Problems and solutions when storing fresh water in brackish aquifers for later use

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ABSTRACT

Typical problems during storage and recovery of fresh water in a brackish or saline aquifer consist of (i) upward bubble drift by density driven flow, (ii) lateral bubble drift, and (iii) undesired water quality changes due to mobilization of Fe, Mn and As by redox reactions and of Na by cation exchange.

In unique field pilots, the effectiveness was tested of 2 smart well systems which are expected to mitigate the effects of bubble drift: a MUltiple Partially Penetrating ASR well (MUPPA) and a HOrizontal Salinization Protected ASR well (HOSPA; also called 'Freshmaker').

The prevention of undesired redox reactions was tested via PHREEQC-2 simulations of adding O_2 and Na_2CO_3 to the infiltration water, and via a unique ASR-simulating column study, in which $KMnO_4$ was added to the infiltration water. The results obtained show that the problems can be satisfactorily mitigated, which amplifies ASR applicability to brackish and saline aquifers.

INTRODUCTION

Aquifer Storage and Recovery (ASR) of fresh (often surface or rain) water is a well-known method to overcome seasonal or periodical water scarcity problems in areas with periodical water excess in contra-phase with peak demands. When the only suitable target aquifer is brackish or saline, ASR becomes more difficult to apply due to (i) upward bubble drift by density driven flow, (ii) earlier negative effects of lateral bubble migration (less mixing allowed for Cl than for constituents that sorb), and (iii) potentially more severe water quality problems by water-aquifer interactions, due to clay mobilization, enhanced cation and anion exchange, and enhanced redox and dissolution reactions. As a result, the recovery efficiency (RE) of the ASR system can become insufficient.

Storage in brackish or saline aquifers is however very attractive, because of several advantages: availability of huge, additional subterranean storage volumes, less interference with other aquifer users, lower pollution levels of admixed ambient groundwater (salt excluded), and direct reversal of salt water intrusion.

In this contribution, we present methods tested in pilots, to solve or mitigate the above mentioned problems, so as to amplify ASR applicability in a salinizing world.

METHODS

Upward bubble drift was studied and mitigated in 2 ASR pilots, each with a different approach. The first consisted of a Multiple Partially Penetrating ASR well (MUPPA) in a semi-confined, brackish (TDS 3,300, Cl 1,000 mg/L) sandy aquifer near Nootdorp (W-Netherlands). This MUPPA enabled injection at the base of the aquifer and recovery at the top (Fig.1), thus buffering the buoyancy effects. The well was fed with rainwater (TDS 60, Cl 5 mg/L) from the roof of a large greenhouse, after pretreatment by subsequently storage in a tank, rapid and slow sand filtration. Infiltration occurred whenever rainfall was sufficient to surpass a specific level in the storage tank. Infiltrated fresh water was recovered in dry periods, whenever available and needed for irrigation of crops in the greenhouse.

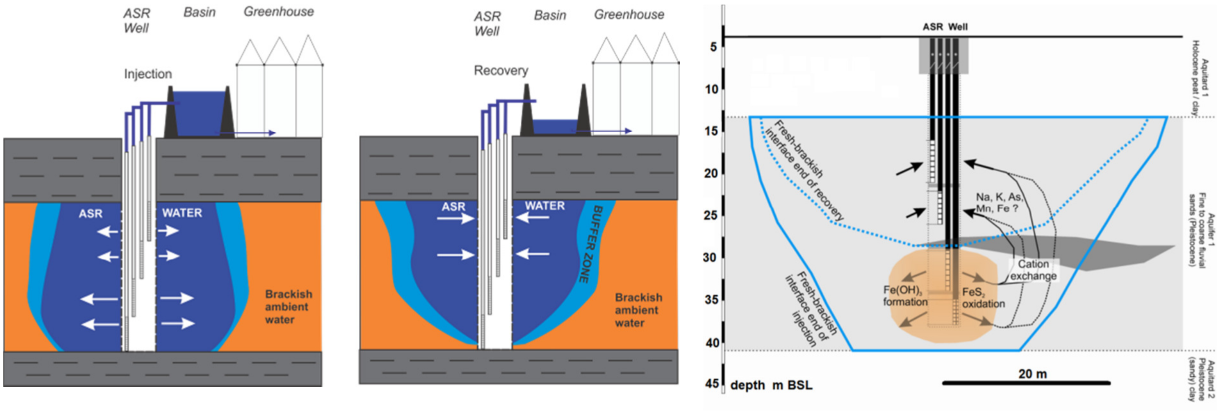

FIG. 1. Left and middle: Use of multiple partially penetrating ASR well for significant improvement of freshwater recovery from a confined brackish aquifer in coastal Netherlands. Right: Shift in position of the fresh water bubble after injection and after recovery, with important hydrogeochemical processes and zones.

