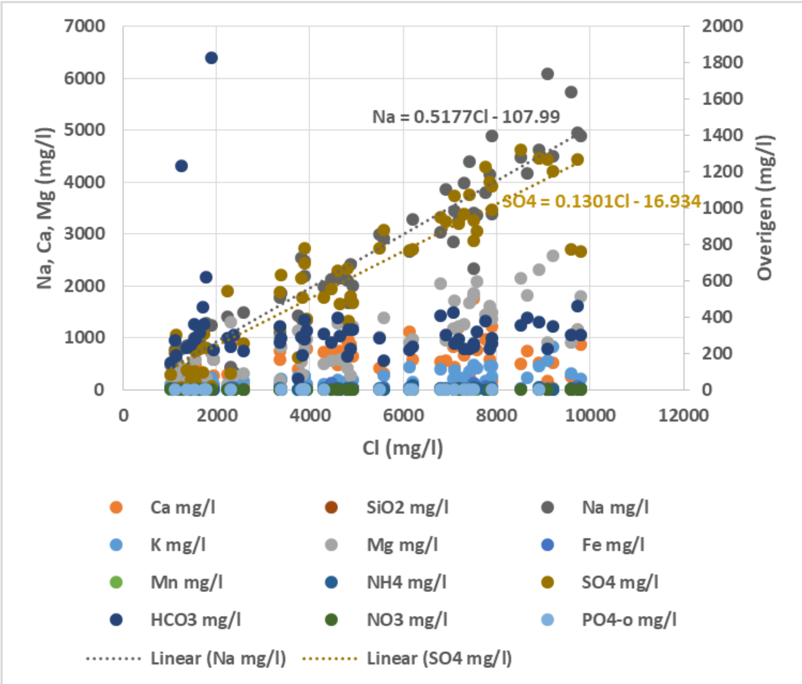
Het bemonsterde brakwater bij Pompstation Scheveningen (Figuur 17) laat een kwaliteit zien die in lijn is met de gemiddelde brakwaterkwaliteit in het gebied. In die zin is de pilotlocatie geschikt. Wel zijn Ca en Mg in een relatief lage concentratie aanwezig, hetgeen met name komt door verzoeting ter plaatse van het filter op -85 mNAP, gekenmerkt door een duidelijk positieve BEX.

Vergelijking te verwachten concentraat met achtergrondconcentratie doelpakket lozing

Het te verwachten concentraat (Tabel 6-2) tijdens de pilot op het pompstation zal met enige zekerheid leiden tot een toename in NH_4, Mn, HCO_3 en SiO_2 in het doelpakket, gezien de duidelijk hogere concentraties in het concentraat. Ten minste een deel van deze toename zal teniet worden gedaan door de vorming van neerslagen na injectie in de ondergrond, zoals aangetoond bij eerdere concentraatinjecties bij Zevenbergen en Noardburgum.

Een toename voor NO_3 wordt berekend op basis van de metingen met een zeer hoge detectielimiet. Vermoedelijk is echter het brakke water vrij van NO_3, waardoor ook in het concentraat de concentraties voldoende laag blijven.

De analyse voor metalen is niet goed te maken door het ontbreken van gegevens van het grondwater in het doelpakket, slechts bij 1 monsters zijn deze parameters geanalyseerd. Wel valt op dat de concentraties in het brakke water dat zal worden onttrokken en ontzilt erg laag zijn.



Figuur 18: Waterkwaliteit van macrochemische parameters uitgezet tegen chloride op basis van de 62 brakwatermonsters uit de database

Tabel 6-2: gemiddelde samenstelling van het concentraat na omgekeerde osmose bij recovery van 50%

Parameter	Eenheid	Gemiddeld	PS_Scheveningen	Ontvangende pakket	Verschil	Verschil
		Concentraat (n=62)	Concentraat (n=2)	(n=7)	Gemiddeld	PS_Scheveningen
EGlab	µS/cm	25573	24090	22415	14%	7%
TDS (calc)	mg/L	16400				
pH	lab			7.2		
Na	mg/l	4854	4831	5789	-16%	-17%
K	mg/l	123	61	194	-37%	-69%
Ca	mg/l	1050	437	451	133%	-3%
Mg	mg/l	547	146	707	-23%	-79%
Fe	mg/l	16	9.5	22	-29%	-57%
Mn	mg/l	1.8	0.9	0.7	162%	36%
NH4	mg/l	8.5	6.4	4.7	82%	37%
SiO2	mg/l	50	42	24	109%	75%
Cl	mg/l	9793	8350	10681	-8%	-22%
SO4	mg/l	1239	1192	1380	-10%	-14%
HCO3	mg/l	664	602	353	88%	71%
NO3	mg/l	1.5	<9.8	2.0	-28%	*381%*
PO4-o	mg/l	3.0	0.2	0.7[1]	367%	-65%
Al	µg/l	4.0	3	0.0[2]		
As	µg/l	7.1	9.4	8.3[2]		
Cu	µg/l	0.3	<6	0.0[2]		
F	µg/l	53	<2	65	-19%	-97%
Ni	µg/l	10	<4	4[2]		
Zn	µg/l	22	<5	14[2]		

