Final author comments on behalf of all co-authors

Referee #1: David Pyne

General: This paper presents an excellent and thorough evaluation of potential mechanisms for salinization of recovered water from ASR storage in brackish aquifers and, in particular, the reduction in recovery efficiency (RE) due to short-circuiting through existing wells open to deeper aquifers. Effective mitigating measures such as the new Freshkeeper technology are of great potential value.

Land use and water quality constraints, and competing uses of coastal aquifer systems to meet diverse objectives are common to many coastal areas globally. The relatively shallow depths of ASR storage aquifers in the coastal dune sands of the Netherlands are much shallower and more saline than coastal plain alluvial aquifer systems in many other parts of the world. The Dutch ASR experience and associated research therefore extends and deepens the understanding of solutions to similar challenges for ASR wells in other parts of the world.

General: It may be helpful to present why the RE was defined for this site by a chloride below 50 mg/l. This makes sense for the Coastal Dunes and greenhouses of the Netherlands, but many readers will wonder why so low compared to drinking water standards, and may tend to be unimpressed by the reported ASR RE values.

Author's response:

The authors agree that these keywords can be added and are willing to do so. We propose to do is in the current Section 2.1

Page Line

1 26 Key words might also include “upconing” and “downconing,” both of which describe “short-circuiting” as referred to in this paper, and as experienced at several operating ASR sites.

Author's response:

The authors agree and have added these keywords

2 16 While the impact of short-circuiting may not have been evaluated in the research literature, it has been experienced in the field at many ASR locations in brackish and saline aquifers, resulting in recognition that adequate confinement is usually needed in order to achieve acceptable recovery efficiency (RE). Upconing through underlying confining layers and downconing through overlying confining layers can adversely and rapidly impact RE, whether through an open borehole or through a leaky confining layer.

Author's response:

The authors agree with the referee that there is more evaluation of the confinement of target aquifers for ASR. This study, however, focuses on short-circuiting only (for the sake of clarity). The authors feel that this focus is clear in the introduction. The authors now mention the earlier work on confinement for ASR, as stated by the reviewer.

6 15 For ASR storage of fresh water in a brackish aquifer, with or without the potential for short-circuiting, we would normally provide for initial formation and then maintenance of a buffer zone (BZ) to separate the stored fresh water from the surrounding (and underlying or overlying) brackish water. An adequate buffer zone addresses not only blending issues but also geochemical issues such as arsenic attenuation. A typical BZ in an aquifer like this might comprise 30% to 50% of the Target Storage Volume (TSV) that is needed for recovery, however the BZ is a one-time addition of water to the well. Formation of the BZ does not count against recovery efficiency. Instead, it is considered to be a final step in well construction. This typically works….except in situations with short-circuiting where often the BZ volume cannot overcome upconing or downconing of saline water through adjacent open boreholes. Where semi-permeable confining layers overly or underlie the storage aquifer, we may over time freshen the overlying or underlying adjacent aquifers, thereby steadily improving recovery efficiency.

This paper sets the RE bar very high initially by aiming to recover all of the stored water (60,000 CM). This may be scientifically defensible and convenient however it is effectively counterproductive. Those who provide funds for ASR implementation are more likely to approve projects that achieve higher RE, even if they do not really understand the science. The buffer zone is one of the keys to achieving high RE, and the cost of the water comprising the buffer zone is usually rather small, especially if amortized over the life of the well.

Drawing RE conclusions based on conducting and/or modeling 2 or 3 cycles, without prior formation of a buffer zone, really stacks the deck against achieving satisfactory RE in moderately brackish aquifers. Without short-circuiting, you may be able to achieve a satisfactory RE after maybe 5 to 15 cycles, or with a single cycle following prior development of a buffer zone. The volume of water forming the buffer zone depends on several factors, including leakance of the storage aquifer, lithology and associated dispersion, density differential, aquifer thickness and porosity. We have successfully stored drinking water in a seawater aquifer that had appropriate storage characteristics.

Author's response: *The authors recognize the potential additional value of introducing a buffer zone for particular settings, especially when short-circuiting and strong buoyancy effects are absent. Its evaluation was however not the scope of this study, so it cannot be stated what the potential benefit may be in this case. However, the authors wish to state that given target aquifer characteristics and relatively small scale of the scheme, the (especially long-term) benefits of a buffer zone will be limited due to severe buoyancy effects, which causes the buffer zone to move to the top of the target aquifer, allowing salinization at the aquifer's base. Furthermore, the greenhouse ASR systems do not have any extra water to form a buffer zone: the available rainfall is infiltrated, the water demand is recovered.*

This study explores this maximum demand in the first cycles, in which the biggest performance increase occurs (Bakker, 2010). For the international perception of ASR, it is very important to note to properly sketch these conditions in order to manage performance expectations of the public. This is a very valid point of the referee. A section on this should be added in the discussion (Section 4.4):

> *'Finally it should be noted that the ASR-system analyzed in this study had very strict water quality limits (practically no mixing allowed) and that a buffer zone (Pyne, 2005) between the injected freshwater and the relatively saline ambient groundwater was not realized before starting the ASR-cycles. The boundary conditions for ASR were therefore already unfavorable. Also, the potential improvement after >3 cycles was not explored. The performance of this ASR-system should therefore not be considered the typical performance of ASR in a brackish-saline aquifers, which controlled by a complex interplay of geological conditions and operational*

parameters (Bakker, 2010), well design (Zuurbier et al., 2015; Zuurbier et al., 2014), and the formation of a buffer zone prior to starting the ASR-cycles (Pyne, 2005).'

19 4 Consider adding a sentence or two near the beginning of the paper explaining why this site was selected for testing. People would not normally locate an ASR well 3 m from an ATES well that is known to short circuit the lower confining layer….except for the opportunity to conduct research on short circuit mechanisms and associated mitigating measures.

Author's response:

In fact, there was no other location available and the short-circuiting was not known at the time of the realization of the ASR wells. This information was added to the methods section (Section 2.1).

19 25 One bar injection pressure is not very high. We typically limit ASR well injection pressures to about two bars, primarily to avoid wellhead transducer seal failures.

Author's response:

For relatively shallow (50 m below surface level) injection wells in an area where pressure head are near the land's surface, 1 bar actually already high. Higher injection pressures than 1 bar can already result in failure of the sealing (Olsthoorn, 1981). No amendments suggested.

Referee #2 (Anonymous)

General comments

This manuscript describes solute transport modelling to evaluate the processes that contribute to salinisation of recovered water from an ASR well, along with possible mitigation strategies. Notably, the recovery efficiency of this ASR system is constrained by an extremely tight limit for chloride concentration in the recovered water of 50 mg/L. The content of this manuscript is suitable for publication in HESS, however considerable revision is required to provide the reader with adequate understanding of the site and the evaluation. It should be noted that this ASR system is not typical of ASR operations internationally. General editing is required to improve the fluency and precision of the language used in the manuscript; particular attention should be paid to improved use of technical descriptions (some examples are outlined in the specific comments below). While this paper stemmed from an unplanned activity (high salinity), the paper should be presented in an organised framework; the current version reads as a somewhat haphazard approach.

Author's response:

The authors agree that the current version reads somewhat like a 'haphazard' approach. In some way, the study was haphazard: it was never the intention to study the effect of short-circuiting on ASR. It was the intention to increase freshwater recovery upon aquifer storage, despite buoyancy effects, using the multiple partially penetrating wells. However, the authors feel that it is relevant to report failures and surprises during the use of

ASR, which is now not always the case (page 2, line 28, original manuscript). To make sure the reader is able to understand and follow the set-up of the system and the operational/monitoring approach, a rather chronological set-up was chosen.

Please refer to the specific comments outlined below.

Specific comments

Page – Line - Comment

1 14 Suggest insert 'confined' into description of aquifers.

Author's response: *amended as such*

1 14 And elsewhere. Suggest replacing 'saltwater' with 'brackish'.

Author's response: *This is a very common discussions among hydrologists in this field and related to universal definition of freshwater, brackish water, and saltwater. Following the frequently used classification by Stuyfzand (1993), brackish water is limited to water with Cl concentrations <1.000 mg/l. We propose not to amend this choice of word.*

1 16 Explain 'properly separated' – the role of the confining layer should be made clear.

Author's response: *We agree with the referee. We added further explanation here by adding after 'separated':*

'(i.e. a continuous clay layer prevented rapid groundwater flow between both aquifers)'

1 17 Suggest replacing SEAWAT with ' variable-density solute transport modelling (SEAWAT)'.

Author's response: *We agree with the referee and this was amended as such.*

1 22 MPPW has not been defined.

Author's response: *We agree with the referee, MPPW should first be defined before using its abbreviation. This is done in the same sentence.*

1 28-30 Explain the role of the confining layer and why confined aquifers are targeted for storage. Introduce impact of inter-aquifer leakage.

Author's response: *We agree with the referee and propose to add this information in this first part of the introduction to highlight the importance of the confining layer in these applications. It was added near the references on this topic, which were suggested by Referee #1.*

1 28-30 First sentence needs revision to ensure it is relevant to content of manuscript –stormwater infiltration is also freshwater storage. Perhaps only include uses of confined aquifer for clarity. ASR is one managed aquifer recharge technique suited to storing fresh water in brackish aquifers.

Author's response: *It is a bit unclear what the exact point of the referee is here. We propose to replace 'Aquifers' by 'Confined and semi-confined aquifers'. Storm water infiltration is not necessarily storage, but rather 'disposal'. We combined this with brine disposal.*

2 1 Over citation of Bonte – revise.

Author's response: *We found that the most recent and relevant work in this relatively new field was performed by Bonte, but we now mention only the most relevant 2 of its papers.*

2 Introduction Previous research on inter-aquifer leakage and modelling of recovery efficiency has not been adequately reviewed.

Author's response: *It is unclear to the authors which other literature is exactly meant here, but the authors are willing to extent the review of inter-aquifer leakage and RE. See also the response to Referee #1 and the added references in the introduction on this matter.*

2 5 Of what wells? All wells globally?

Author's response: *This concerns all wells worldwide. We added 'worldwide' after 'wells'*

2 7 Soil fractures should be described as fractures (aquifer is not soil zone).

Author's response: *Amended as suggested.*

2 18 Is it necessary to cite 3 Zuurbier papers? Expand review of literature as many others have stored freshwater in confined aquifer, a necessary reference is R.D.G. Pyne's Aquifer Storage Recovery: A Guide to Groundwater Recharge through Wells.

Author's response: *We diversified the references here, amongst others by mentioning Pyne (2005) here as well (although it was already in line 31 of page 1 as well).*

3 3 Suspect error in number, 270,000 not 270,0000.

