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Desalination of brackish groundwater and concentrate disposal by deep well injection

Nico Wolthek[a,*], Klaasjan Raat[b], Jan Arie de Ruijter[c], Antoine Kemperman[d], Ate Oosterhof[a]

[a]*Vitens NV, P.O. Box 1090, 8200 BB Lelystad, The Netherlands*
Email: nico.wolthek@vitens.nl
[b]*KWR Watercycle Research Institute, P.O. Box 1072, 3430 BB Nieuwegein, The Netherlands*
[c]*Hatenboer-Water, Mercuriusweg 8, 3113 AR Schiedam, The Netherlands*
[d]*University of Twente, P.O. Box 1113, 8900 CC Leeuwarden, The Netherlands*

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ABSTRACT

In the province of Friesland (in the Northern part of The Netherlands), problems have arisen with the abstraction of fresh groundwater due to salinization of wells by upcoming of brackish water. A solution to this problem is to intercept (abstract) the upcoming brackish water, desalinate it with a brackish water reverse osmosis installation, and dispose the concentrate in a deeper, confined aquifer. The fresh-brackish interface in the source aquifer is stabilized by simultaneous abstraction of the fresh and brackish parts. After desalination, the abstracted brackish water provides an additional source for drinking water. To demonstrate the feasibility of this concept a pilot study was set up. In one year about 220.000 m^3 of concentrate was produced and injected. The reverse osmosis installation was carried out under anaerobic conditions without pretreatment and antiscalant dosing. Despite the high iron concentrations (40 mg Fe/l) in the feed water, the installation performed was very stable. Although the concentrate was supersaturated toward carbonate and phosphate minerals (SI > 1), scaling or fouling of the membranes did not occur at recoveries of 50, 70, and 75%. The mass transfer coefficient or normalized flux (at 10℃) was stable at $0.85 \cdot 10^{-8}$ m s^{-1} kPa^{-1}. Water quality changes in the target aquifer were monitored by two observation wells, at 12 and 24 m distances from the injection well. Also the injection of the supersaturated concentrate did not lead to mineral precipitation in the target aquifer, indicating that deep well injection is technically feasible without risks of injection well or aquifer clogging. The fresh-brackish water interface in the source aquifer remained stable by the simultaneous abstraction of fresh and brackish water. This showed that the so called "fresh-keeper" concept works in practise, providing a successful remedy against salinization of fresh water abstraction wells. Overall, the pilot study showed that brackish groundwater provides an excellent, additional source for drinking water in The Netherlands or in other coastal areas worldwide, where fresh groundwater is scarce or where fresh water wells are threatened by salinization.

Keywords: Desalination; Brackish water; Reverse osmosis; Concentrate disposal

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*Corresponding author.

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1. Introduction

Vitens, the largest water supply company in the Netherlands, supplies 330 Mm^3 of drinking water to domestic and industrial clients yearly. The main source for the production of this water is groundwater with salinity concentrations lower than 150 mg/L. In the province of Friesland, in the northern part of the Netherlands, problems have arisen with the abstraction of fresh groundwater due to salinization of wells by upcoming of brackish water. A solution to this problem is to intercept (abstract) the upcoming brackish water, desalinate it with a brackish water reverse osmosis installation (BWRO) and dispose the concentrate in a deeper, confined aquifer. The fresh–brackish interface in the source aquifer is stabilized by simultaneous abstraction of the fresh and brackish parts of the aquifer. After desalination, the abstracted brackish water becomes an additional source of drinking water.

During a test period of one year roughly 220,000 m^3 of concentrate has been injected into the deeper aquifer. A detailed program was initiated to monitor the different types of water flows, including the effects of concentrate injection on the deep aquifer.

The aim of the pilot was twofold. Firstly, it was initiated to show that brackish groundwater is a good source for the production of drinking water and that the RO treatment process is stable and cost effective. Secondly, it aimed to demonstrate that concentrate disposal by deep well injection is technically feasible, does not have a negative effect on water quality in the subsoil (in relation to permits) and is a good alternative to other disposal options such as disposal to surface waters.