[1] *Slechts 2 monsters van de 7 zijn hierop geanalyseerd.*

[2] *Slechts 1 monster van de 7 is hierop geanalyseerd.*

6.2 Appendix II – Overview table

Reference	Country	Location	Distance to sea	Well depth	Aquifer thickness	Aquifer name/formation	Aquifer # : unconfined/confined	Aquifer water quality	Cl	End-user	Type sediment
Unit	-	-	km	m	m	-	-	-	mg/L	-	-
Briao et al, 2014	Brazil	Sao Paulo	56	960	500	Guarani aquifer system / Botucatu Formation	Confined by the Serra Geral Formation (600 meters of basalt-rock)	TDS = 1059 - 1321 mg/L, EC = 1702 - 1842 uS/cm, Cl = 85	98	Drinking water	Sandstone
Koen Zuurbier et al, 2017	Netherlands	Dessin	3			Peize-Waalre Formation	Confined		2222		
Aparicio et al, 2018 & Valdes-Abellan et al, 2003	Spain	Alicante / San Vicente del Raspeig	7	33	16	Quarternary	1: Unconfined	EC = 6000-8010 uS/cm, Cl = 1267-1655 mg/L	1655	Irrigation water	Silts and sands, with a low presence of clays, overlying an impervious loam. Imbedded CaSO4 layers are frequently found
Haidari et al, 2017	Netherlands	Ridderkerk	35	60-70	15	Fluvial	3: Confined	TDS = 981 mg/L, Cl = 380 mg/L	380	?	Alternation of fine sands and poorly developed impermeable clay layers
Raat et al, 2012; Groenendijk et al, 2010	Netherlands	Zevenbergen	65	90-115	57	Maassluis Formation	2b: Confined	EC = 138 mS/m, Cl = 311 mg/L	311	Drinking water	
Wolthek et al, 2013 & Raat et al, 2012	Netherlands	Noordburgum	19	Fresh extraction: 60-80, brackish extraction: 130-150, disposal: 180	100	Enschede/Harderwijk Formation	1b: Confined by clay layers in aquifer 1a	EC = 242 mS/m, Cl = 650 mg/L	650	Direct disposal to improve drinking water	Coarse sand - gravel
Moudjeber et al, 2013	Algarian	In Salah / Oued Rjem	970	400 - 1800	n.a.	Albian aquifer	n.a.	EC = 2.94 - 3.14 mS/cm, Cl = 495 mg/L	495	Drinking water	Sandstone, sparingly CaCO3 and CaSO4
Jahnke et al, 2019	Egypt	El Gouna town	1	25-150	Different strata of 10 - 30 meters, separated by aquitards	Coastal aquifer: Quarternary/Pliocene	Confined	Mixture of TDS 5-15 g/L (brackish groundwater) to TDS 42-44 g/L (Red Sea water + disposed concentrate)	4800	Drinking water and irrigation water supply	Interchange of coarse alluvial fan deposits with finer grained stream/beach deposits, and shallow marine sandy muds and siltstones with carbonates. CaSO4 and CaCO3.
Bason et al, 2016	Israel	Granot	8	n.a.	n.a.	n.a.	n.a.	Start: TDS = 1497 ppm, Cl = 685 ppm; After 10 years: TDS = 1832 ppm, Cl = 803	685	Drinking water + disposal	SiO2
Afonso et al, 2004	Jordan	Zarqa desert	120	n.a.	n.a.	Zarqa aquifer	n.a.	Investigated: TDS = 0,948 - 2,288 g/L. EC = 1568-3500 uS/cm; Zarqa basin: 1,632-3,072 g/L, EC = 3070-4720 µS/cm, Cl = 0,593-1,610 g/L	1610	Drinking water supply	CaCO3, MgCO3 (CaSO4 at some locations)

Brackish water RO plants operating on comparable feed water qualities as average feed water of Meijendel

Reference	Plant name / location	Average feed water quality [mg/L]														
		Ca	Mg	Na	Cl	SO4	SiO2	NO3	NH4+	HCO3	O2	Fe	Mn	TDS	EGV [µS/cm]	pH [-]
Briao et al, 2014	Sao Paulo / Brazil	29	14	192	98	346	14	0.52	n.a.	n.a.	n.a.	0.1	n.a.	1410	1846	8.8
Ahmed et al, 2001	Zahar / Oman	226	117	733	1616	423	n.a.	9	n.a.	318	n.a.	0.00	0.00	3326	4525	7.3
	Assadanat / Oman	369	165	1112	1813	621	n.a.	3	n.a.	186	n.a.	0.02	0.00	4221	6720	7.2
	Haima / Oman	632	252	3255	5636	2406	n.a.	n.a.	n.a.	n.a.	n.a.	0.09	0.00	n.a.	17360	3.1
	Hitam / Oman	499	336	3190	6089	1850	n.a.	35	n.a.	130	n.a.	0.08	0.04	12107	16050	7.7
	Safah / Oman	232	130	2445	2760	2313	n.a.	n.a.	n.a.	150	n.a.	0.02	n.a.	8100	12200	8.1
Zuurbier et al, 2017	ASRRO Westland	247	160	1136	2222	49	17	0	13	534	0	8	2		6896	7.2
Aparicio et al, 2018 & Valdes-Abellan et al, 2012, Prats et al, 1997	University of Alicante / Spain	323	225	1003	1290	1727	17.5	137.9	n.a.	326.1	n.a.	n.a.	n.a.	4689	6990	7.0
Ruiz-Garcia et al, 2018 & 2015	Island Gran Canaria / Spain	202	273	1478	2181	716	37	227	n.a.	774	n.a.	n.a.	n.a.	5468	5300	7.5
Haidari et al, 2017	Ridderkerk / The Netherlands	169	34	89	380	2	25	0	3.39	280	n.a.	n.a.	n.a.	981	n.a.	7.1
Raat et al, 2012; Groenendijk et al, 2010	Zevenbergen	123	n.a.	172	311	5	n.a.	n.a.	n.a.	375	n.a.	n.a.	n.a.	1040	1380	n.a.
Wolthek et al, 2013 & Raat et al, 2012	Noordburgum / The Netherlands	359	30.1	87.7	650	2	16	n.a.	0.85	345	n.a.	40	1	1507	2420	6.8
Mogheir et al, 2013	Al-Nuwairi / B. Suhaila - Khanyounis, Palestine	80	30	400	600	110	n.a.	45	n.a.	n.a.	n.a.	n.a.	n.a.	1100	2000	7.5
	Al-Sharqia / Khanyounis, Palestine	60	40	975	1300	215	n.a.	150	n.a.	n.a.	n.a.	n.a.	n.a.	2500	4100	7.3
	Al-Balad / Deir El-Balah, Palestine	100	190	1150	2200	215	n.a.	95	n.a.	n.a.	n.a.	n.a.	n.a.	3700	6100	7
	Al-Bureij / Al-Bureij, Palestine	85	95	900	1550	200	n.a.	45	n.a.	n.a.	n.a.	n.a.	n.a.	2500	4100	7
	Al-Salam / Rafah, Palestine	55	80	800	1250	200	n.a.	210	n.a.	n.a.	n.a.	n.a.	n.a.	2600	3800	7.4
	Al-Saada / Khanyounis, Palestine	85	105	800	1200	175	n.a.	220	n.a.	n.a.	n.a.	n.a.	n.a.	2200	3600	6.8
Ahmed et al, 2001	Hamriyah / United Arab Emirates	48	85	498	779	407	42	5	n.a.	216	n.a.	0.00	0.00	1949	3300	7.3
Elazhar et al, 2014	Marroco	20	88	780	1325	126	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	2690	n.a.	8.1
Moudjeber et al, 2013	in Salah / Algarian	172	88	299	495	567	n.a.	28	0.06	n.a.	n.a.	0	0	n.a.	3140	6.9
Jahnke et al, 2019 (paper + supplementary information)	El Gouna town / Egypt	836	429	1533	3763	2028	n.a.	10	n.a.	129	n.a.	n.a.	n.a.	n.a.	11750	7.2
Ahmed et al, 2001	Umm Al-Qwain / United Arab Emirates	49	110	755	1182	562	37	8	n.a.	275	n.a.	0.00	0.00	2851	4680	7.8
	Kalba / United Arab Emirates	446	245	536	2103	265	32	21	n.a.	133	n.a.	0.00	0.00	3700	6190	7.5
Bason et al, 2016	Granot inland BWRO plant / Israel	120	80.6	309	685	84.5	29.2	58	n.a.	379	n.a.	n.a.	n.a.	1497	n.a.	6.9
Afonso et al, 2004	pilot study extrapolated to full scale installation, Zarqa aquifer Jordan	202	91	409	994	267	19	47	0.10	305	n.a.	0.08	0.18	2309	3664	7.2