Author's response: *Indeed, amended.*

3 Method An overview of the hydrogeology is required. Suggesting moving section 3.1 to methods.

Author's response: *We have had similar considerations, but decided to put this in Section 3 as the geological characterization contains many newly obtained results. However, we agree that this may better suit in section 2. Section 3.1 was moved to Section 2.*

3 Method A summary of ASR cycles is required. Suggest adding a table with dates, injection and recovery volumes for each ASR well.

Author's response: *We agree with the referee. Although the operations during the cycles are reported in Section 3, a summary of the ASR-cycles presented in a table is now implemented in Section 2.*

3 3-13 The reader needs to understand all characteristics of the site, such as aquifer targeted for ASR and for ATES, EC, Cl, SO4 concentrations for each aquifer and for roof runoff. Detail in text is not adequate.

Author's response: *We feel that we give the reader the desired detail by moving Section 3.1 to the methods section.*

3 8 Need information about hydrogeology before describing the need for MPPW. Screen intervals for all wells should be given in text or table. Distance from ASR wells should be given for ATES and monitoring wells.

Author's response: *The authors agree with the referee and now provide this information*

3 8 Give distance of ATES wells from ASR well, clearly identify new and old, suggest giving unique identifier (K3-a and K3-b)

Author's response: *The distance is now mentioned in Section 2.1. A unique identifier is added as proposed, also in the related figures and the rest of the text.*

3 13 Give the chloride concentrations for each end-member and quantify the amount of mixing <

Author's response: *We agree with the reviewer and added this information in Section 2.2.*

14 1 The monitoring wells shown in Figure 2 have not been mentioned in the text.

Author's response: *This information is now reported in text and in the table as requested by the reviewer*

4 5 Give sampling frequency.

Author's response: *We added the exact moments of sampling*

4 6 Were stable field parameters also used to indicate adequate purging?

Author's response: *Yes, upon purging of each well, it was checked if all field parameters were stable. We added this information to this section.*

4 16 Suggest replacing 'electronic recording' with 'continuous monitoring'.

Author's response: *We can see an improved clarity by implementing this suggestion. Amended as suggested.*

4 21 Suggest deleting 'In'. 4 21 Give some explanation of model choice.

Author's response: *We agree with the referee, this was a typo. We now also elaborate on the choice for SEAWAT (variable density, etc.)*

4 21 Sentence requires editing, move 'to' to after Chiang 2012.

Author's response: *Indeed, a second typo in this sentence. Amended as such.*

5 1 Replace 'te' with 'the'.

Author's response: *Typo, amended as suggested.*

5 8 Justify choice of end-member concentrations; text should be more specific rather than general description.

Author's response: *We added specific justification here, as proposed by the referee.*

5 Overall The description of the modelling method could be improved by stating a set of clear aims for the modelling.

Author's response: *The authors agree that the reader should be taken by the hand in this section by elaborating on the modelling aims and added the following at the start of the section:*

'Groundwater transport modelling was executed to validate the added value of the MPPW set-up under the local conditions. In the later stage of the research, the groundwater transport model was used to test potential pathways for deeper groundwater to enter the target aquifer and explore the characteristics of a potential conduit via scenario modelling. Correction for groundwater densities in the flow modelling was vital, due to significant contrast between the aquifer's saltwater and the injected rainwater.'

6 Table 1 Suggest removing VANI heading. Suggest adding more detail to show properties of each layer.

Author's response: *The authors feel that the table (including VANI) provides the relevant characteristics of the model layers. VANI is replaced by reporting the* K_v *in this column for the sake of clarity.*

7 Table 2 Suggest replace ‘infiltration’ with ‘injection’.

Author’s response: *The authors agree with the reviewer and replaced infiltration by injection, throughout the manuscript.*

7 26 ‘close by’ is vague, be specific.

Author’s response: *The authors agree and propose to replace ‘close by pumping test’ by ‘a pumping test at approximately 500 m from the ASR wells,’*

7 Section 3.1 As mentioned previously, suggest moving to methods.

Author’s response: *The authors agree, amended as indicated.*

9 2 As mentioned previously, give summary of ASR cycles in Table.

Author’s response: *The authors agree, amended as indicated.*

9 Figure 5 Discussion on mixing is based on Cl, but you are showing EC in Figure. Suggest plotting EC, Cl and SO4.

Author’s response: *We thank the reviewer for this suggestion. However, the reason to plot the EC here is the extremely high frequency of the analyses, which gives far more information that the regularly measured Cl.*

9 Figure 5 Suspect part a y-axis should be volume not EC.

Author’s response: *Indeed, the authors amended the title on this axis (correct = pumped volume* (m^3*/yr)*

9 2-8 Give reader more detail, explain that mixing would be expected on fringe of injected bubble and therefore become evident toward end of recovery cycle.

Author’s response: *The authors realize that in this section somewhat more information on what was expected, such that the reader can better understand the deviations and added this information in Section 3.1.*

9 2-8 Explain the freshening process in monitoring wells before describing salinisation during recovery.

Author’s response: *The authors agree, this also relates to the previous comment.*

10 10 Were any other tracers used to identify leakage? Age tracers?

Author's response: *As indicated in the Methods Section, only macrochemical analyses were performed. Especially* SO_4 *showed to be a good tracer, followed by HCO3 (which however had a much lower contrast. No amendments suggested.*

17 Table 4 Recovery of 10018

Author's response: *It is unclear to the authors what is meant by the reviewer here.*

11 Have the authors considered the economic feasibility of such a scheme? Interception of a significant volume of water must lead to significant pumping costs. What is the driver for such a scheme?

Author's response: *Up to now, an extensive evaluation of the costs of this scheme has not been executed. However, it is known that due to low price of electricity in The Netherlands, this impact will be limited. At the end of Section 4.3, some reflection on this matter is added.*

23 16 Bonte et al 2014 not cited

Author's response: *Citation removed. This reference incidentally ended up in the reference section.*

References Some editing required, script errors evident for CO2.

Author's response: *This was due to some problems with Endnote and the desired format of HESS. Will be corrected during typesetting.*

Consequences and mitigation of saltwater intrusion induced by short-circuiting during aquifer storage and recovery (ASR) in a coastal subsurface

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Abstract. Coastal aquifers and the deeper subsurface are increasingly exploited. The accompanying perforation of the subsurface for those purposes has increased the risk of short-circuiting of originally separated aquifers. This study shows how this short-circuiting negatively impacts the freshwater recovery efficiency (RE) during aquifer storage and recovery (ASR) in coastal aquifers. ASR was applied in a shallow saltwater aquifer overlying a deeper, confined, saltwater aquifer, which was targeted for seasonal aquifer thermal energy storage (ATES). Although both aquifers were considered properly separated (i.e. a continuous clay layer prevented rapid groundwater flow between both aquifers), intrusion of deeper saltwater into the shallower aquifer quickly terminated the freshwater recovery. The presumable pathway was a nearby ATES borehole. This finding was supported by field measurements, hydrochemical analyses, and variable-density solute transport modelling (SEAWAT)~~SEAWAT transport modelling~~. The potentially rapid short-circuiting during storage and recovery can reduce the RE of ASR to null. When limited mixing with ambient groundwater is allowed, a linear RE decrease by short-circuiting with increasing distance from the ASR well within the radius of the injected ASR-bubble was observed. Interception of deep short-circuiting water can mitigate the observed RE decrease, although complete compensation of the RE decrease will generally be unattainable. Brackish water upconing from the underlying aquitard towards the shallow recovery wells of the ~~MPPW~~ ASR system with multiple partially penetrating wells (MPPW-ASR) was observed. This 'leakage' may lead to a lower recovery efficiency than based on current ASR performance estimations.

KEYWORDS: aquifer storage and recovery, ASR, saltwater intrusion, coastal aquifers, short-circuiting, hydraulic connections, numerical modelling, upconing, downconing

1 Introduction

~~Aquifers~~ Confined and semi-confined aquifers are increasingly being used for stormwater ~~infiltration~~ and (Ferguson, 1990)~~,~~ brine disposal (Stuyfzand and Raat, 2010; Tsang et al., 2008)~~,~~ and storage of freshwater (aquifer storage and recovery or ASR; Pyne, 2005), heat (aquifer thermal energy storage or ATES; Bonte et al., 2011a), and CO_2 (Steeneveldt et al., 2006).

Additionally, they are perforated for exploitation of deep fossil and geothermal energy and traditionally used for abstraction of drinking and irrigation water. The increased use of the subsurface can lead to interference among aquifer storage systems (e.g., Bakr et al., 2013) or affect the groundwater quality (Bonte et al., 2011b; Bonte et al., 2013; Zuurbier et al., 2013b). These consequences form relevant fields of current and future research.

The perforation of aquifers and aquitards accompanying the subsurface activities imposes an additional risk by the potential creation of hydraulic connections ('conduits') between originally separated aquifers or aquifers and surface waters. This risk is plausible, as estimations indicate that about two-thirds of the wells worldwide may be improperly sealed (Morris et al., 2003), although the attention for this potential risk is limited (Chesnaux, 2012). Additionally, many of the new concepts to use the subsurface (e.g., ATES, ASR, brine disposal) require injection via wells, which may cause ~~soil~~ fractures, even when the annulus is initially properly sealed, by exceedance of the maximum-permissible injection pressure (Hubber and Willis, 1972; Olsthoorn, 1982). The soil fractures are undesirable for most groundwater wells in the relatively shallow subsurface, since they create new connections between originally separated aquifers.

The resulting short-circuiting or leakage process has been studied at laboratory (Chesnaux and Chapuis, 2007) and field scale (Jiménez-Martínez et al., 2011; Richard et al., 2014), and for deep geological CO_2 storage (Gasda et al., 2008). Santi et al. (2006) evaluated tools to investigate cross-contamination of aquifers. Chesnaux et al. (2012) used numerical simulations of theoretical cases to demonstrate the consequences for pumping test and hydrochemistry of hydraulic connections between granular and fractured-rock aquifers, which clearly demonstrated the significant hydrochemical cross-contamination when short-circuiting aquifers have a distinct chemical composition. The impact of short-circuiting on ASR are however not evaluated to date. However, reliably confined aquifers are vital to successfully store energy (Bonte et al., 2011a) and freshwater (Maliva et al., 2016; Maliva and Missimer, 2010; Missimer et al., 2002; Pyne, 2005; Zuurbier et al., 2013a) to bridge periods of surplus and demand, as inter-aquifer leakage may result in a loss of freshwater or undesirable admixing groundwater with a poorer quality, and therefore a reduced ASR performance. And although the risks of short-circuiting by perturbation are acknowledged by scientists, it seems that the practical and regulatory communities are less aware (Chesnaux, 2012). This is underlined by the fact that certification for mechanical drilling (applied since the Industrial Revolution) in The Netherlands was not obliged before 2011 (Stichting Infrastructuur Kwaliteitsborging Bodembeheer, 2013a), while for the subsurface design and operation of ATES systems (>1500 systems since the nineties (Bonte et al., 2011a; CBS, 2013)) certification was obliged only since early 2014 (Stichting Infrastructuur Kwaliteitsborging Bodembeheer, 2013b).