2. Materials and methods

2.1. Setup of the BWRO pilot

The pilot at Noardburgum is situated within a former well field, which was abandoned in 1993 because of salinization. The BWRO installation is equipped with five pressure vessels in a single stage

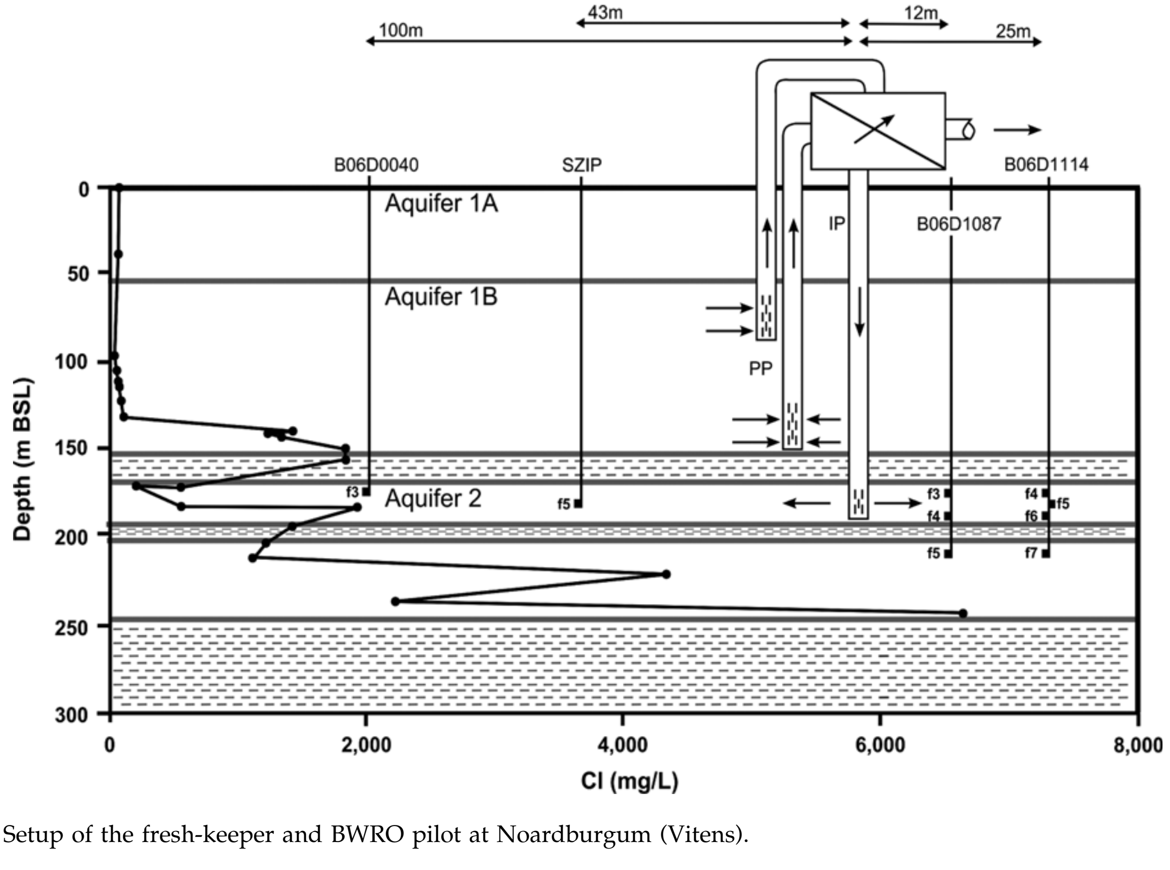

Fig. 1. Setup of the fresh-keeper and BWRO pilot at Noardburgum (Vitens).

which houses six 8-inch membrane elements (DOW FILMTEC LE-440*i*). A single well with two extraction filters (aquifer 1B, see Fig. 1) is used to extract 50 m^3/h of fresh water (60–80 m depth) and 50 m^3/h brackish water (130–150 m depth). The brackish water is fed, under anaerobic conditions, directly to a RO installation with only 5-µm cartridge filters as pre-treatment. The RO installation has a feed capacity of 50 m^3/h. The permeate is treated further to drinking water, together with the abstracted fresh water, in the production facility of Noardburgum, close to the abstraction well. The concentrate is injected into a deeper, confined aquifer 2 (180-m depth), which is separated from the upper aquifer by a 10-m-thick aquitard of clay (see Fig. 1). As it is not allowed to infiltrate non-natural products into the subsoil of the Netherlands, scale inhibitors are not used in the RO. This limits the recovery of the RO process. The BWRO is also equipped with a cleaning in place unit to perform a chemical cleaning of the membranes if necessary. The BWRO was initially operated with a recovery of 50%. Later the recovery was increased to 70 and 75%, despite the advice by the manufacturer of a minimum flow leaving the last element in the vessel. The low recovery of 50% was maintained to prevent severe mineral super-saturation of the concentrate, which could cause scaling of the membranes and/or clogging of the injection well and aquifer 2 (see Fig. 1) due to precipitation of minerals. Later the recovery level was increased to determine the level at which membrane scaling and/or injection well clogging would be problematic.