Brackish water RO plants operating on comparable feed water qualities as average feed water of Meijendel

Reference	Plant name / location	Membrane system	Membrane type	Anti-scalant	Recovery	Concentrate flow	Brine disposal method(s)
					[%]	[m3/day]	
Briao et al, 2014	Sao Paulo / Brazil	RO	Koch Model 3838 HR-NYV	n.a.	75%	1	Various options mentioned, nothing specific
Ahmed et al, 2001	Zahar / Oman	RO	n.a.	Flocon-100	63%	18.5	Disposal in unlined bore
	Assadanat / Oman	RO	n.a.	Flocon-100	60%	20	Disposal in bore
	Haima / Oman	RO	n.a.	Flocon-100, sulphuric acid	38%	62	Evaporation pond
	Hitam / Oman	RO	n.a.	Flocon-100	25%	75	Disposal in small bore
	Safah / Oman	RO	n.a.	n.a.	50%	50	Evaporation pond
Zuurbier et al, 2017	ASRRO Westland	RO	Toray TM700D	None	45%	110	Well injection
Aparicio et al, 2018 & Valdes-Abellan et al, 2012, Prats et al, 1997	University of Alicante / Spain	RO	Hydranautics (8040~UHY-ESPA	3,8 mg/L PERMATREAT191 (actieve stof 50% = aminotrimethylenephosphonique acid N(CH2PO3HNa)3) + acid dosing	72%	126	Discharge to ephemeral creek
Ruiz-Garcia et al, 2018 & 2015	Island Gran Canaria / Spain	RO	DOW FILMTEC BW30-400	6 mg/L Osmotech 1141	60%	240	n.a. (probably disposal in sea, as it is an island)
Haidari et al, 2017	Ridderkerk / The Netherlands	RO	FILMTEC LE-440i	no A.S. applied	50%	300	Deep well injection
Raat et al, 2012; Groenendijk et al, 2010	Zevenbergen	RO	DOW FILMTEC LE-440i	no A.S. applied.	50%	600	Deep well injection
Wolthek et al, 2013 & Raat et al, 2012	Noordburgum / The Netherlands	RO	DOW FILMTEC LE-440i	no A.S. applied.	50%	600	Deep well injection
Mogheir et al, 2013	Al-Nuwairi / B. Suhaila - Khanyounis, Palestine	RO	Koch membrane model	n.a.	75%	300	'disposal in environment', not stated where exactly
	Al-Sharqia / Khanyounis, Palestine	RO	Koch membrane model	n.a.	70%	396	'disposal in environment', not stated where exactly
	Al-Balad / Deir El-Balah, Palestine	RO	Koch membrane model	n.a.	75%	360	'disposal in environment', not stated where exactly
	Al-Bureij / Al-Bureij, Palestine	RO	Koch membrane model	n.a.	83%	245	'disposal in environment', not stated where exactly
	Al-Salam / Rafah, Palestine	RO	Koch membrane model	n.a.	80%	288	'disposal in environment', not stated where exactly
	Al-Saada / Khanyounis, Palestine	RO	Koch membrane model	n.a.	70%	576	'disposal in environment', not stated where exactly
Ahmed et al, 2001	Hamriyah / United Arab Emirates	RO	n.a.	n.a.	70%	870	Disposal in creek
Elazhar et al, 2014	Marroco	RO/NF comparison	DOW FILMTEC BW30LE-4040 /	0,2 mg/L anti-scalant (type	80% / 84%	540	n.a.
Moudjeber et al, 2013	in Salah / Algarian	RO	DOW FILMTEC XLE-440	no A.S. applied, HCl additio	50%	1750	Deep well injection
Jahnke et al, 2019 (paper + supplementary information)	El Gouna town / Egypt	RO	n.a.	salts of polycarboxylic acids	50%	4750	Deep(er) injection well, dillution + fish farm, evaporation lagoon, surface discharge
Ahmed et al, 2001	Umm Al-Qwain / United Arab Emirates	RO	n.a.	n.a.	75%	3480	Disposal in creek with connection to ocean
	Kalba / United Arab Emirates	RO	n.a.	n.a.	67%	4550	Disposal in sea
Bason et al, 2016	Granot inland BWRO plant / Israel	RO	DOW Filmtec BWRO and SWRO membranes in each installation (first stage 'open' SWRO elements, second stage 'closed' BWRO elements with respect to boron-removal efficiency.	Applied to prevent calcium carbonate and/or silica precipitation in RO or disposal pipeline. Selected on Si-precipitation prevention. Phosphonate A.S. did not work, so dispersant blend and carboxylic and phosphonic acid based A.S. were tested. Phosphorus-based anti-scalant worked best in their case (Bason et al, 2015) and Acid injection to decrease pH from 7,3 to 6,9-7,0.	84%	8464	Discharge into the Mediterranean Sea via 30 km long pipeline
Afonso et al, 2004	pilot study extrapolated to full scale Installation, Zarqa aquifer Jordan	RO	DOW FILMTEC SW30-2521	3 mg/L SHMP or Flocon 10(	85%	20455	Disposal in dead sea

Brackish water RO plants operating on comparable feed water qualities as average feed water of Meijendel