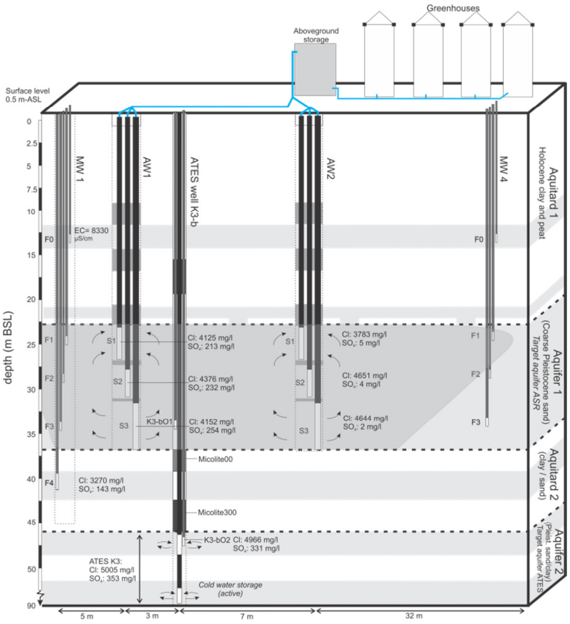
The lack of proper design and regulation of subsurface activities using wells can be partly caused by the lack of clear field examples of how well-intentioned use of the subsurface for sustainability purposes can fail thanks to earlier activities underground. This lack can be caused by the fact that short-circuiting may not be easy to observe (Santi et al., 2006), or because failing or disappointing projects often do not make it to public or scientific reports. Therefore, we present in this study how short-circuiting via a deeper borehole led to failure of freshwater recovery during ASR in a coastal aquifer. The objective of this paper is to demonstrate and characterize the potential consequences of perturbations for coastal aquifer storage and recovery (ASR) systems. Additionally, the use of deep interception of saltwater to improve shallow recovery of freshwater upon ASR was assessed. The Westland ASR site in the coastal area of The Netherlands served as demonstration and reference case.

2 Methods

2.1 Set-up Westland ASR system and pilot

The Westland ASR system is installed to inject the rainwater surplus of 270,000~~0~~ m^2 of greenhouse roof in a local shallow aquifer (23 to 37 m-below sea level (m-BSL), surface level = 0.5 m-above sea level (m-ASL)) with negligible lateral displacement (Zuurbier et al., 2013a) for recovery in times of demand. For this purpose, two multiple partially penetrating wells (MPPW) were installed (Figure 1~~Figure 1~~), such that water can be injected preferably at the aquifer base, and recovered at the aquifer top in order to increase the recovery (Zuurbier et al., 2014). Due to the limited space available at the greenhouse site, the ASR well was installed close to an existing ATES well, injecting (in winters) and abstracting (in summers) cold water of about 5 °C. All ASR (AW1 and AW2, installed in 2012) and ATES (K3-a, installed in 2006 and replaced by K3-b ~~close by~~at 3 m from AW1 and 7 m from AW2 in 2008) wells were installed using reverse-circulation rotary drilling, while the monitoring wells (MW1-5, Figure 2~~Figure 2~~) were installed using bailer drillings. Bentonite clay was applied to seal the ASR wells (type: Micolite300) and ATES well K3 (Micolite000 and Micolite300). The depth of the well screens is shown in Table 1. The monitoring wells were installed at 5 m (MW1), 15 m (MW2), 30 m (MW3), 32 m (MW4) and 60 m (MW5).

The ASR wells used a 3.2 m high standpipe to provide injection pressure, whereas the ATES well used a pump to meet the designed injection rate of 75 m^3/h. The maximum Cl concentration in the recovered water accepted at the site is 50 mg/l.~~, which meant that the water should be recovered practically unmixed~~. The ASR operation was relatively ‘dynamic’ due to the incorporation of the ASR system in the water supply of a greenhouse: injection occurred in times of high levels in the aboveground rainwater reservoirs, while recovery occurred when low reservoir levels were observed. This led to the general ASR cycles as presented in Table 2.


Greenhouses
Aboveground storage
Surface level 0.5 m-ASL
depth (m BSL)
0
2.5
5
7.5
10
15
20
25
30
35
40
45
50
90
MW 1
AW1
ATES well K3-b
AW2
MW 4
Aquitard 1
Holocene clay and peat
Aquifer 1
(Coarse Pleistocene sand)
Target aquifer ASR
Aquitard 2
(clay / sand)
Aquifer 2
(Pleist. sand/clay)
Target aquifer ATES
F0
EC= 8330 μS/cm
F0
F1
F2
F3
F4
S1
S2
S3
Cl: 4125 mg/l
SO_4: 213 mg/l
Cl: 4376 mg/l
SO_4: 232 mg/l
K3-bO1
Cl: 4152 mg/l
SO_4: 254 mg/l
S1
S2
S3
Cl: 3783 mg/l
SO_4: 5 mg/l
Cl: 4651 mg/l
SO_4: 4 mg/l
Cl: 4644 mg/l
SO_4: 2 mg/l
F1
F2
F3
Micolite00
Cl: 3270 mg/l
SO_4: 143 mg/l
Micolite300
K3-bO2 Cl: 4966 mg/l
SO_4: 331 mg/l
ATES K3:
Cl: 5005 mg/l
SO_4: 353 mg/l
Cold water storage
(active)
5 m
3 m
7 m
32 m

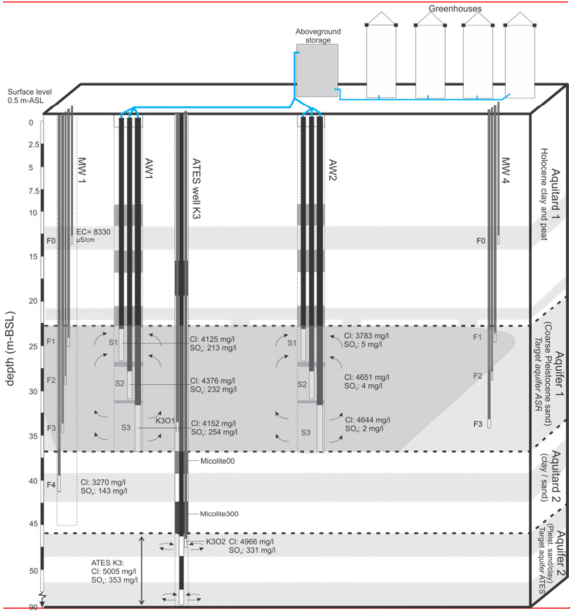

Greenhouses
Aboveground storage
Surface level 0.5 m-ASL
depth (m-BSL)
0
2.5
5
7.5
10
15
20
25
30
35
40
45
50
90
MW 1
AW1
ATES well K3
AW2
MW 4
Aquitard 1
Holocene clay and peat
Aquifer 1
(Coarse Pleistocene sand)
Target aquifer ASR
Aquitard 2
(clay / sand)
Aquifer 2
(Pleist. sand/clay)
Target aquifer ATES
F0
EC= 8330 μS/cm
F0
F1
F2
F3
F4
S1
S2
S3
Cl: 4125 mg/l
SO_4: 213 mg/l
Cl: 4376 mg/l
SO_4: 232 mg/l
K3O1
Cl: 4152 mg/l
SO_4: 254 mg/l
S1
S2
S3
Cl: 3783 mg/l
SO_4: 5 mg/l
Cl: 4651 mg/l
SO_4: 4 mg/l
Cl: 4644 mg/l
SO_4: 2 mg/l
F1
F2
F3
Micolite00
Cl: 3270 mg/l
SO_4: 143 mg/l
Micolite300
K3O2 Cl: 4966 mg/l
SO_4: 331 mg/l
ATES K3:
Cl: 5005 mg/l
SO_4: 353 mg/l

Figure 1: Cross-section of the Westland ASR site to schematize the geology, ASR wells, ATES well, and the typical hydrochemical composition of the native groundwater. Horizontal distances not to scale.

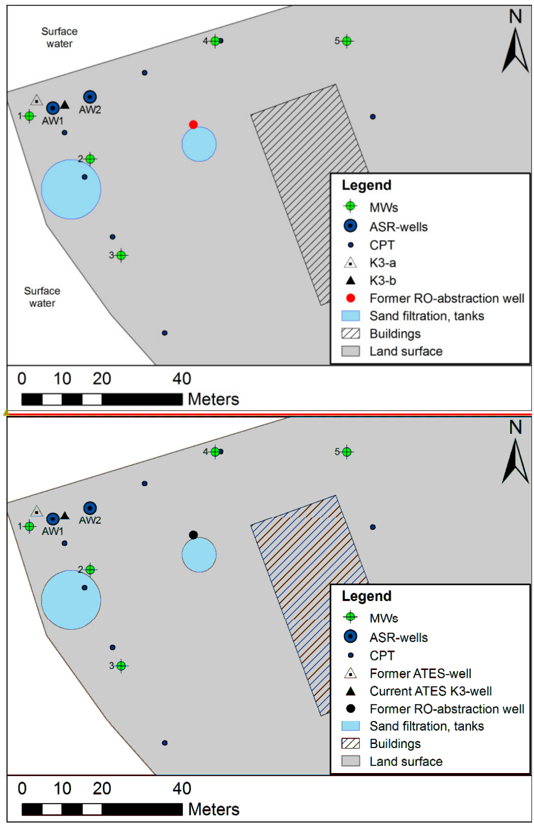


Figure 2: Locations of ASR (AW), ATES, and monitoring wells (MW).