The Maximum Permissible Concentration (MPC) for crops (Na<11 mg/L, monitored as EC<25 mS/m) determined when to stop recovery. The pilot was intensively monitored in 2012 (Zuurbier et al. 2014a).
The second pilot (Fig.2) is running since 2013, in an elongated, narrow creek ridge aquifer near Ovezande (SW-Netherlands), using a HOrizontal Salinization Protected ASR well (HOSPA; also called ‘Freshmaker’). It consists of 2 parallel, superimposed Horizontal Directional Drilled Wells (HDDWs) 70 m long, the upper one (at 7 m BSL) being the ASR well and the lower one (at 14.5 m BSL) being the interception well of underlying saltwater.
Surface water is taken in from a local water course (fresh when significant rainfall), and is pretreated by sedimentation in a small basin. The saline groundwater (TDS 39,000, Cl 16,800 mg/L) is pumped out continuously (40 m^3/d), and discharged downstream of the water course which discharges to the Scheldt estuary. The fresh water recovered is used for irrigation in an apple orchard. The MPC was set at 250 mg Cl/L, monitored as EC<150 mS/m. The pilot is being intensively monitored (Zuurbier et al. 2014b).
Results of the fresh/salt interface monitoring were simulated with SEAWAT, and used to extrapolate recovery efficiencies (REs) of future ASR scenario’s, and to demonstrate that REs would have been 50% lower with normal ASR wells.

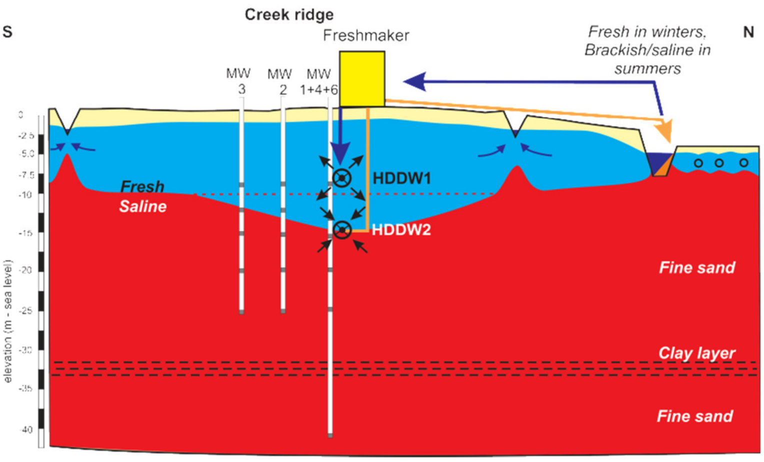

FIG. 2. Cross section over the creek ridge near Ovezande where a HOSPA is enlarging the fresh water reserve while saline groundwater is pumped out continuously. HDDW1 = horizontal ASR well; HDDW2 = horizontal interception well. MW = vertical Monitor Well.

A unique ASR column setup was developed to simulate oxic tap water injection and recovery from originally deeply anoxic sand saturated with brackish groundwater (Fig.3; Table 1). Undisturbed cores from the brackish aquifer at the Nootdorp pilot were thus tested via 2 series of 4 conventional ASR cycles, in which tap water was injected (Antoniou et al. submitted). The tests revealed a persisting Mn(II), Fe(II) and As mobilization due to pyrite oxidation and manganous siderite dissolution, as happened in field pilot Nootdorp (Fig.1) and in field pilot Herten (see Antoniou et al. 2013). This mobilization is feared because the recovered water needs to be distributed without post-treatment. In order to temper the mobilization, the cores were flushed during the second ASR cycle (of the second series) with a dilute 0.02 M $KMnO_4$ solution (Table 1), and after its recovery the column was flushed with tap water again.
In addition, the effects of adding extra O_2 and Na_2CO_3 to oxic tap water were modeled using a calibrated flow-tube PHREEQC-2 model.