Reference	Plant name / location	Water quality permeate / postt	Pretreatment	Chemical cleaning
Briao et al, 2014	Sao Paulo / Brazil		n.a.	HNO3, pH=2 acid flush only
Ahmed et al, 2001	Zahar / Oman	Chlorine, limestone	sodium meta bisulphite	EDTA, citric acid, sodium hydroxide
	Assadanat / Oman	Chlorine, limestone	sodium meta bisulphite	Citric acid, sodium hydroxide, sodium dodecyle sulphate
	Haima / Oman	chlorine, lime powder	sodium meta bisulphite, chlorine	EDTA, citric acid, ammonia, sodium hydroxide
	Hitam / Oman	Chlorine, limestone	chlorine, sodium meta bisulphite	EDTA, sodium hydroxide, citric acid
	Safah / Oman	n.a.	n.a.	n.a.
Zuurbier et al, 2017	ASRRO Westland	Virtually demineralized water, except for CH4 and NH4. Strip tower for CH4 removal	1 micron cartridge filter	Genesol 703 (yearly)
Aparicio et al, 2018 & Valdes-Abellan et al, 2012, Prats et al, 1997	University of Alicante / Spain	Ca(OH)2 addition for pH increase	Hypochlorite, acid, antiscalant, Sand filtration, cardridge filters, bisulphite dosing, -> RO	n.a.
Ruiz-Garcia et al, 2018 & 2015	Island Gran Canaria / Spain	Permeate was used for irrigation, so no post-treatment applied.	5µm cardridge filter	Osmotech 2691 (alkaline) and Osmotech 2575 (acid)
Haidari et al, 2017	Ridderkerk / The Netherlands	n.a.	Cardridge filters	
Raat et al, 2012; Groenendijk et al, 2010	Zevenbergen		2 stage 5µm en 1µm filters	
Wolthek et al, 2013 & Raat et al, 2012	Noordburgum / The Netherlands		2 stage 5µm en 1µm filters	
Mogheir et al, 2013	Al-Nuwairi / B. Suhaila - Khanyounis, Palestine	n.a.	suggestion for applying NF before RO	n.a.
	Al-Sharqia / Khanyounis, Palestine	n.a.	suggestion for applying NF before RO	n.a.
	Al-Balad / Deir El-Balah, Palestine	n.a.	suggestion for applying NF before RO	n.a.
	Al-Bureij / Al-Bureij, Palestine	n.a.	suggestion for applying NF before RO	n.a.
	Al-Salam / Rafah, Palestine	n.a.	suggestion for applying NF before RO	n.a.
	Al-Saada / Khanyounis, Palestine	n.a.	suggestion for applying NF before RO	n.a.
Ahmed et al, 2001	Hamriyah / United Arab Emirates	n.a.	n.a.	n.a.
Elazhar et al, 2014	Marroco	Post-treatment is remineralisation, to make water suitable for drinking water. Lime (59,2 g/m3) and silicates (51 g/m3).	Sand filter 5µm & MF cardridge filter 10µm	n.a.
Moudjeber et al, 2013	in Salah / Algarian	n.a.	n.a.	n.a.
Jahnke et al, 2019 (paper + supplementary information)	El Gouna town / Egypt	n.a.	n.a.	n.a.
Ahmed et al, 2001	Umm Al-Qwain / United Arab Emirates	n.a.	Sand filtration	n.a.
	Kalba / United Arab Emirates	n.a.	n.a.	n.a.
Bason et al, 2016	Granot inland BWRO plant / Israel	Permeate WQ meets Israeli Water Authority and Israeli Ministry of Health regulations: boron and chloride concentration limits of 0,35 ppm and 20 ppm, respectively. Permeate concentrations of TDS, Chloride and Boron were <20 ppm, <10 ppm and <0,2 ppm, respectively.	80 µm mesh filters followed by Micronics 5 µm filter	n.a.
Afonso et al, 2004	pilot study extrapolated to full scale installation, Zarqa aquifer Jordan	pH adjustment, chlorination for permeate. pH adjustment and aeration-induced biological degradation of organic matter as post-treatment for concentrate stream	pH adjustment to 6, degassing to remove CO2, chlorination for disinfection and Fe/Mn/DOC oxidation, coagulation & dualmedia filtration for turbidity removal, dechlorination, anti-scalant dosing.	Citric acid

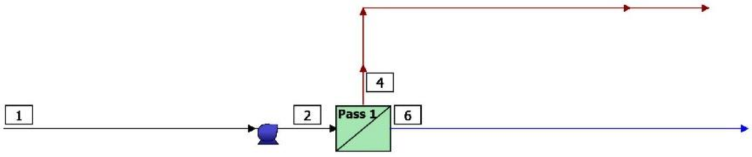
Brackish water RO plants operating on comparable feed water qualities as average feed water of Meijendel							
Reference	**Plant name / location**	**Energy consumption**	**CAPEX / OPEX**	**Costs drinking water**	**Remark costs**	**In operation since**	**Capacity**
		kWh/m3	**k€/year**	**[X/m3] produced water**		**[year]**	**[m3 intake/day]**
Briao et al, 2014	Sao Paulo / Brazil			n.a.	n.a.	n.a.	4
Ahmed et al, 2001	Zahar / Oman	n.a.	n.a.	n.a.	n.a.	1985	50
	Assadanat / Oman	n.a.	n.a.	n.a.	n.a.	1985	50
	Haima / Oman	n.a.	n.a.	n.a.	n.a.	1996	100
	Hitam / Oman	n.a.	n.a.	n.a.	n.a.	1985	100
	Safah / Oman	n.a.	n.a.	n.a.	n.a.	1983	100
Zuurbier et al, 2017	ASRRO Westland	1.80		0.96 eur/m3	CAPEX and OPEX	2015	200
Aparicio et al, 2018 & Valdes-Abellan et al, 2012, Prats et al, 1997	University of Alicante / Spain	1.5 kWh (/m3?) for abstraction 1 kWh/m3 for RO passage 0.08 kWh/m3 for post-RO transport	CAPEX: 360 OPEX: 45,48	0,30 €/m3	Due to construction in 1997, more recently build installation will cost less	1997	450
Ruiz-Garcia et al, 2018 & 2015	Island Gran Canaria / Spain	1,40-1,70		0,37 €/m3	Costs increase in time due to ageing of membranes, more frequent CIP, increase energy consumption	2004	600
Haidari et al, 2017	Ridderkerk / The Netherlands	0.45	CAPEX: 66,4 OPEX: 37,9	0,35 €/m3	0,34 €/m3 for conventional BWRO estimated in Nl case! no water extraction taxes, no pretreatment and no posttreatment costs are considered in both situations.	2014	600
Raat et al, 2012; Groenendijk et al, 2010	Zevenbergen	0.58		0,47 €/m3	Kosten inclusief winning, waarnemingsfilters, zuivering en infiltratie brak grondwater, kosten grondwaterbelasting (nihil) en exclusief kosten voor kelders en pompgebouw		1200
Wolthek et al, 2013 & Raat et al, 2012	Noordburgum / The Netherlands	0.63	CAPEX: 350 OPEX: 20,9	0.21		2009	1200
Mogheir et al, 2013	Al-Nuwairi / B. Suhaila - Khanyounis, Palestine	1.20	n.a.	0,34 US$/m3	-	2010	1200
	Al-Sharqia / Khanyounis, Palestine	1.09	n.a.	0,31 US$/m3	-	1997	1320
	Al-Balad / Deir El-Balah, Palestine	2.00	n.a.	0,72 US$/m3	-	1991	1440
	Al-Bureij / Al-Bureij, Palestine	1.00	n.a.	0,28 US$/m3	-	2009	1440
	Al-Salam / Rafah, Palestine	1.00	n.a.	0,27 US$/m3	-	2010	1440
	Al-Saada / Khanyounis, Palestine	0.75	n.a.	0,34 US$/m3	-	1998	1920
Ahmed et al, 2001	Hamriyah / United Arab Emirates	n.a.	n.a.	n.a.	n.a.	1997	2900
Elazhar et al, 2014	Marroco	n.a.	CAPEX: 50,15 OPEX: 1456,35	1,33 $/m3	With the new plant, costs start around 4 $/m3 for RO and 3,5 $/m3 for NF. After 10 years of service, costs do come down to around 2 $/m3 for both RO and NF. End price for RO is 1,33 $/m3, endprice for NF is 1,19 $/m3	n.a.	3000
Moudjeber et al, 2013	in Salah / Algarian	n.a.	CAPEX: 114 OPEX: 90,90	0.0406	It should be noted that this comparison includes only the cost of pumping, of membrane pressure vessels and of membrane elements, considering that all the other cost parameters (for operating, materials, and capital expenses) will remain the same for all three examined scenarios.	n.a.	3500
Jahnke et al, 2019 (paper + supplementary information)	El Gouna town / Egypt	n.a.	n.a.	n.a.	n.a.	1995	9500
Ahmed et al, 2001	Umm Al-Qwain / United Arab Emirates	n.a.	n.a.	n.a.	n.a.	1985	13920
	Kalba / United Arab Emirates	n.a.	n.a.	n.a.	n.a.	1995	13788
Bason et al, 2016	Granot inland BWRO plant / Israel	n.a.	n.a.	n.a.	n.a.	2004 Granot 1, 2011 Granot 2, 2014 Granot 3, 2015 Granot 4, 2016 Granot 5	52900
Afonso et al, 2004	pilot study extrapolated to full scale installation, Zarqa aquifer Jordan	0.83	CAPEX: 95755 OPEX: 4143	0,73 - 0,84 US$/m3 for distribution and production. Pilot study shows 0,26 euro per m3.	The cost of BWRO pilot (€0,26/m3) would increase if the costs of land, groundwater abstraction, brine disposal, water distribution, and interests on invested capital had been taken into account.	1995	136364