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Table 1: Depth of the various well screens

Well screen	top *(m-BSL)*	bottom *(m-BSL)*
AW1.1 + AW2.1	23.1	26.6
AW1.2 + AW2.2	27.6	30.6
AW1.3 + AW2.3	31.6	36.4
ATES K3-b	53	61
	80	85

Table 2: Summary of the ASR operation

Stage	**Date**	**Wells**
Injection Cycle 1.1	December 12 (2012) – January 11 (2013)	AW1 + AW2
Recovery Cycle 1.1	January 11 – January 28 (2013)	AW1.1 + AW2.1
Injection Cycle 1.2	February 4 – February 8 (2013)	AW1 + AW2
Recovery Cycle 1.2	March 5 – March 11 (2013)	AW2.1 + AW2.2
Injection Cycle 2	September 11 (2013) – March 5 (2014)	AW1 + AW2
Recovery Cycle 2	March 5 – June 24 (2014)	AW2.1 + AW2.2

2.2 Detailed hydrogeological characterization based on local drillings

The target aquifer for ASR (Aquifer 1) was found to be 14 m thick and consists of coarse fluvial sands (average grain size: 400 µm) with a hydraulic conductivity (K) derived from head responses at the monitoring wells upon pumping of 30 – 100 m/d. Aquifer 2 (target aquifer for ATES) has a thickness of more than 40 m, but is separated in two parts at the ATES well K3-b by a 20 m thick layer clayey sand and clay. A blind section was installed in this interval, and the borehole was backfilled with coarse gravel in this section. The K-value of the fine sands in Aquifer 2 derived from a ~~close by~~ pumping test at approximately 500 m from the ASR-wells is 10 to 12 m/d and is in line with the estimated K-value from grain size distribution (Mos Grondmechanica, 2006). The effective screen length of K3-b in this aquifer is only 8 ~~(upper section: 53-61 m-BSL)~~ and 5 m (Table 1) ~~(lower section: 80-85 m-BSL)~~.

The groundwater is typically saline, with observed Cl concentrations ranging 3,793 to 4,651 mg/l in Aquifer 1 and approximately 5,000 mg/l in Aquifer 2 (see also Figure 1~~Figure 1~~). This means that with the accepted Cl-concentrations during recovery, only around 1% of admixed ambient groundwater is allowed. A sand layer in Aquitard 2 contains remnant fresher water (Cl = 3,270 mg/l). SO_4 is a useful tracer to identify the saltwater from Aquifer 1 and 2: it is virtually absent in

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Aquifer 1 (presumably younger groundwater, infiltrated when the Holocene cover was already thick), whereas it is high in Aquifer 2 (older water, infiltrated through a thinner clay cover which limited SO_4-reduction, see Stuyfzand (1993) for more details): 300 to 400 mg/l SO_4.

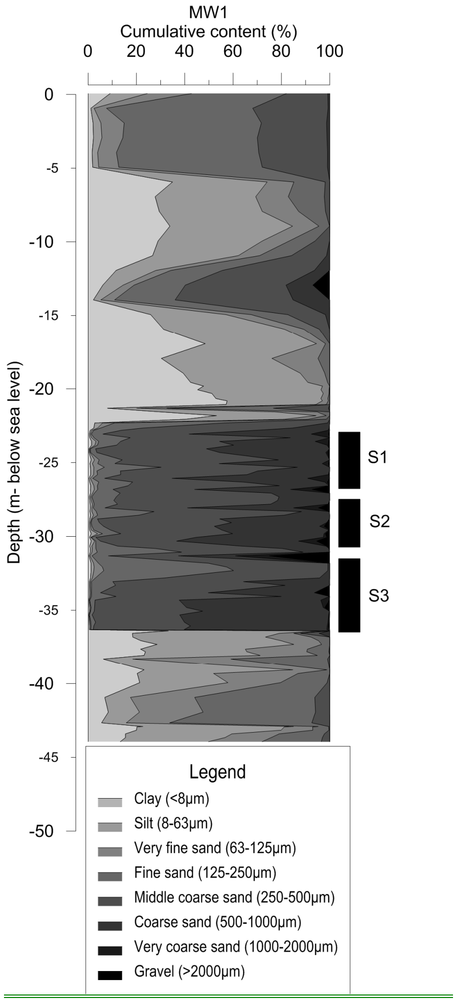

Figure 34: Cumulative grain size contents observed at MW1 (at 5 m from ASR well 1) in this study. S1-S3 mark the depth intervals of the ASR well screens.

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2.~~2~~ 3 Monitoring during Westland ASR cycle testing

All ASR and monitoring well screens were sampled prior to ASR operation (November and December, 2012). MW1 and 2 were sampled with a high frequency during the first breakthrough of the injection water at MW1 (December 2012, January 2013), while all wells were sampled on a monthly basis (Table 3). Three times the volume of the well casing was removed and stable field parameters were attained prior to sampling. The injection water was sampled regularly during injection phases. All samples were analyzed in the field in a flow-through cell for EC (GMH 3410, Greisinger, Germany), pH and temperature (Hanna 9126, Hanna Instruments, USA), and dissolved oxygen (Odeon Optod, Neotek-Ponsel, France). Samples for alkalinity determination within one day after sampling on the Titralab 840 (Radiometer Analytical, France) were stored in a 250 ml container. Samples for further hydrochemical analysis were passed over a 0.45 µm cellulose acetate membrane (Whatman FP-30, UK) in the field and stored in two 10-ml plastic vials, of which one was acidified with 100 µl 65% HNO_3 (Suprapur, Merck International) for analysis of cations (Na, K, Ca, Mg, Mn, Fe, S, Si, P, and trace elements) using ICP-OES (Varian 730-ES ICP OES, Agilent Technologies, U.S.A.). The second 10 ml vial was used for analysis of F, Cl, NO_2, Br, NO_3, PO_4, and SO_4 using the Dionex DX-120 IC (Thermo Fischer Scientific Inc., USA), and NH_4 using the LabMedics Aquakem 250 (Stockport, UK). All samples were cooled to 4 ^oC and stored dark immediately after sampling.

CTD-divers (Schlumberger Water Services, Delft, The Netherlands) were used for ~~electronic recording~~continuous monitoring of conductivity, temperature, and pressure in the target aquifer at MW1 and MW2. Calibrated, electronic water meters were coupled to the programmable logic controller (PLC) of the ASR system to record the operation per well screen.

Table 3~~2~~: Sampling rounds at the Westland ASR site (2012-2014). 'IN' = injection water

Well(s)	**Date**
K3-b, K3-bO2	August 22, 2012
AW1, AW2	November 6, 2012
MW1 - MW5	December 5, 2012
MW1	December 14, 2012
MW1	December 17, 2012
MW1, MW2, IN	December 18, 2012
MW1, MW2	December 20, 2012
MW1, MW2, IN	December 21, 2012
MW1, MW2	December 24, 2012
MW1, MW2	December 27, 2012
MW1, MW2	December 31, 2012
MW1, MW2, MW4	January 4, 2013
MW1, MW2, IN	January 11, 2013

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AW1, AW2	January 14, 2013
MW1, MW2, MW4	January 17, 2013
AW1, AW2	January 25, 2013
MW1, MW2, MW4, IN	February 12, 2013
AW1, AW2	March 8, March 11, March 19, April 8, 2013 March 11, March 14, March 17, March 21, March 28, April 2, April 15, April 17, April 28, May 5, May 22, June 2, 2014
MW1, MW2, MW3, MW4	March 11, April 8, September 17, October 2, November 6, December 11, 2013 January 14, Februari 19, April 2, May 5, 2014
K3-bO1	March 21, March 28, April 8, April 28, May 5, 2014

2.~~3~~ 4 Set-up Westland ASR groundwater transport model

Groundwater transport modelling was executed to validate the added value of the MPPW set-up under the local conditions. In the later stage of the research, the groundwater transport model was used to test potential pathways for deeper groundwater to enter the target aquifer and explore the characteristics of a potential conduit via scenario modelling. Correction for groundwater densities in the flow modelling was vital, due to significant contrast between the aquifer's groundwater and the injected rainwater. ~~In~~ In order to incorporate variable density flow and the transport multiple species, SEAWAT Version 4 (Langevin et al., 2007) was used ~~to~~ with PMWIN 8 (Chiang, 2012) to simulate the ASR operation. A half-domain was modelled to reduce computer runtimes. Cells of 1x1 m were designated to an area of 20x20 m around the ASR wells. The cell size increased to 2.5x2.5 m (30x40 m around the well) and was then gradually increased to a maximal cell size of 200x200 m at 500 m from the ASR wells. The pumping rate of each well screen was distributed over the models cells with the well package based on the transmissivity (thickness x hydraulic conductivity) of each cell. The third-order total-variation-diminishing (TVD) scheme (Leonard, 1988) was used to model advection and maintain the sharp edges of the freshwater bubble by limiting numerical dispersion.

Equal constant heads were imposed at two side boundaries of the aquifers, the top of the model (controlled by drainage) and at the base of the model. No-flow boundaries were given to the other two side boundaries of the model. Initial Cl-concentrations were based on the results of the reference groundwater sampling at MW1. SO_4 concentrations in Aquifer 1 were based on MW2, since these concentrations were considered ~~more~~ most representative for the field site: this well was close to the ASR wells, but not potentially disturbed by the ATES or ASR wells. For Aquifer 2, the concentrations found at ATES well K3-b (bulk) and the observation well K3-bO.1 were used (see Figure 1~~Figure 1~~). The density of the groundwater was based on the Cl concentration using:

$$\rho_w = 1000 + 0.00134 \times Cl(mg/l)$$

Density and viscosity were not corrected for temperature, as all temperatures (background groundwater, injected ASR water, and injected ATES water) were in the range of 8 to 12 °C and should not significantly impact the flow pattern (Ma and Zheng, 2010). A longitudinal dispersivity of 0.1 m was derived from the freshwater breakthrough at MW1 and was applied to the whole model domain. Constant heads were based on the local drainage level (top model layer) and the observed heads in the aquifer. The regional hydraulic gradient was derived from regional groundwater heads (TNO, 1995)

The recorded pumping rates of the ASR wells and the ATES K3-b well during two ASR cycles were incorporated in the SEAWAT model. The ASR operation was modelled with a properly sealed and an unsealed ATES borehole. In the latter case, a hydraulic conductivity (K) of 1000 m/d was given to the cells (1.0 x 1.0m) in Aquifer 1, Aquitard 2, and Aquifer 2 at the location of the ATES pumping well to force a significant borehole leakage. This K was considered realistic since apart from filter sand around the well screen, the borehole was backfilled with gravel with a grain size of 2 to 5 mm. In later scenarios, the ATES well was moved towards the fringe of the ASR well stepwise (10 m further away from AW1 in each scenario), after which Cycle 2 was simulated again. This was to examine the impact of borehole leakages at various distances from the ASR-wells.

