Journal of Hydrology 509 (2014) 430–441

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

How multiple partially penetrating wells improve the freshwater recovery of coastal aquifer storage and recovery (ASR) systems: A field and modeling study

Koen G. Zuurbier [a,b,*], Willem Jan Zaadnoordijk [a,c], Pieter J. Stuyfzand [a,b]

[a] KWR Watercycle Research Institute, Groningenhaven 7, 3433 PE, The Netherlands
[b] Critical Zone Hydrology Group, Department of Earth Sciences, VU University Amsterdam, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands
[c] Water Resources Section, Faculty of Civil Engineering and Geosciences, Delft University of Technology, 2628 CN Delft, The Netherlands

ARTICLE INFO

Article history:
Received 23 September 2013
Received in revised form 22 November 2013
Accepted 27 November 2013
Available online 4 December 2013
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief, with the assistance of Renduo Zhang, Associate Editor

Keywords:
Aquifer storage and recovery
ASR
Recovery efficiency
Well configuration
Multiple partially penetrating wells

SUMMARY

Aquifer storage and recovery (ASR) of freshwater in brackish or saline aquifers can be an efficient technique to bridge freshwater shortages in coastal areas. However, buoyancy effects may cause salinization at the bottom of the ASR well during recovery, making a part of the freshwater irrecoverable. This study shows how such freshwater losses can be reduced applying deep injection and shallow recovery by independently operated multiple partially penetrating wells (MPPW) in a single borehole. A small-scale ASR system with such an MPPW was installed in January 2012 and its operation was extensively monitored until October 2012. A SEAWAT model was built and calibrated on the field measurements of this first ASR cycle. The model was used to compare the MPPW with a conventional fully and partially penetrating well. The freshwater recovery of those wells was 15% and 30% of the injected water, respectively, which is significantly less than the 40% recovered by the MPPW. In subsequent cycles, no more than 60% could be recovered by the MPPW, as mixing in the lower half of the aquifer remained a source of freshwater losses. However, this recovery is significantly higher than the recovery of the conventional well types. This study therefore shows that for less ideal ASR conditions, a viable system can still be realized using MPPW.

1. Introduction

Aquifer storage and recovery (ASR) involves the injection and recovery of water by wells into natural porous media and can be an efficient technique to store and recover large volumes of water (e.g., Maliva and Missimer, 2010; Pyne, 2005). Periods with shortage of for instance drinking, industrial, and irrigation water can be bridged this way, claiming little surface area aboveground. The injected water bubble is less vulnerable to surface contamination (Hermann, 2005) as this storage type is typically applied in deep, confined aquifers. Successful ASR applications were reported by Dillon et al. (2006), Pyne (2005), Vacher et al. (2006), and Ward et al. (2009). About one third of the current ASR systems is already situated in brackish to saline aquifers (Pyne, 2005), as more and more freshwater shortages occur in coastal areas due to climate change, overexploitation, and seawater intrusion (e.g., Arnell, 1999; Schröter et al., 2005; Werner et al., 2013). Success of especially small-scale ASR in those areas may be very limited, as the injected freshwater gets mixed with and displaced by ambient brackish or saline groundwater due to background lateral flow and buoyancy effects (Bakker, 2010; Kumar and Kimbler, 1970; Ward et al., 2009; Zuurbier et al., 2013). This displacement of fresh by saline water enables saline water to enter the lower parts of the well early during recovery, which may significantly reduce the recovery efficiency (RE). RE is defined as the fraction of the injected water that is recovered by the ASR system. When RE is low, ASR can either not satisfy the water demand, or the costs of the water recovered exceed the benefits.

Strategies were proposed to prevent low REs in brackish and saline aquifers. For instance, a large volume may be injected without recovery, prior to injecting the water that is to be recovered (the so-called target storage volume; Pyne, 2005). A targeted volume of unmixed injection water may be recovered this way. However, the water required for such a first phase without recovery may not be available. In addition, buoyancy effects may still cause early salinization at the bottom of the ASR well, especially in case of small-scale ASR in combination with lateral flow and/or saline seepage. Another method to improve RE can be optimization of the well design, enabling preferential recovery at the aquifer top, which may be combined with preferential injection at deeper parts of the aquifer. This strategy was proposed for improved recovery of

* Corresponding author. Tel.: +31 (0) 30 60 69 511; fax: +31 (0) 30 60 61 165.
E-mail address: koen.zuurbier@kwrwater.nl (K.G. Zuurbier).

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http://dx.doi.org/10.1016/j.jhydrol.2013.11.057

hot water by the use of partially penetrating wells during aquifer thermal energy storage, where buoyancy effects may also induce low RE (Buscheck et al., 1983; Molz et al., 1983a,b). More recently, preferential recovery has also been proposed for ASR in brackish aquifers using one-way (flapper) valves, inflatable packers, or an extra partially penetrating well (Maliva et al., 2006). Maliva and Missimer (2010) additionally proposed installation of a deeper partially penetrating well for preferential injection at deeper parts of the aquifer. Miotliński et al. (2013) studied the use of a multiple (rhombic) injection and recovery well system for aquifer transfer and recovery in a brackish aquifer, using four partially penetrating injection and two production wells. In this study, focus was on mixing with brackish background water and the attenuation of contaminants through adequately long residence times. However, density effects were not considered. Optimization of freshwater recovery by this well system under conditions where buoyancy effects otherwise negatively influence RE was therefore not studied.