6.3 Appendix III – DOW WAVE prediction BWRO performance Meijendel

WATER APPLICATION VALUE ENGINE
DOW WATER & PROCESS SOLUTIONS

RO Summary Report

RO System Flow Diagram



#	Description	Flow (m³/h)	TDS (mg/L)	Pressure (bar)
1	Raw Feed to RO System	5,250	9,144	0.0
2	Net Feed to Pass 1	5,247	9,148	19.1
4	Total Concentrate from Pass 1	2,625	18,121	16.9
6	Net Product from RO System	2,623	160.0	0.0

RO System Overview

Total # of Trains	1	Online =	1	Standby =	0	RO Recovery	50.0 %
System Flow Rate	(m³/h)	Net Feed =	5,250	Net Product =	2,623		

Pass		Pass 1
Stream Name		Stream 1
Water Type		Well Water (SDI < 3)
Number of Elements		2628
Total Active Area	(m²)	107426
Feed Flow per Pass	(m³/h)	5,247
Feed TDS[a]	(mg/L)	9,148
Feed Pressure	(bar)	19.1
Flow Factor		0.85
Permeate Flow per Pass	(m³/h)	2,623
Pass Average flux	(LMH)	24.4
Permeate TDS[a]	(mg/L)	160.0
Pass Recovery		50.0 %
Average NDP	(bar)	9.1
Specific Energy	(kWh/m³)	1.33
Temperature	(°C)	10.0
pH		7.3
Chemical Dose		
RO System Recovery		50.0 %
Net RO System Recovery		50.0%

Footnotes:

[a]Total Dissolved Solids includes ions, SiO_2 and $B(OH)_3$. It does not include NH_3 and CO_2

RO Flow Table (Stage Level) - Pass 1

Stage	Elements	#PV	#Els per PV	Feed: Feed Flow (m³/h)	Feed: Recirc Flow (m³/h)	Feed: Feed Press (bar)	Feed: Boost Press (bar)	Concentrate: Conc Flow (m³/h)	Concentrate: Conc Press (bar)	Concentrate: Press Drop (bar)	Permeate: Perm Flow (m³/h)	Permeate: Avg Flux (LMH)	Permeate: Perm Press (bar)	Permeate: Perm TDS (mg/L)
1	XLE-440	438	6	5,247	0.00	18.8	0.0	2,625	16.9	1.9	2,623	24.4	0.0	160.0

WATER APPLICATION VALUE ENGINE
DOW WATER & PROCESS SOLUTIONS

RO Solute Concentrations - Pass 1

Concentrations (mg/L as ion)				
		Concentrate	Permeate	
	Feed	Stage1	Stage1	Total
NH_4^+	4.29	8.41	0.19	0.19
K^+	61.00	120.7	1.29	1.29
Na^+	2,427	4,804	49.96	49.96
Mg^{+2}	274.0	545.0	2.95	2.95
Ca^{+2}	525.0	1,044	5.52	5.52
Sr^{+2}	0.00	0.00	0.00	0.00
Ba^{+2}	0.00	0.00	0.00	0.00
CO_3^{-2}	1.29	6.27	0.00	0.00
HCO_3^-	308.8	606.2	3.86	3.86
NO_3^-	0.70	1.31	0.09	0.09
Cl^-	4,897	9,701	91.47	91.47
F^-	0.03	0.05	0.00	0.00
SO_4^{-2}	619.0	1,233	4.42	4.42
SiO_2	25.01	49.75	0.25	0.25
Boron	0.00	0.00	0.00	0.00
CO_2	15.78	18.03	16.24	16.24
TDS[a]	9,144	18,121	160.0	160.0
pH	7.3	7.5	5.6	5.6

Footnotes:

[a]Total Dissolved Solids includes ions, SiO_2 and $B(OH)_3$. It does not include NH_3 and CO_2