Table 4~~1~~: Hydrogeological properties of the geological layers in the Westland SEAWAT model

Geological Layer	Model layers	Base (m-BSL)	K_h (m/d)	~~VANI~~K_v ~~(K_h/K_v)~~(m/d)	Ss (m^{-1})	n (-)	Initial C (mg/l Cl)	Initial C (mg/l SO_4)
Aquitard 1	6	22.3	0.2 - 1	~~100~~0.002-0.01	10^{-4}	0.2	2000-3000	4
Aquifer 1	12	33.7	35	~~1~~35	10^{-7}	0.3	4000-4800	4
	3	36.4	100	100				
Aquitard 2 (clay-sand)	8	47.5	0.05-10	0.0005~~1~~-10	10^{-4}	0.2-0.3	3200	160
Aquifer 2	6	96	12	~~1~~12	10^{-6}	0.3	4100-7900	331-375

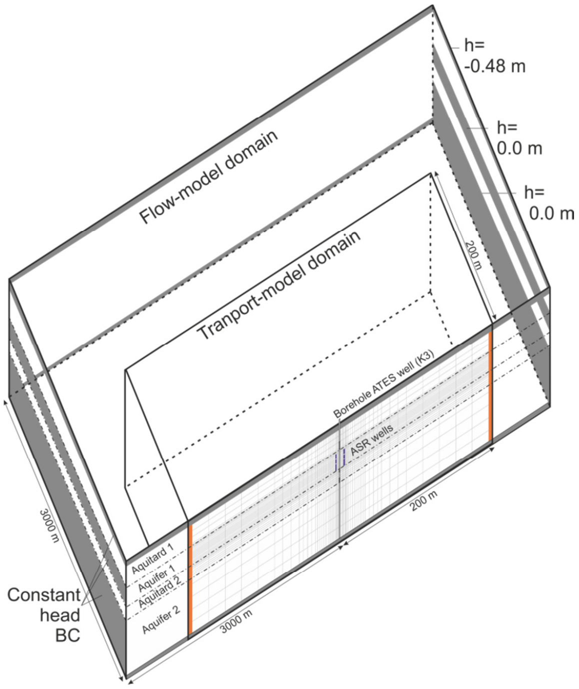

Figure 4~~3~~: Set-up of the Westland ASR groundwater transport model (half-domain).

2.~~4~~ 5 The maximal recovery efficiency with and without leakage at the Westland ASR site.

The collected data on the aquifer characteristics in the SEAWAT groundwater model were used to analyze the future performance of the MPPW-ASR system for the current (with leakage) and a ‘normal field site’ (without leakage from deeper aquifers via a perturbation, or after sealing of the perturbation). The SEAWAT model was used to simulate three consecutive ASR-cycles with the representative operational characteristics from Table 5~~Table 2~~ for the Westland site (Zuurbier et al., 2012). Once the recovered Cl concentration exceeded 50 mg/l, the model was stopped, and the length of the stress period with recovery was adjusted, such that no water with Cl>50 mg/l was recovered. Subsequently the model was run again after adding another cycle.

Table 5~~2~~: Set-up of the modelled, representative ASR-cycle for the Westland subsurface without short-circuiting of deeper saltwater.

Stage	Duration	Pumping rate

~~Infiltration~~Injection	120 days	60,000 / 120 = 500 m^3/d
Storage	30 days	0 m^3/d
Recovery	120 days	-60,000 / 120 = -500 m^3/d
Idle	65 days*	0 m^3/d

* Longer when early salinization occurred during recovery.

3 Results

~~3.1 Detailed hydrogeological characterization based on local drillings~~

~~The target aquifer for ASR (Aquifer 1) was found to be 14 m thick and consists of coarse fluvial sands (average grain size: 400 µm) with a hydraulic conductivity (K) derived from head responses at the monitoring wells upon pumping of 30 – 100 m/d. Aquifer 2 (target aquifer for ATES) has a thickness of more than 40 m, but is separated in two parts at the ATES well K3 by a 20 m thick layer clayey sand and clay. A blind section was installed in this interval, and the borehole was backfilled with coarse gravel in this section. The K-value of the fine sands in Aquifer 2 derived from a close by pumping test is 10 to 12 m/d and is in line with the estimated K-value from grain size distribution (Mos Grondmechanica, 2006). The effective screen length of K3 in this aquifer is only 8 (upper section: 53-61 m-BSL) and 5 m (lower section: 80-85 m-BSL).~~

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~~The groundwater is typically saline, with observed Cl concentrations ranging 3,793 to 4,651 mg/l in Aquifer 1 and approximately 5,000 mg/l in Aquifer 2 (see also Figure 1). A sand layer in Aquitard 2 contains remnant fresher water (Cl = 3,270 mg/l).~~ ~~SO_4 is a useful tracer to identify the saltwater from Aquifer 1 and 2: it is virtually absent in Aquifer 1 (presumably younger groundwater, infiltrated when the Holocene cover was already thick), whereas it is high in Aquifer 2 (older water, infiltrated through a thinner clay cover which limited~~ ~~SO_4-reduction, see Stuyfzand (1993) for more details): 300 to 400 mg/l~~ ~~SO_4.~~

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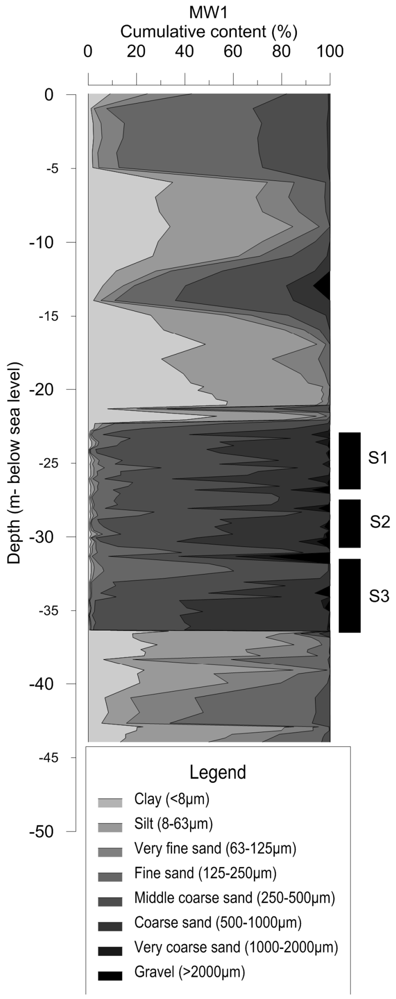

~~**Figure 4: Cumulative grain size contents observed at MW1 (at 5 m from ASR well 1) in this study. S1-S3 mark the depth intervals of the ASR well screens.**~~

3.~~2~~1 Cycle 1 (2012/2013): first identification of borehole leakage

The first ASR-cycle started in December 2012. The first recovery started halfway January 2013. Despite the abstraction with only the shallow wells of the MPPW, a rapid and severe salinization was found within the first days of recovery, after injecting freshwater for about 1 month (Figure 5~~Figure 5~~). It was expected that due to mixing and buoyancy effects during

ASR, MW2 would salinize first, followed by MW1, and finally the ASR wells (AW1 and AW2) towards the end of the recovery phase, with each time the deepest well screens salinizing first. This salinization would then be caused by the replacement of freshwater by ambient groundwater (very low SO_4 concentrations) from the same aquifer (Ward et al., 2009). Remarkably, the salinization at ~~ASR well 1 (~~AW1~~)~~ preceded salinization of the monitoring wells situated further from the ASR wells (MW1, MW2). ~~High~~ Furthermore, SO_4 concentrations (up to >50 mg/l) were found in the recovered water, which could not be explained by the SO_4-concentration attained by pyrite oxidation by oxygen and nitrate present in the injection water (Zuurbier et al., 2016), which would result in SO_4 concentrations of less than 15 mg/l.

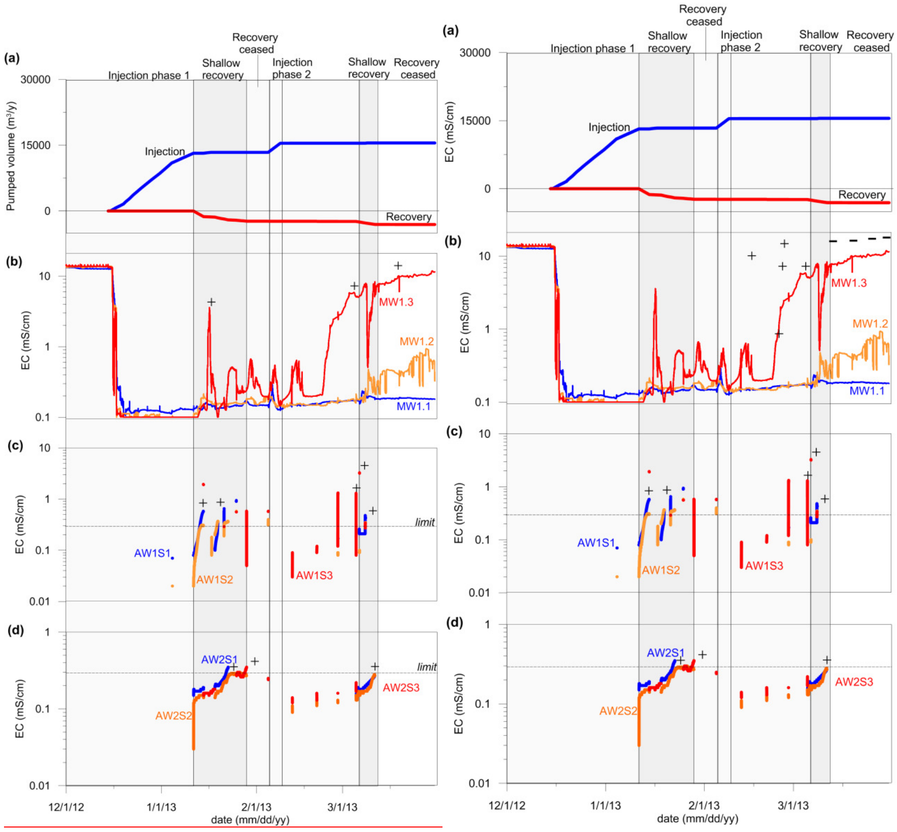

Figure 5: Pumping of the ASR system during cycle 1 (2012/2013), EC observations at MW1 (5 m from AW1), and the EC in the recovered water at AW1 and AW2. MW= monitoring well, AW= ASR well.

The SEAWAT model underlined that tilting of the freshwater-saltwater interfaces at the fringe of the ASR bubble did not cause the early salinization observed, as this would have led to a much later salinization (Figure 6~~Figure 6~~) without enrichment of SO_4 (other than be pyrite oxidation), even if the recovery period was extended (results not shown). When the leaky borehole was incorporated in the model (by assigning K=1000 in a 1 x 1 m column at the location of the current ATES well), it was able to introduce the early recovery of deep (SO_4-rich) water (Figure 7~~Figure 7~~). Other scenarios that were tested, but unable to improve the simulation of the observed SO_4-trends were: leakage from via the former ATES K3-a well further from the ASR wells (arrival of SO_4 too late), a high-K borehole (2000 m/d; arrival too early, flux too high), a low-K borehole (500 m/d; arrival too late, flux too low), a vertical anisotropy in the aquifers (K_h/K_z = 2; arrival too early, flux too high), and omission of the deep cold water abstraction from Aquifer 2 via the ATES well in Aquifer 2 (SO_4-flux too high).