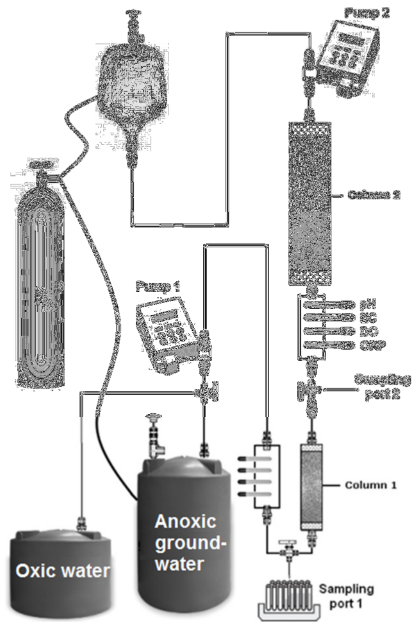

FIG. 3. A unique ASR column setup, showing reservoirs of oxic tap water and (deeply) anoxic groundwater, column 1 simulating the ASR proximal aquifer zone, and column 2 simulating the remote buffer zone.

RESULTS AND DISCUSSION

The MUPPA and HOSPA (Freshmaker) pilots showed that a sufficiently high RE (>50% and 100% respectively) could be realized, while the SEAWAT modeling indicated a far lower RE (<20% and <50% respectively) for both, if a normal ASR well (without buoyancy buffering and without salt water interception, respectively) had been used.
The realized RE's are excellent, considering the very stringent MPC for Na (11 mg/L) on the Nootdorp pilot, and MPC for Cl (250 mg/L) on the Ovezande pilot. These values correspond with an allowed admixing of only 3% brackish and 0.9% saline groundwater, respectively.
The MUPPA's RE could be further improved by a steady, slow abstraction of brackish groundwater (which could be used after desalination via RO), and by periodically also using the upper ASR well screen for infiltration. The latter helps to build up more ferrihydrite coatings which sorb the Fe, Mn and As mobilized in the deeper parts of the aquifer (Fig.1).

TABLE 1. Overview of water quality parameters for the brackish groundwater in the sand cores from Nootdorp (native groundwater), tap water (normal source water), and the diluted $KMnO_4$ solution.

	pH	EC	Alkalinity	NH_4	Cl	SO_4	Na	K	Ca	Mg	Fe	Mn	As
		µS/cm	mg/L										µg/L
Native water	6.8	3540	1102	12.3	1120.5	0.7	618.0	25.9	267.0	66.7	15.2	1.4	1.0
Normal source water	8.0	392	235	0.0	8.8	0.1	13.2	1.1	69.9	5.4	0.0	0.0	0.0
$KMnO_4$ source solution 0.02M	8.4	2400	56	-	-	0.1	1.6	782.0	1.6	0.0	0.0	1098.8	2.2

The horizontal wells in the HOSPA could also form a solution in case of lateral bubble drift, if aligned in the direction of regional groundwater flow. In that case the wells should be equipped with valves that can be closed so as to infiltrate via the upgradient section and recover in the downgradient parts.

The $KMnO_4$ treatment helped to increase RE from 15 to 84 % during the next conventional ASR cycle using tap water. This beneficial result is due to the combination of (i) the very strong oxidizing activity of $KMnO_4$, (ii) the increase of sorption capacity through the generation of Mn-oxide precipitates, (iii) the coating (inactivation) of reactive pyrite, and (iv) the resulting pH increase, which helps to immobilize Fe and Mn. The reactions with pyrite (FeS_2) and organic matter (CH_2O) are schematized as follows:

$$4MnO_4^- + 3CH_2O + 4H^+ \rightarrow 4MnO_2 + 3CO_2 + 5H_2O \quad (1)$$

$$5MnO_4^- + FeS_2 + H^+ \rightarrow 5MnO_2 + 2SO_4 + FeOOH \quad (2)$$

Although the use of $KMnO_4$ in water treatment is well established, in ASR some further research is required to solve questions regarding the dose, treatment frequency and costs.

Addition of only O_2 provoked an undesired pH decline, which stimulated Mn mobilization. When combined with a pH raising solute like Na_2CO_3 much better results in immobilizing Fe and Mn were obtained (Antoniou et al. 2013).

CONCLUSIONS

Even brackish and saline aquifers can be used to store fresh water for later use, if ASR wells are properly designed to reduce or buffer bubble drift, and if adverse water quality changes in an anoxic aquifer are mitigated by an oxidizing and pH increasing treatment.

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