RO Design Warnings

None

RO Flow Table (Element Level) - Pass 1

Stage	Element	Element Name	Recovery (%)	Feed Flow (m^3/h)	Feed Press (bar)	Feed TDS (mg/L)	Conc Flow (m^3/h)	Perm Flow (m^3/h)	Perm Flux (LMH)	Perm TDS (mg/L)
1	1	XLE-440	11.6	12.0	18.8	9,149	10.6	1.39	34.0	86.13
1	2	XLE-440	11.6	10.6	18.3	10,339	9.36	1.23	30.1	109.0
1	3	XLE-440	11.5	9.36	17.9	11,684	8.29	1.07	26.2	140.2
1	4	XLE-440	11.0	8.29	17.6	13,175	7.37	0.91	22.3	183.1
1	5	XLE-440	10.3	7.37	17.3	14,783	6.61	0.76	18.6	242.8
1	6	XLE-440	9.4	6.61	17.1	16,454	5.99	0.62	15.2	326.0

Footnotes:

[a]Total Dissolved Solids includes ions, SiO_2 and $B(OH)_3$. It does not include NH_3 and CO_2

RO Solubility Warnings

Warning	Pass No
Stiff & Davis Stability Index > 0	1
Anti-scalants may be required. Consult your anti-scalant manufacturer for dosing and maximum allowable system recovery.	1

RO Chemical Adjustments

	Pass 1 Feed	RO 1st Pass Conc
pH	7.3	7.5
Langelier Saturation Index	0.49	1.22
Stiff & Davis Stability Index	0.08	0.54
TDS[a] (mg/l)	9,144	18,121
Ionic Strength (molal)	0.19	0.38
HCO_3^- (mg/L)	308.8	606.2
CO_2 (mg/l)	15.78	18.03
CO_3^{-2} (mg/L)	1.29	6.27
$CaSO_4$ (% saturation)	18.6	42.4
$BaSO_4$ (% saturation)	0.00	0.00
$SrSO_4$ (% saturation)	0.00	0.00
CaF_2 (% saturation)	0.01	0.08
SiO_2 (% saturation)	26.3	52.4
$Mg(OH)_2$ (% saturation)	0.00	0.00

Footnotes:

[a]Total Dissolved Solids includes ions, SiO_2 and $B(OH)_3$. It does not include NH_3 and CO_2

6.4 Appendix IV – Genesys Membrane Master 4 prediction BWRO Meijendel

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MM4 Report

User & Plant Details

Project Name / Reference	Dunea BWRO Meijendel
Contact Name	Gertjan Zwolsman
Company	Dunea
Date	13-9-2019
Report Author	Luuk de Waal
Contact Number	030-6069551
Email Address	luuk.de.waal@kwrwater.nl

Water and Membrane Details

Water Type	Brackish Water
Membrane Manufacturer	Dow
Membrane Type	FilmTec XLE-440
Average Salt Passage	1.0 %

Recommended Product GENESYS LF

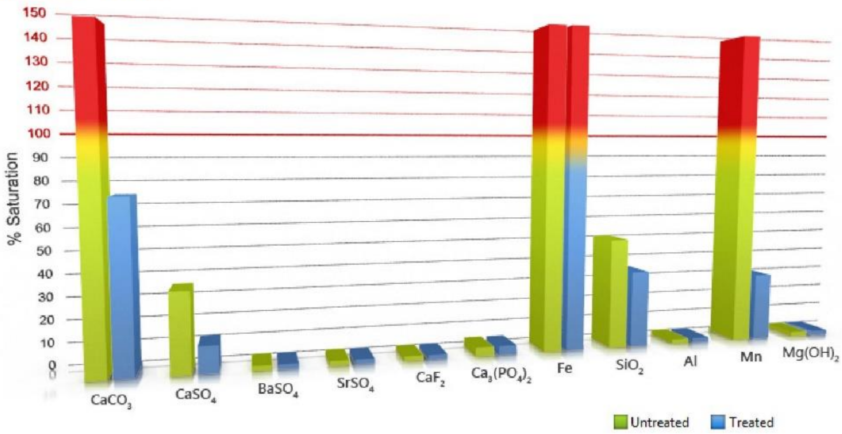
Dosing Data

For Scale Control - Feed	4.58 mg/l
For Iron Control - Feed	737.06 mg/l
Total Dosage	741.65 mg/l
Dose In Concentrate	1483.30 mg/l
Set Dosing Pump To	2926215.57 ml/hr
Daily Requirement	93404.80 kg/day

Acid Dosing

Acid dosing is not required.

Saturation Graph



Scaling Indices

	$CaCO_3$	$CaSO_4$	$BaSO_4$	$SrSO_4$	CaF_2	$Ca_3(PO_4)_2$	$Fe(OH)_3$	SiO_2	$Al(OH)_3$	$Mn(OH)_2$	$Mg(OH)_2$
Conc. Untreated	144.82	33.22	0.00	0.00	0.00	0.00	11879	51.13	0.41	445.47	0.03
Conc. Treat.	74.91	11.86	0.00	0.00	0.00	0.00	791.95	34.09	0.27	29.70	0.00

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MM4 Report

Water Analysis Data

Component	Feed Water mg/l	Concentrate mg/l
Ca^{2+}	525.00	1039.50
Mg^{2+}	274.00	542.52
Na^{+}	2456.09	4863.05
K^{+}	61.00	120.78
Ba^{2+}	0.00	0.00
Sr^{2+}	0.00	0.00
Fe^{3+}	8.00	15.84
Al^{3+}	0.00	0.00
Mn^{2+}	0.90	1.78
SO_4^{2-}	619.00	1225.62
Cl^{-}	4897.00	9696.06
F^{-}	0.00	0.01
HCO_3^{-}	336.69	666.64
CO_3^{2-}	0.75	1.48
CO_2	17.03	17.03
NO_3^{-}	0.70	1.39
SiO_2	25.00	49.50
PO_4^{3-}	1.50	2.97

Operation Details

Permeate Flow	62971.0 m^3/day
Recovery Rate	50.0 %
Feed Flow	125942.0 m^3/day
Concentration Factor	2.00
Concentrate Flow	62971.0 m^3/day
pH Raw Water	7.2
pH Feed Water	7.3
Operating Pressure	19.1 Bar
Operating Temperature	10.0 °C
Operating Time	24.0 hr/day

Water Indices

Index	Feed Water	Concentrate
pH	7.30	7.45
TDS	9200.19	18216.38
Ionic Strength (I)	0.19	0.37
LSI	0.60	1.34
Alkalinity ppm $CaCO_3$	272.74	550.25

Scaling Indices Feed

Scalant Type	Feed Water Untreated (%)	Feed Water Treated (%)
$CaCO_3$	120.00	62.07
$CaSO_4$	12.35	4.41
$BaSO_4$	0.00	0.00
$SrSO_4$	0.00	0.00
CaF_2	0.00	0.00
$Ca_3(PO_4)_2$	0.00	0.00
$Fe(OH)_3$	5595	373.01
SiO_2	26.26	17.51
$Al(OH)_3$	0.21	0.14
$Mn(OH)_2$	209.82	13.99
$Mg(OH)_2$	0.01	0.00