The hydrochemical observations and model outcomes of Cycle 1 indicated that the source of the early salinization was the intrusion of saltwater from Aquifer 2. Considering the lithology, thickness, and continuity of Aquitard 2 (confirmed by grain size analyses and cone penetrating tests on the site), leakage via natural pathways through this separating layer was unlikely. According to the rate and sequence of salinization, the leakage could well be situated at the ATES K3-b well close to AW1.

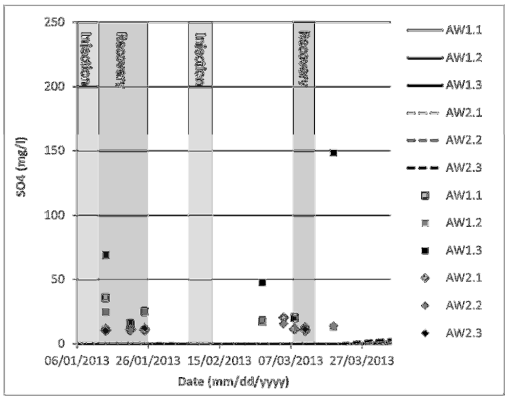

Figure 6: Modelled (solid lines) and observed (data points) SO_4 concentrations without borehole leakage. High concentrations indicate admixing of deeper saltwater. Observed SO_4 concentrations by far exceed the modelled concentrations.

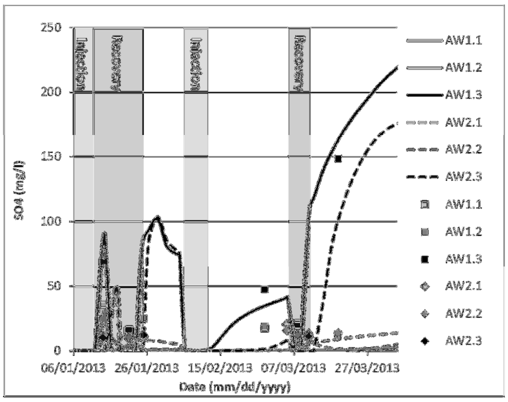

Figure 7: Modelled (solid lines) and observed (data points) SO_4 concentrations. Borehole leakage at the location of the current ATES K3 well via a 1x1 m borehole with K=1000 m/d. High concentrations indicate admixing of deeper saltwater. Observed SO_4 concentrations become in line with the modelled concentrations.

3.~~3~~ 2 Cycle 2 (2013/2014): improving the ASR operation

Cycle 2 started with the injection of 66,178 m^3 of rainwater using both ASR wells between September 2013 and March 2014, which was followed by recovery solely at the downstream AW2 (start: March 5, 2014). A rapid salinization by SO_4-rich saltwater was again observed (Figure 8~~Figure 8~~) and the recovery was terminated after 26 days (March 21, 2014) after recovering no more than 2,500 m^3. During this cycle, a monitoring well present in the gravel pack of the ATES K3-b well (coded K3-bO1; a 1m-well screen at 33 m-BSL, Figure 1) was also sampled and equipped with a CTD-diver and continuously pumped with a rate of 1 m^3/h, unraveling high ECs and presence of SO_4-rich saltwater from the deeper aquifer in the centre of the injected freshwater body (Figure 8~~Figure 8~~). This presence of intruding deep saltwater was also found at MW1S3 (5m from the ASR wells) as a consequence of displacement while re-injecting part of the abstracted freshwater from the shallow AW2S1 wells screen at the deeper AW2S3 well screen and density-driven flow (spreading over de base of the aquifer). The observed Cl concentration (268 mg/l) on April 2, 2014 at MW1S4 (situated in Aquitard 2 at 5 m from AW1) was significantly lower than at MW1S3 (2,528 mg/l) and K3-bO1 (3,341 mg/l), indicating that salinization of the shallow target aquifer (Aquifer 1) preceded salinization of Aquitard 2.

In order to re-enable recovery of freshwater, the deepest wells of the MPPWs (AW1S3 and AW2S3) were transformed to interception wells or 'Freshkeepers' (Stuyfzand and Raat, 2010; Van Ginkel et al., 2014), abstracting the intruding saltwater and injecting this in a deep injection well in Aquifer 2 at 200 m distance from the ASR-site. This way, an acceptable water quality (Cl <50 mg/l) could be recovered at AW2S1 and AW1S2 again (from April 15, onwards). As a consequence, the deeper segments of the target aquifer (S3 levels, Figure 8~~Figure 8~~bcd) first freshened, followed by again salinization as recovery proceeded. Saline water was continuously observed at K3-bO1, indicating that leakage via the K3-b borehole continued. After recovery of in total 12,324 m^3 of practically unmixed rainwater (18.6% of the injected water), the recovery had to be ceased due to the increased salinity. During this last salinization, the water at the deep (S3-)levels of the target aquifer at AW1, MW1, and MW2 showed low SO_4-concentrations, indicating salinization by saltwater from Aquifer 1 instead of deep saltwater from Aquifer 2. High SO_4-concentrations (>100 mg/l) were only found close to the ~~current~~ K3-b ATES well (the presumable conduit) in this phase (AW1 and K3-bO1).

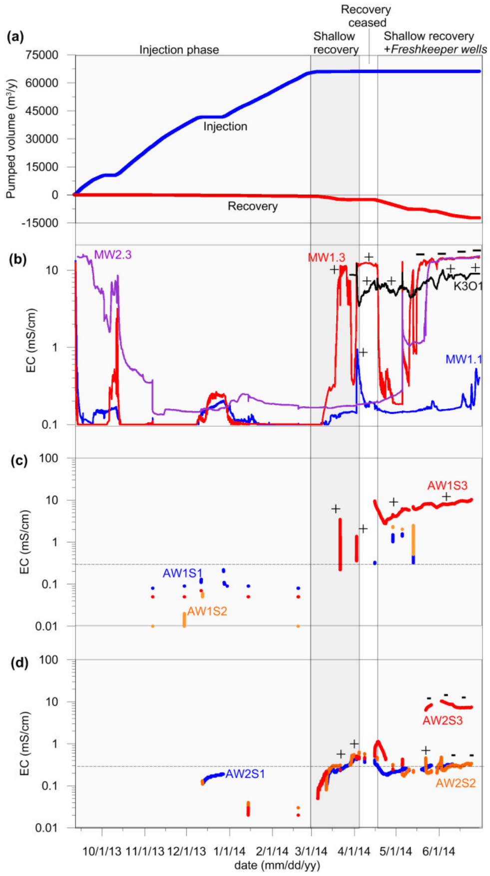

Figure 8: Pumping of the ASR system during cycle 2 (2013/2014), EC observations at MW1 (5 m from AW1), and the EC in the recovered water at AW1 and AW2. AW2.1 and AW2.3 were used for freshwater recovery (12,324 m^3). Presence of increased SO_4-concentrations (deep saltwater) are marked by '+', while its absence is marked by '-' (indicating shallow saltwater).

The SEAWAT model with leakage via the borehole of ~~the current ATES well~~ K3-b was able to reasonably simulate the water quality trends regarding SO_4 and Cl in Cycle 2 (Figure 9~~Figure 9~~ and Figure 10~~Figure 10~~). Remaining deviations in observed concentrations were contributed to uncertainties in the model input, mainly aquifer heterogeneity, potential stratification of the groundwater quality in Aquifer 2, and disturbing abstractions and injections in the surroundings, mainly by nearby ATES and brackish water reverse osmosis systems, the latter abstracting from Aquifer 1 and injecting in Aquifer 2.

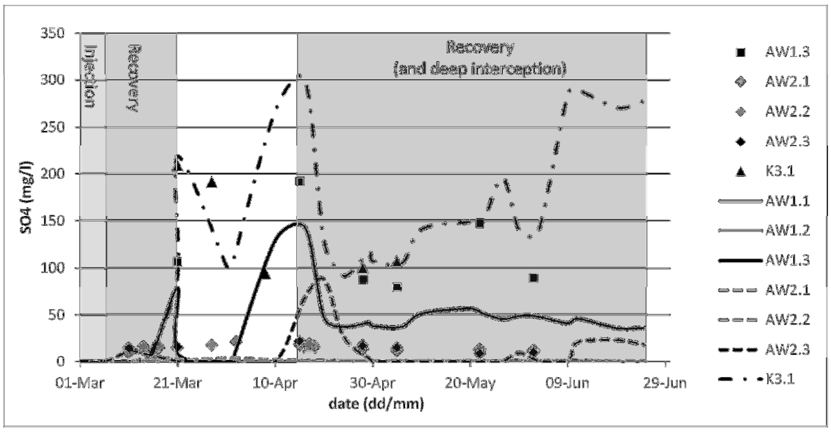

Figure 9: Modelled and observed SO_4-concentrations at the most relevant well screens.

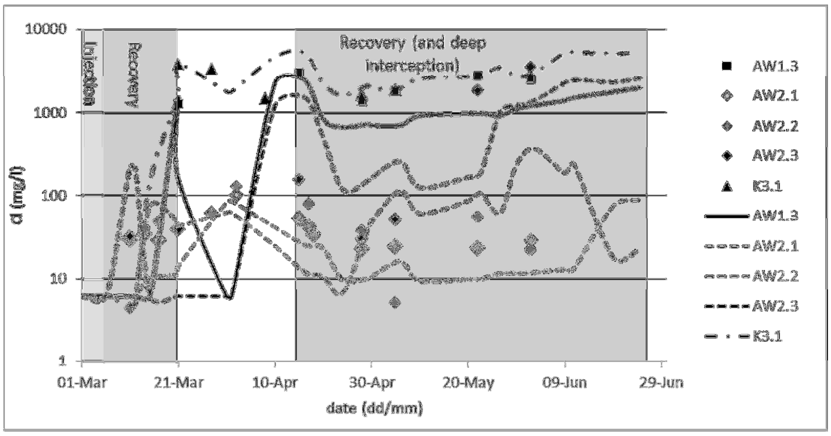

Figure 10: Modelled and observed Cl-concentrations at the most relevant well screens.

Modelling of Cycle 2 demonstrated that salinization during recovery was independent of the injected freshwater volume. Salinization occurred after recovery with the same rate as in Cycle 1, despite a four times larger injection volume. Analysis of the modelled concentration distribution and pressure heads showed that injected freshwater could not reach deep into the deeper saline aquifers since the freshwater head in the leaky ATES borehole during injection was more or less equal to the freshwater head in the deeper saltwater aquifer. In other words: little freshwater was pushed through the conduit into the deeper aquifer. Further on, the freshwater that did reach the deeper aquifer got rapidly displaced laterally as a result of buoyancy effects (Figure 11~~Figure 11~~).