The potential benefits of optimized well designs for ASR under conditions where density effects may cause a significantly lower RE are practically still unexplored. Nevertheless, many small greenhouse ASR systems in Dutch coastal areas are already equipped with multiple partially penetrating wells in a single borehole (MPPW) to inject and recover roofwater surpluses. This way, lower well segments can be closed off once salinization occurs. ASR owners may be able to achieve a higher RE this way than predicted by recent ASR performance tools (Zuurbier et al., 2013), but there are neither field nor modeling studies known to date that quantify the potential benefits.

The objectives of this study are to validate and quantify the potential benefits of MPPW for a small-scale freshwater ASR system suffering from buoyancy effects. A greenhouse ASR system injecting less than 14,000 m^3/y in a Dutch brackish coastal aquifer was extensively monitored for this purpose from January to October 2012. Using MPPW, freshwater was injected preferentially at deeper parts of the aquifer, whereas recovery was performed in the upper part of the aquifer. The monitoring results were used to calibrate a SEAWAT transport model, simulating the aquifer injection, storage, and recovery. Both a fully penetrating and a single shallow partially penetrating well was simulated with this model for equal ASR operational parameters, in order to quantify the long-term RE increase by an MPPW-equipped ASR system.

2. Study area

2.1. Irrigation water demand and supply

The study area is dominated by greenhouse horticulture with a typically high water demand, using on average 759 mm of the mean yearly gross precipitation of 853 mm (Paalman et al., 2012). With the average distribution of water availability and demand throughout the year, a mean freshwater shortage of 60% of the winter surpluses exists (Zuurbier et al., 2013). Furthermore, there are high water quality standards concerning salinity, with especially sodium concentrations being critical (maximum permissible concentrations <12 to <69 mg/l, depending on plant species). Fresh irrigation water supply in this area is currently realized by storage of rainwater in basins or tanks, use of surface water, and desalination of brackish groundwater. ASR can be a valuable technique to store more of the large (winter) precipitation surplus in order to bridge water shortages in the area during (summer) droughts, but its use is limited to date because of expected low REs in the brackish to saline coastal aquifers (Zuurbier et al., 2013).

2.2. Hydrogeological setting

Unconsolidated Pleistocene and Holocene fluvial and marine deposits are found in the upper ~120 m in the study area (Busschers et al., 2005). Regional groundwater flow is controlled by the North Sea in the west and the drainage levels of the low polders in the Oostland area and a large industrial groundwater extraction, as illustrated by the regional head contours (Fig. 1). Groundwater in the shallow ASR target aquifer (10–50 m below sea level (m BSL)) is typically brackish to saline (Fig. 1), with highest salinities (up to ~5000 mg/l Cl) found near the coast and in low-lying polders (Oude Essink et al., 2010).

2.3. Nootdorp ASR field trial

The ASR field trial is situated near the village of Nootdorp, where chloride concentrations in the target aquifer are typically around 1000 mg/l (Fig. 1). Based on regional mapping of the groundwater heads on April 28, 1995 (TNO-NITG, 2011), a hydraulic gradient of 2.7×10^{-4} m/m was deduced. This gradient

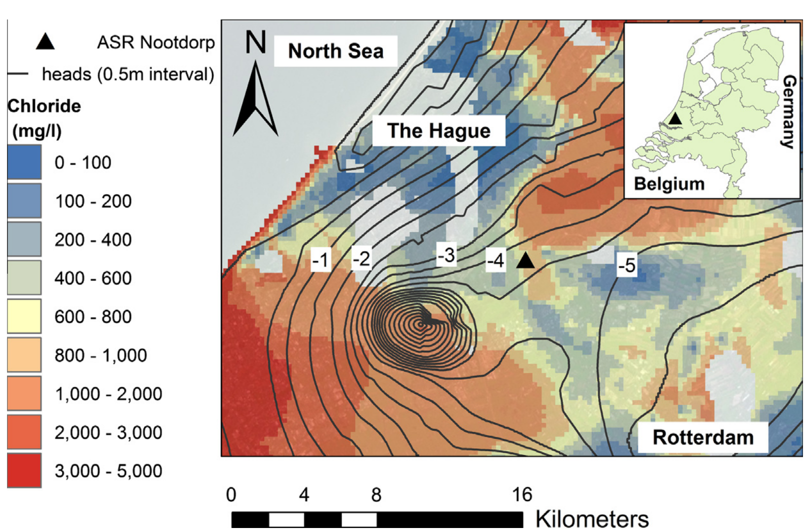

Fig. 1. Regional piezometric head contours (TNO, 1995) and chloride concentrations (Oude Essink et al., 2010) in the centre of the ASR target aquifer, with location of the Nootdorp ASR field trial (black triangle).