2.2. Monitoring program

A detailed monitoring program was developed to evaluate the performance of the BWRO installation, abstraction and injection wells, water flow and changes in water quality in aquifer 1B and injection aquifer (aquifer 2). The performance of the BWRO installation was evaluated by online monitoring of flows, pressures (pressure drop over the membranes), conductivity of feed water, permeate and concentrate. In addition, water quality of the feed water, concentrate and permeate was analyzed regularly for presence of macro-elements and large amounts of trace elements. Performance of the abstraction and injection wells was monitored by online measurement of the abstraction and injection pressures. Pressure heads of the groundwater were determined online in several of the observation wells, both in aquifer 1B and the injection aquifer, providing information on water flow in these aquifers. A number of observation screens in the injection aquifer were equipped with electrical conductivity sensors, in order to carefully detect the breakthrough of the injected concentrate. Special attention was paid to the development of the fresh–brackish interface in the source aquifer (aquifer 1B), following the simultaneous abstraction of upper fresh and lower brackish groundwater. The position of the interface was monitored online using a conductivity sensor installed along the pumping well. Changes in water quality in the injection aquifer were monitored with several observation wells, at multiple depths and distances from the injection well.

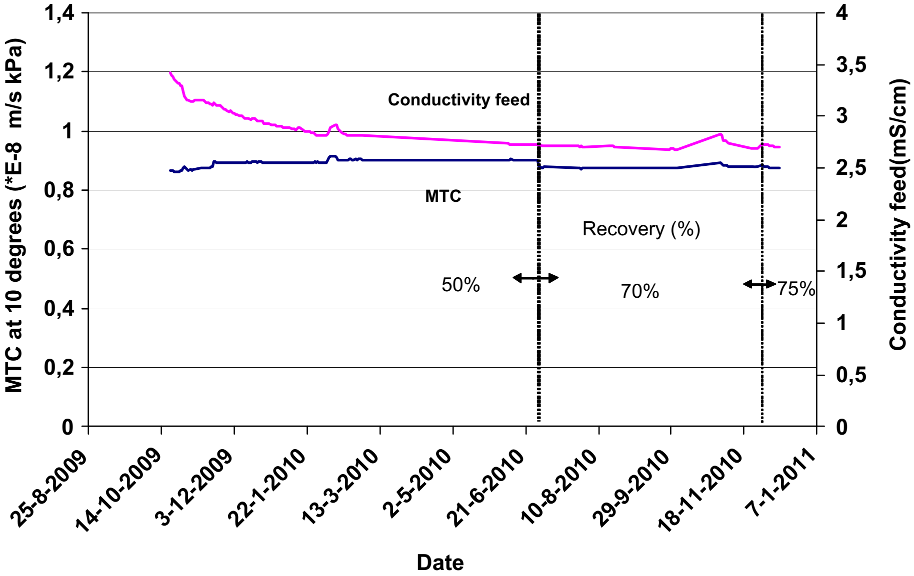

Fig. 2. MTC and the feed water conductivity of the BWRO.