A significant head difference (Δh(fresh)= 0.3 m to 0.65 m) was observed in the model during recovery. In combination with the high permeability of the ATES borehole, this resulted in a significant intrusion of deeper (SO_4-rich) saltwater. Even during storage phases, a freshwater head difference (Δh(fresh)= 0.15 m) was observed as a consequence of replacement of saltwater by freshwater in the target aquifer, causing intrusion of deep saltwater, yet with a lower rate than during recovery.

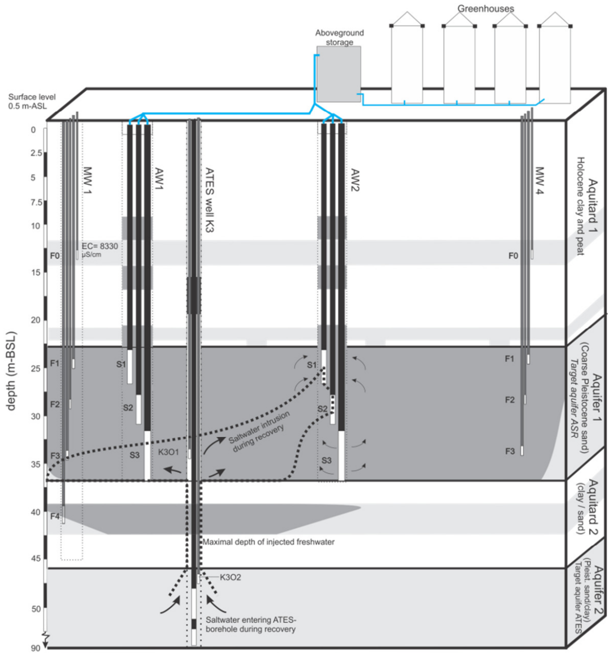

Figure 11: Deep saltwater intrusion via~~ the current~~ ATES K3-b borehole during shallow recovery of injected freshwater at the Westland ASR site at the start of Cycle 2.

3.~~4~~3 Analysis of the leakage flux via the borehole

An analytical solution was presented by Maas (2011) to calculate the vertical leakage via a gravel or sand pack. In this solution, it is presumed that an aquitard was pierced during drilling and the annulus was filled up with sand or gravel without installing a clay seal. The leakage is then calculated as function of the different hydraulic conductivities, pressure difference, and the radius of the borehole and well screen:

$$Q_{VGP} = \frac{\Delta h_{GP}}{W}$$

where: Q_{VGP} = vertical leakage via gravel pack (m^3/d), Δh_{GP} = hydraulic head difference between 2 sections of the gravel pack, one being the inflow and the other the outflow section (m), and W = leakage resistance (d/m^2) and is calculated as:

$$W \approx \frac{(0.005(\ln(\alpha))^2 - 0.058\ln(\alpha) + 0.19)}{(r_1\sqrt{K_{HIN}K_{VIN}})}$$

And a as:

$$\alpha = \frac{K_{VGP}(r_1^2 - r_0^2)}{2K_{VIN}r_1^2} /$$

where: r_0 = radius of well screen [m]; r_1 = radius of borehole [m]; K_{VGP} = vertical hydraulic conductivity of gravel pack [m/d]; K_{VIN} = vertical hydraulic conductivity of inflow aquifer layer [m/d]; K_{HIN} = horizontal hydraulic conductivity of the inflow aquifer layer [m/d].

Calculating the leakage flux using the $\boldsymbol{\Delta h_{GP}}$ from the SEAWAT model underlines that the pressure differences induced by density differences and enhanced during abstraction for freshwater recovery in combination with an unsealed borehole leads to a saltwater intrusion (Q_{VGP}) of around 50 to 200 m^3/d, which is in line with the observed leakage flux in the SEAWAT model.

Table 6~~3~~: Calculated leakage flux Q_{VGP} via the (unsealed) borehole based on Maas (2011) for different net recovery rates ($Q_{recovery, net}$).

		Storage (no recovery)	**Low recovery rate**	**High recovery rate**
$Q_{recovery,\ net}$	*(m^3/d)*	0	77	371
Δh_{GP}	*(m)*	0.15	0.30	0.66
Q_{VGP}	*(m^3/d)*	49	99	215
W	*(m^2/d)*	0.0031	0.0031	0.0031
α		4.7	4.7	4.7
r_0	*(m)*	0.1	0.1	0.1
r_1	*(m)*	0.4	0.4	0.4
K_{HIN}	*(m/d)*	100	100	100
K_{VIN}	*(m/d)*	100	100	100
K_{VGP}	*(m/d)*	1000	1000	1000

3.~~6~~4 The maximal recovery efficiency with and without leakage at the Westland ASR site.

The SEAWAT model was used to evaluate the ASR performance at the Westland field site with three different ASR strategies (Table 7~~Table 4~~), with and without the saltwater leakage. During the 120 days of recovery it was aimed to recover as much of freshwater (marked by Cl <50 mg/l) as possible. Equal abstraction rates were maintained for both ASR wells (AW1 and AW2) in the scenario's without leakage, while only AW2 was used for recovery in the scenario's with leakage.

Recovery with conventional, fully penetrating ASR wells will be limited to around 30% of the injected freshwater in a case without the saltwater leakage. For the case with leakage, freshwater recovery will be impeded by the short-circuiting during the storage phase: the wells will produce brackish water already at the start of the recovery phase. The use of a MPPW for deep injection and shallow recovery has a limited positive effect due to the limited thickness of the aquifer: one-third of the injected water can be recovered in a case without leakage. The improvement of RE by introduction of the MPPW is limited in comparison with the conventional ASR well since some saltwater from Aquitard 2 was found to move up to the shallower recovery wells of the MPPW-system ('upconing') rapidly after the start of recovery. The slight increase in Cl concentrations caused by this process is sufficient to terminate the recovery due to exceedence of the salinity limit. Before the fringe of the freshwater bubble reached the recovery wells, recovery was already terminated. In the case of saltwater leakage, salinization occurred within 2 days, limiting the RE to only 1%.

Table 74: Modelled recovery efficiencies at the Westland ASR site without short-circuiting using different pumping strategies. The relative pumping rate per MPPW well screen is given for each particular screen.

Strategy	**Distribution pumping rate**	**RE (short-circuiting / no short-circuiting)**	**Intercepted brackish-saline water** (via deep (S3-)wells)
Conventional ASR-well	In: 100% via one fully penetrating well Out: 100% via one fully penetrating well	Year 1: 0/15% Year 2: 0/25% Year 3: 0/30% Year 4: 0/32%	
Deep injection, shallow recovery (MPPW-ASR)	In: 10/20/70% (Year 1) In : 0/20/80% (Year 2-3) Abstract: 60/40/0% (Year 1-3)	Year 1: 1/19% Year 2: 1/ 29% Year 3: 1/32% Year 4: 1/33%	
MPPW-ASR + 'Freshkeeper'	In: 10/20/70% (Year 1) In : 0/20/80% (Year 2) Abstract: Decreasing from 60/40/0% to 60/0/0% (Year 1-3) Intercept Freshkeeper: increasing from 100 to 500 m^3/d	Year 1: 29/40% Year 2: 32/46% Year 3: 33/47% Year 4: 33/48%	Year 1: 32,700/ 18,500 m^3 Year 2: 33,000 / 20,500 m^3 Year 3: 31,900 / 21,500 m^3 Year 4: 31,500 / 19,300 m^3

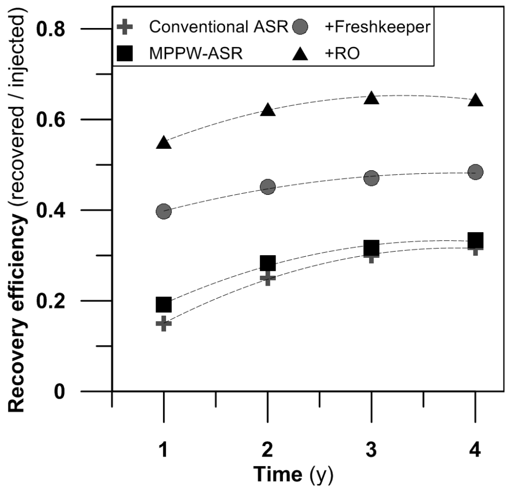

Figure 12: Recovery efficiencies at the Westland ASR site with and without the borehole leakage resulting from the SEAWAT groundwater transport model for a conventional ASR well (one well screen, fully penetrating), deep injection and shallow recovery via multiple partially penetrating wells without a 'Freshkeeper' (scenario MPPW), for a MPPW in combination with a 'Freshkeeper' (scenario Freshkeeper), and for a scenario in which RO is applied on the intercepted brackish water to produce additional freshwater (50% of the abstracted brackish water).

The introduction of the Freshkeeper to protect the shallow recovery wells by interception of this deeper saltwater significantly extended the recovery period, enabling recovery of 40% in the first year for direct use. Ultimately, this will yield a RE of almost 50% of virtually unmixed (Cl <50 mg/l) injected freshwater in Cycle 4 in a case without leakage. This will require interception of 18,500 m^3 (Cycle 4) to 21,500 m^3 of brackish-saline groundwater, such that almost 30,000 m^3 of freshwater can be recovered.

When this ASR operational scheme with the Freshkeeper was applied to the field pilot, where short-circuiting saltwater hampered freshwater recovery, approximately one-third of the injected freshwater could be recovered. The ASR-well close to the leaking borehole (AW1) was unable to abstract freshwater in this case. Only AW2 could be used for freshwater recovery, in the end only via the shallowest well (AW2S1). The freshwater loss by short-circuiting cannot be eliminated completely since a large volume of unmixed freshwater is abstracted together with intruding saltwater during the required. The RE will therefore remain lower than in an undisturbed geological setting (RE: 48%). At the same time, the required interception of brackish-saline water will be higher (Table 7~~Table 4~~), with a total volume of more than 30,000 m^3, while around 20,000 m^3 of freshwater is recovered.

4 Discussion

4.1 Saltwater intrusion during the Westland ASR pilot

In this study, the first focus was on the causes for the significantly lower observed freshwater RE of the system. This RE was initially less than a few percent, whereas recovery of around one-third of the injected water was expected. The hydrochemical analyses clearly indicated that the observed salinization was caused by unexpected intrusion of deeper saltwater, as marked by substantially higher SO_4 concentrations, which could not be caused by arrival of saltwater from the target aquifer or the upper aquitard, or by the SO_4 release upon oxidation of pyrite in the target aquifer. The high SO_4-concentrations also exclude early salinization by larger buoyancy effects than initially expected, for instance by a higher K or higher ambient salinities in the target aquifer. The high SO_4 concentrations also excluded rapid lateral drift of injected water, as this would also have led to salinization by saltwater with low SO_4 concentrations. Additionally, lateral drift would also result in limited REs after addition of the Freshkeeper, which was not the case.