Scaling Indices Concentrate

Scalant Type	Concentrate Untreated (%)	Concentrate Treated (%)
$CaCO_3$	144.82	74.91
$CaSO_4$	33.22	11.86
$BaSO_4$	0.00	0.00
$SrSO_4$	0.00	0.00
CaF_2	0.00	0.00
$Ca_3(PO_4)_2$	0.00	0.00
$Fe(OH)_3$	11879	791.95
SiO_2	51.13	34.09
$Al(OH)_3$	0.41	0.27
$Mn(OH)_2$	445.47	29.70
$Mg(OH)_2$	0.03	0.00

The data used in Genesys Membrane Master 4 is provided in good faith.
The system operation is outside our control and we accept no product liability for consequential results

MM4 Software Version: v1.36.6 (DLL v1.11.22(D))
Report generated at 16:36:04 on 13/09/2019

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6.5 Appendix V – Noardburgum site description

Table 6-3: Lithology and aquifer characteristics of Noardburgum site

	Top	Bottom	Formation	Information
	[m below MSL]	[m below MSL]	[m below MSL]	
Top aquitard	0	-60	Drenthe, Drachten, Urk	Boulder clay, clay, loam and fine to coarse sands
First aquifer	-60	-150	Urk and Peize complex	Mainly coarse to very coarse sands
First aquitard	-150	-160	(Peize) Tegelen	6-10 m of clay and fine sands
Second aquifer	-160	-240	Peize complex and Waalre	Fine to coarse sands with small clay layers

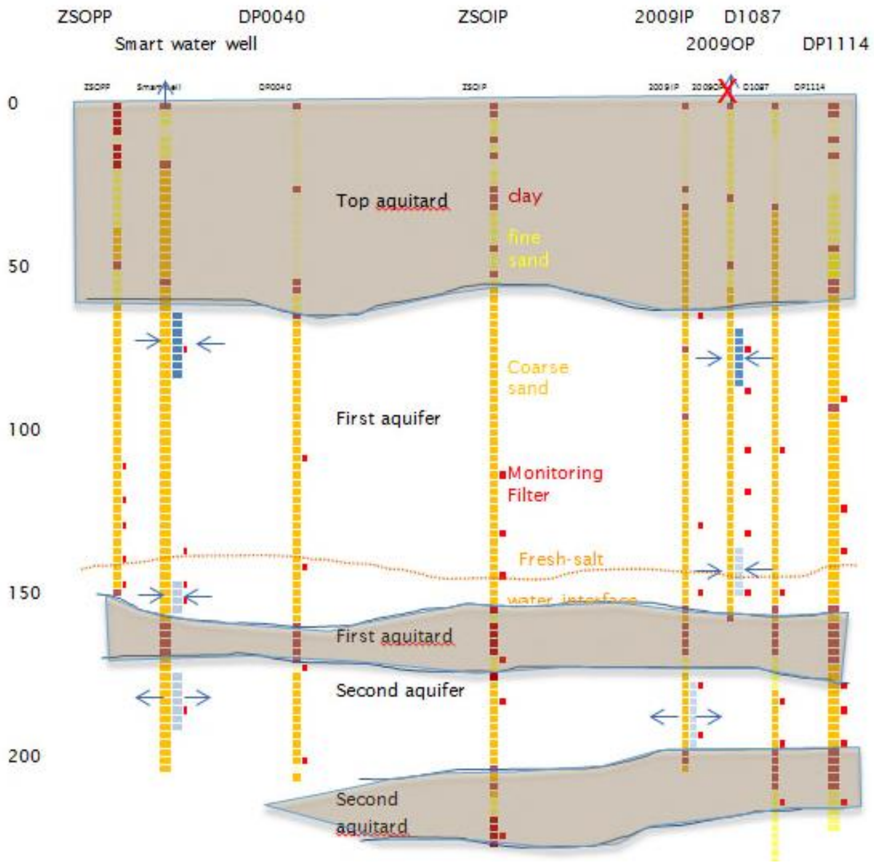

Figure 6-3: Interpretation of the lithology and chloride stratification at the well field of Noardburgum, including the Freshkeeper wells of the first pilot (2009IP and 2009OP) and the Freshkeeper well of the second pilot (smart water well).