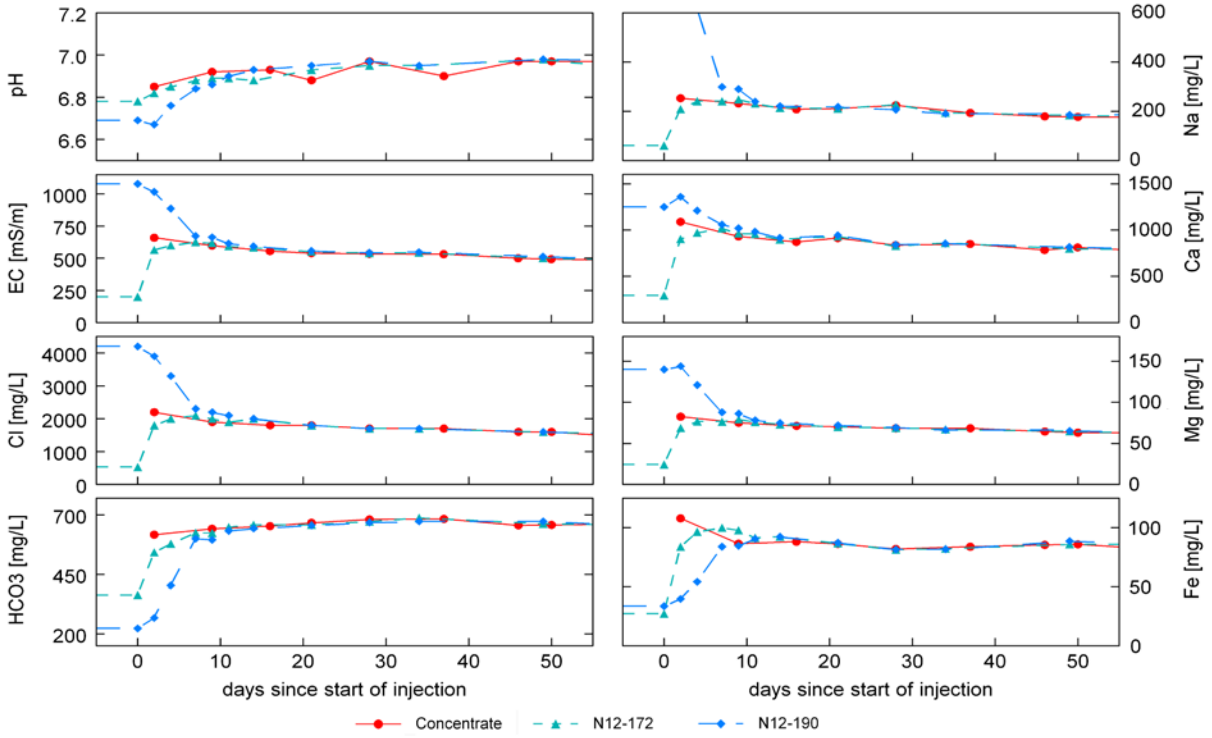

Fig. 3. Breakthrough patterns at 12-m distance of the injection well.

Table 1
Calculated super-saturation levels in BWRO concentrate

SIs		Recovery	
		50%	70%
Calcite	$CaCO_3$	0.69	1.03
Dolomite	$CaMg(CO_3)_2$	0.43	1.12
Hydroxyapatite	$Ca_5(PO_4)_3OH$	0.97	2.1
Quartz	SiO_2	1.25	1.47
Rhodochrosite	$MnCO_3$	0.4	0.7
Siderite	$FeCO_3$	1.81	2.11
SiO2(a)	SiO_2	−0.11	0.12
Vivianite	$Fe_3(PO_4)_2{:}8H_2O$	2.55	3.12

3. Results and discussion

3.1. Performance of the RO installation

The RO system has been in operation since October 2009. Despite the high concentrations of iron in the feed water (40 mg/L), the reverse osmosis installation performed as expected under anaerobic conditions. The pressure drop and normalized flux values indicate no scaling or fouling, even though the concentrate is oversaturated towards carbonate (calcite, dolomite, siderite) and phosphate (vivianite) minerals. The mass transfer coefficient (MTC) or normalized flux (at 10°C) was stable at $0.85 \times 10^{-8}\,\mathrm{m\,s^{-1}\,kPa^{-1}}$ at a recovery of 50% and even of 70% (concentrate flows leaving the last element in the vessels were lower than specified by the manufacturer). At the end, the installation was operated for a short period (2 weeks) at a recovery of 75%. At this level, the MTC dropped gradually due to precipitation of phosphate minerals (see Fig. 2), which was obviously caused by a combination of absence of

Table 2
Water quality of the BWRO feed water and the comparison of the initial and the final concentrations in the target aquifer after 7 months of injection of BWRO concentrate