Knowing the source of the salinization, several transport routes can be presumed. First of all, intrusion of deep saltwater may occur when Aquitard 2 has a significantly lower K than derived from grain size analyses, despite the distinct groundwater qualities observed. A more diffuse salinization via Aquitard 2 can then be expected. However, this salinization would be more gradual and better distributed around the wells. It would also mean that Aquitard 2 would quickly freshen during injection and salinize first during recovery. However, the later salinization of Aquitard 2 observed at MW1S4 with respect Aquifer 1 (observed at MW1S3 and K3-bO1) indicated that Aquitard 2 is by-passed by deeper saltwater during recovery. The presence of (a) conduit(s) therefore provide (a) probable pathway(s) for by-passing saltwater, meaning short-circuiting was occurring between Aquifer 1 and 2. The SEAWAT model underlines that this can indeed explain the early and rapid intrusion by deep saltwater. Since the highest Cl and SO_4 concentrations were found in the borehole of ~~the current ATES~~ K3-b well (K3-bO1), this borehole provides the most presumable location of (a) conduit(s). Natural conduits are considered unlikely due to continuity and thickness of Aquitard 2 observed in the surrounding of the ASR wells and the geological genesis (unconsolidated, horizontal lagoonal deposits). The conduit(s) at or around the ~~ATES~~ K3-b borehole may originate from the time of installation (improper sealing) or operation, as recorded operation data of the ATES system reports that incidentally exceeded the maximum injection pressure in the well of 1 bar during maintenance in 2009.

4.2 The consequences of short-circuiting on ASR in coastal aquifers

The potential effects of short-circuiting induced by deep perturbation on aquifer storage and recovery (ASR) in a shallower coastal aquifer were subsequently explored. In this case of freshwater storage in a confined, saline aquifer, pressure differences induced by the difference in density between injected freshwater and native groundwater provoked intrusion of native groundwater in the injected freshwater bubbles via the presumed conduit. It is illustrated that a complete failure of the ASR system can occur when the short-circuiting via such a conduit occurs close to the ASR wells and little mixing with ambient saltwater is allowed.

The negative effects of short-circuiting on ASR on coastal aquifers are mainly related to the hydraulics around the conduits. First, freshwater is not easily transported downwards through the conduits into a deeper aquifer, while it is easily pushed back into the shallower aquifer when ~~infiltration~~injection is stopped or paused. Secondly, the freshwater reaching a deeper aquifer is subjected to buoyancy effects and migrates laterally in the top zone of this deeper aquifer. Finally, during storage and especially during recovery, the pressure differences in combination with a high hydraulic conductivity rapidly induce a strong flux of saltwater from the whole deeper aquifer into the shallower ASR target aquifer, where a relatively low hydraulic head is present. This short-circuiting induced by such a pressure difference is hampered by the low permeability of the aquitard in a 'pristine situation'. A continuous, undisturbed aquitard is therefore indispensable for the success of ASR in such a setting, as intrusion of deeper saltwater is not desired.

With an increasing distance between the ASR wells and a nearby conduit, the proportion of mixed saltwater in the recovered water decreases while the arrival time increases. When the conduit is situated outside the radius of the injected freshwater body in the target aquifer, a decrease in RE is not expected.

The Westland field example highlights how design, installation, and operational aspects are vital in the more-and-and more exploited subsurface in densely-populated areas. First of all, old boreholes are unreliable and their presence should better be avoided when selecting new ASR well sites (Maliva et al., 2016). Secondly, installation and operation of (especially injection) wells should be regulated by strict protocols to prevent the creation of new pathways for short-circuiting. Finally, it is important to recognize that similar processes may occur in unperturbed coastal karst aquifers, where natural vertical pipes can be present (Bibby, 1981; Missimer et al., 2002).

4.3 Mitigation of short-circuiting on ASR in coastal aquifers

In order to mitigate the short-circuiting and improve the freshwater recovery upon aquifer storage under these unfavourable conditions, several strategies can be recognized. Obviously, sealing of the conduits would be an effective remedy. However, it may not be viable to 1) locate all conduits, for instance when the former wells are decommissioned or when the confining clay layer is fractured upon deeper injection under high pressure, and 2) successfully seal a conduit at a great depth. This underlined by the fact that limited reports of successful sealing of deep conduits can be found.

Apart from sealing, one can also try to deal with these unfavourable conditions. Multiple partially penetrating wells (MPPW) were installed at the Westland ASR site, for instance, enabled interception of intruding saltwater by using the deeper well screens as 'Freshkeepers'. After this intervention, about one-third of virtually unmixed injected freshwater becomes recoverable. This way, the RE is brought to a level similar to the level obtained by an MPPW-equipped ASR system without the Freshkeeper interception and without short-circuiting, while the RE would otherwise remain virtually null. It does require interception of a significant volume of brackish-saline groundwater, however, which must be injected elsewhere or disposed of. The addition of a Freshkeeper will therefore inevitably increase the investment costs (additional infrastructure for re-injection / disposal) and operational costs (electricity required for pumping).

A significant part of the unmixed freshwater is blended with saltwater in the Freshkeeper wells, such that the freshwater recovery becomes lower than in the situation in which the Freshkeeper is applied and saltwater intrusion via short-circuiting is absent. At the Westland field site, this is compensated by desalinating the intercepted brackish-saline groundwater, which is a suitable source water for reverse osmosis (RO) thanks to its low salinity. The freshwater (permeate) produced in this process is used for irrigation, while the resulting saltwater (concentrate) is disposed of in Aquifer 2. The resulting RE increase is plotted in Figure 12~~Figure 12~~. Even when no unmixed freshwater is available, desalination of injected water mixed with groundwater can be continued with this technique to further increase the RE. In comparison with conventional brackish water RO this leads to a better feed water for RO (lower salinity), while salinization of the groundwater system by a net extraction of freshwater is prevented by balancing the freshwater injection and abstraction from the system.

4.4 On the performance of ASR in coastal aquifers without leakage: upconing brackish water from the deeper aquitard

In case of a strict water quality limit and relatively saline groundwater, brackish groundwater upconing from the deeper confining aquitard toward shallow recovery wells is a process to take into account, apart from the buoyancy effects in the target aquifer itself. This was shown by the SEAWAT model runs without short-circuiting, which showed a small increase in Cl-concentrations at the ASR wells prior to the full salinization caused by arrival of the fringe of the ASR bubble. The SEAWAT model indicated that the (sandy) clay/peat layer (Aquitard 2) below the target aquifer was the source of upconing brackish-saline groundwater. Although this layer has a low hydraulic conductivity, it is not impermeable and salinization via diffusion can occur in this zone, while brackish pore water can physically be extracted from this aquitard. The transport processes in this deeper aquitard are comparable with the borehole leakage water via conduits in this aquitard: freshwater is not easily pushed downwards during injection, but brackish water is easily attracted during recovery. After the recovery phase this zone salinizes until the next injection phase starts, so a gradual improvement in time is limited. Brackish water may also be attracted from the upper aquitard (‘downconing’), but this process is counteracted by the buoyancy effects and did not lead to early termination of the freshwater recovery in the Westland case.

The release of brackish water from the deeper aquitard in coastal aquifers can be relevant when quality limits are strict, the native groundwater is saline, and the native groundwater in the target aquifer is displaced far from the ASR wells. The performance of ASR may than be much worse than is predicted by existing ASR performance estimation methods (e.g. Bakker, 2010; Ward et al., 2009), which assume that impermeable aquitards confine the target aquifer. Even in the first MPPW field test (Zuurbier et al., 2014), this process was not observed, due to a smaller radius of the freshwater bubble, resulting in earlier salinization ~~duo~~ due to buoyancy effects. The upconing water can optionally be intercepted by a (small, deep) Freshkeeper well screen to extent the recovery of unmixed freshwater, likewise the interception of intruding saltwater at the Westland site.

Finally it should be noted that the ASR-system analyzed in this study had very strict water quality limits (practically no mixing allowed) and that a buffer zone (Pyne, 2005) between the injected freshwater and the relatively saline ambient groundwater was not realized before starting the ASR-cycles. The boundary conditions for ASR were therefore already unfavorable. Also, the potential improvement after >3 cycles was not explored. The performance of this ASR-system should therefore not be considered the typical performance of ASR in a brackish-saline aquifers, which controlled by a complex interplay of geological conditions and operational parameters (Bakker, 2010), well design (Zuurbier et al., 2015; Zuurbier et al., 2014), and the formation of a buffer zone prior to starting the ASR-cycles (Pyne, 2005).

5 Conclusions

This study shows how short-circuiting negatively affects the freshwater recovery efficiency (RE) during aquifer storage and recovery (ASR) in coastal aquifers. ASR was applied in a shallow saltwater aquifer (23-37 m-BSL) overlying a deeper saltwater aquifer (> 47.5 m-BSL) targeted for aquifer thermal energy storage. Intrusion of deeper saltwater was marked by chemical tracers (mainly SO_4) and quickly terminated the freshwater recovery. The most presumable pathway was the borehole of an ATES well at 3 m from the ASR well (forming a conduit) and was identified by field measurements, hydrochemical analyses, and SEAWAT transport modelling. Transport modelling underlined that the potentially rapid short-circuiting during storage and recovery can reduce the RE to null. This is caused by a rapid intrusion of the deep saltwater already during storage periods, and especially during recovery. Transport modelling also showed that when limited mixing with ambient groundwater is allowed, a linear RE decrease by short-circuiting with increasing distances from the ASR well within the radius of the injected ASR-bubble is found. Old boreholes should therefore rather be avoided during selection of new ASR sites, or must be situated outside the expected radius.

Field observations and groundwater transport modelling showed that interception of deep short-circuiting water can mitigate the observed RE decrease, although complete compensation of the RE decrease will generally be unattainable since also unmixed freshwater gets intercepted. At the Westland ASR site, the RE can be brought back to around one-third of the injected water, which is comparable to the RE attained with an ASR system without the Freshkeeper in the same, yet undisturbed setting. With the same Freshkeeper, the set-up would be able to abstract around 50% of the injected water unmixed, if the setting would be undisturbed. This underlines the added value of such a interception well for ASR. Finally, it was found that brackish water upconing from the underlying aquitard towards the shallow recovery wells of the MPPW-ASR system can occur. In case of strict water quality limits, this process may cause an early termination of freshwater recovery, yet it was neglected in many ASR performance estimations to date.

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