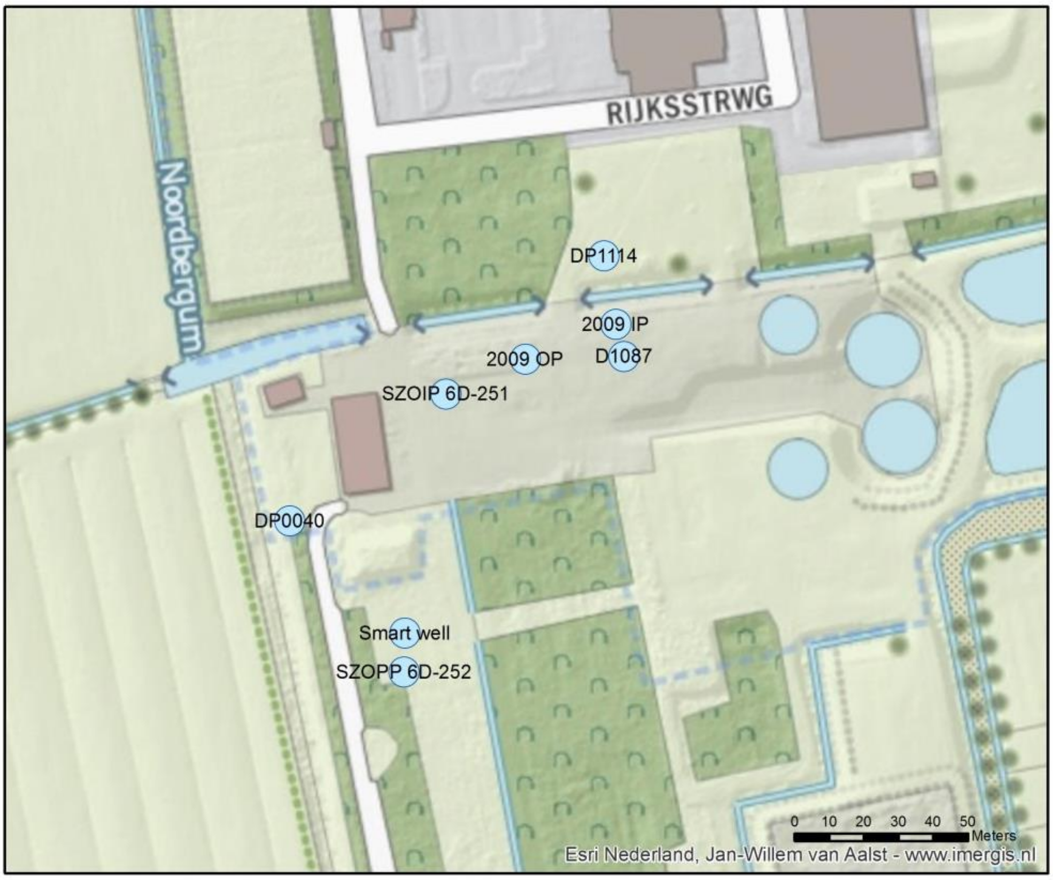

Figure 6-4: Well field in Noardburgum with the wells that are used for monitoring during this pilot.2009 OP: extraction well from the first pilot in 2009. 2009 IP: infiltration well from the pilot in 2009.

Noord	CH4	Cl	HCO3	Ca	Sr	Fe	BEX	Watertype	B	Ba
Bergum	mg/L						meq/L		ug/L	
-63		51	362	108			0.6	F3CaHCO3o		
-73		70	373	117			0.0	F3CaHCO3o		
-85		35	389	100			1.4	F3CaHCO3+		
-87		31	401	108			0.5	F3CaHCO3		
-103		38	404	120			0.5	F3CaHCO3o		
-104		29	417	108			0.6	g3CaHCO3+		
-110		37	418	122			0.5	F3CaHCO3		
-115		49	437	123			0.2	F3CaHCO3		
-120		57	399	116			-0.1	F3CaHCO3		
-125		63	412	131			-0.1	F3CaHCO3o		
-127		66	394	130			-0.3	F3CaHCO3o		
-127		75	397	128			-0.5	F3CaHCO3o		
-134		510	358	274			-10.8	B3CaCl-		
-140		1200	322	555			-26.6	b3CaCl-		
-145		1800	272	764			-40.4	b3CaCl-		
-146		1800	270	762			-40.8	b3CaCl-		
-147		1800	267	717			-41.4	b3CaCl-		
AQUITARD 2										
-170	9.30	110	325	114	0.41	7.38	-1.3	F3CaHCO3-	24	44
-172	11.00	370	329	222	0.78	16.10	-7.4	B3CaCl-	21	128
-179	14.00	530	363	292	0.97	27.10	-11.3	B3CaCl-	14	186
-179	12.00	870	348	426	1.48	32.00	-17.1	B3CaCl-	28	789
-180	12.00	670	331	324	1.11	29.70	-14.8	B3CaCl-	18	226
-190	0.21	4200	223	1250	5.35	33.60	-82.2	b2CaCl-	43	1580
-191	0.09	4500	227	1370	5.98	34.00	-85.8	b2CaCl-	51	1660
-208	0.10	3200	240	1060	4.96	23.60	-64.1	b2CaCl-	60	624
-208	0.21	4100	233	1200	5.36	24.10	-81.0	b2CaCl-	63	829

Figure 6-5: Hydrochemistry of the Noardburgum BWRO source and disposal aquifer. Water was abstracted from aquifer 1B, at two depths: 67 - 86 (fresh water, blue arrow) and 134 - 148 m depth (brackish water, BWRO feed water, pink arrow). BWRO concentrate was injected in aquifer 2, at a depth of 173 - 192 m (red arrow).

6.6 Appendix VI – Zevenbergen site description

Zeven Bergen	CH4	Cl	HCO3	Ca	Sr	Fe	BEX	Watertype	B	Ba
	mg/L						meq/L		ug/L	
-6	28.00	225	499							
-8		130	317							
-8	22.00	610	305							
-8	18.00	185	430							
AQUITARD 1										
-34	7.60	85	311							
-35		46	339							
-35	17.00	57	335							
-35	7.40	80	314							
AQUITARD 2										
-63	21.00	36	376							
-80		140	367	100	0.40	1.90	0.6	F3CaHCO3o	550	4
-80	6.40	110	402	102	0.41	2.00	0.8	F3CaHCO3	370	0
-83	3.50	130	382	106	0.50	1.90	0.7	F3CaHCO3o	280	6
-91		190	376	111	0.67	1.10	0.4	f3CaHCO3o	590	2
-98	1.50	275	358	132	0.87	1.80	-1.7	f3CaClo	590	0
-101	5.90	510	368	230	1.80	3.00	-6.5	B3CaCl-	520	10
-109		580	357	182	1.90	1.10	-4.4	B3NaCl-	760	4
-109	0.20	800	337	270	3.50	2.10	-9.1	B3CaCl-	690	8
-111	0.19	1100	348	380	5.60	3.20	-15.8	b3CaCl-	940	9
-114	2.30	1400	445	470	8.40	4.10	-19.3	b3CaCl-	560	31
AQUITARD 3										
-150	0.27	290	417	82	2.50	0.60	1.8	f3NaCl	1100	10
-166	0.07	375	431	78	4.70	0.72	2.2	B3NaCl	870	16
-168	0.06	385	444	64	4.60	0.69	2.8	B3NaCl+	1000	0
-169	0.38	375	418	99	3.50	0.96	0.8	B3NaClo	680	8
-173		400	449	62	4.50	0.64	3.2	B3NaCl+	940	4
-175	0.05	465	445	44	3.10	0.00	4.0	B3NaCl+	970	4
-176	0.06	435	452	52	4.10	0.56	3.5	B3NaCl+	1000	0
-181	0.05	420	448	52	4.00	0.00	3.5	B3NaCl+	880	4
-182	0.04	465	450	42	3.00	0.50	3.9	B3NaCl+	1000	0
-185	0.07	520	452	40	2.30	0.42	2.8	B3NaCl+	1100	34
AQUITARD 4										
-252		2400	676	29	1.20	0.03	3.2	b4NaCl	5600	11
-253	0.02	2600	700	1	1.20	0.20	-3.2	b4NaCl	7699	110
-284	0.06	3600								
-303	0.03	4400								

Figure 6-6: Hydrochemistry of the Zevenbergen BWRO source and disposal aquifer. RO feed water was a mixture of water abstracted from aquifer 2 (90 - 115 m depth; 49.2 $m^3\,hr^{-1}$) and aquifer 4 (250 - 255 m depth; 0,8 m $m^3\,hr^{-1}$). BWRO concentrate was injected in aquifer 3, at a depth of 168 - 182 m.