	BWRO	Target aquifer 172–190 m	
	Feed water	Initial	End
pH	6.80	6.70–6.85	7.01
EC (mS/m)	242	153–1,026	441
CH_4 (mg/L)	16	0.09–12.00	15.4
Cl (mg/L)	650	370–4,500	1,317
Br (mg/L)	2.56	1.3–15.1	5.96
F (mg/L)	0.07	0.03–0.08	<0.05
HCO_3 (mg/L)	345	227–331	678
SO_4 (mg/L)	<2	<2–160	<2
PO_4 (mg-P/L)	0.15	0.13–0.20	0.29
TOC (mg/L)	4.3	2.7–4.7	9.0
Na (mg/L)	87.7	47–849	170
K (mg/L)	3.4	2.9–14.6	6.2
Ca (mg/L)	359	222–1,370	710
Mg (mg/L)	30.1	21–157	58.8
Fe (mg/L)	39.6	16–34	75.6
Mn (mg/L)	0.820	0.6–1.5	1.62
Ba (mg/L)	0.251	0.128–1,660	0.504
Sr (mg/L)	1.26	0.777–5,980	2.49
NH_4 (mg-N/L)	0.85	0.7–4.4	1.4
SiO_2 (mg-Si/L)	16	13–14	30

a scale inhibitor (which was not allowed) and maintenance of a recovery at which the concentrate flows were as low as specified by the manufacturer.

3.2. Fresh-keeper concept

The fresh/brackish water interface was monitored through automatic conductivity sensors placed along the abstraction well in aquifer 1B. Since the start of the abstraction of fresh and brackish water, the interface has remained stable and even the salinity of the abstracted brackish water has decreased (Fig. 2). This indicates that the fresh-keeper concept operates as intended. In addition, it shows that simultaneous abstraction and injection did not lead to short-circuiting of the injected water between the injection and source aquifer.

3.3. Changes in water quality following concentrate injection

Observations wells were positioned at 12- and 25-m distance from the injection well, and were used to closely monitor the changes in water quality in the target aquifer. The injected concentrate could be traced accurately, as indicated by the conductivity breakthrough curves in the observation wells (Fig. 3).

As mentioned, the concentrate was supersaturated towards carbonate and phosphate minerals (Table 1), but this did not lead to precipitation of minerals in the target aquifer. Breakthrough parameters such as EC, HCO_3, Ca, Mg and Fe were not retarded compared to the conservative tracers. After breakthrough, water quality in the observation wells mimicked the composition of the concentrate and parameters such as EC, HCO_3, Ca, Mg and Fe equalled the levels in the BWRO concentrate. Similar results were found for the second observation well.

The net effect of concentrate injection on water quality in the target aquifer is shown in Table 2. The table lists the quality of BWRO feed water and the initial water quality of the target aquifer as well as the water quality at the end of the field tests at approximately 25-m distance from the injection wells, after flushing both the aquifers with several pore volumes of concentrate. The final concentrations of most elements fell within the water quality ranges of the native groundwater, except for bicarbonate, phosphate, total organic carbon (TOC), iron and silica. Of these, most were almost within the range of the native groundwater and, in addition, their environmental relevance was limited, i.e. (concentrations of) these elements did not pose an environmental or health risk. The only exception perhaps was iron, with final concentrations of about 70 mg/L. Although this level is exceptionally high, even for brackish waters, the environmental relevance of high levels of Fe is limited.

The results indicate that deep well injection is technically feasible, without any risks of clogging of the injection well or the target aquifer due to precipitation of minerals.

4. Conclusions

(1) At the pumping and injecting rates used, the fresh-keeper concept, i.e. simultaneous abstraction of fresh and brackish water, is a successful remedy against salinization of freshwater abstraction wells.
(2) Direct treatment (without pre-treatment, only cartridge filters) of anaerobic groundwater with membrane filtration is applicable also for feed water with high concentrations of iron.
(3) At the injection rates and the tested concentrate concentrations used, deep well injection of (oversaturated) membrane concentrate is technically feasible, providing a possible solution to the problem of concentrate disposal.
(4) At Noardburgum, RO recovery levels can be increased to 70%, without the use of scale inhibitors, and without problems such as membrane fouling or injection well clogging.

In summary, the pilot shows that brackish groundwater is an excellent, additional source of drinking water in the Netherlands, especially in areas where fresh groundwater is scarce or where fresh water wells are threatened by salinization.

Acknowledgements

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Further studies

The pilot at Noardburgum will be continued for three more years to study long-term effects on both source aquifer and injection aquifer. The BWRO will be retrofitted into a two-stage system to allow concentrate flows leaving the last element of the vessel, specified by the manufacturer of the membranes and to increase the recovery of the BWRO.