D2.5 Completed demonstration of the use of extensively treated wastewater for ASR Coastal (TRL7)

ASR-Coastal Dinteloord

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Executive Summary

In Dinteloord (The Netherlands), an advanced sustainable freshwater supply was realized using ASR-Coastal within Subsol. The Dinteloord water system consists of rapid filtration, ultra-filtration (UF) and finally RO-treatment unit for wastewater from a sugar factory, an ASR-Coastal well field, and a 5 km distribution loop connecting all water to with the ASR-Coastal scheme that stores and recovers the water between autumn and spring/summer.

Eventually, more than 200.000 m^3 of wastewater is to be effectively stored and reused each year. The system is an example of hybrid grey and green infrastructure. It is collectively owned by the greenhouse owners and costs are covered by a pay-per-use system. In 2016, the wells field’s operational system and the first ASR well were realized and extensively tested.

Based on the 2016 test cycle, the potential for a successful ASR scheme (recovering virtually all the yearly infiltrated water after several cycles) was underlined. Because of the strict Na limit, also the enrichment of Na should be further analysed in future cycles, although based on the test cycle and groundwater modelling, the loss of freshwater by Na-enrichment will eventually be limited. Release of Fe and Mn to the infiltrated water must be further analysed in the future cycles and may pose a threat for direct use of recovered water. The first tens of m^3 water stored nearby the ASR well is unacceptably impacted by mineral dissolution, potentially enforced by earlier distortion during drilling and strong oxidation reactions by air intrusion. This phenomenon is subject to further study.

The impacts of the ASR scheme based on measurements and modelling are acceptable and were approved by the water authority. The costs for storage of the reused water with ASR are below 0.4 euro/m^3, which is very competitive to the alternative aboveground storage in basins (almost 1.0 euro/m^3).

Introduction

In Dinteloord (The Netherlands), an advanced sustainable freshwater supply was realized using ASR-Coastal within Subsol, together with the Tuinbouwontwikkelingsmaatschappij (TOM) for the modern greenhouse area called ‘Nieuw-Prinsenland’ (260 ha). In this salinizing coastal area without a significant external freshwater supply, the availability of high-quality water (sodium <2.4 mg/l) for greenhouse irrigation during droughts was major challenge. Effluent reuse in combination with ASR-Coastal provided the ultimate solution for the area.

Set-up of the Dinteloord sustainable water supply system

Wastewater from the food industry (sugar factory Suiker Unie) is reused for greenhouse irrigation and food industries upon aquifer storage and recovery (ASR) with the newly developed configuration in a brackish water aquifer (‘ASR-Coastal’). This creates a crucial bridge between availability of the reused water (September – January) and the later demand (March – August). The Dinteloord water system consists of an RO-treatment unit for the wastewater, an ASR-Coastal well field, and a 5 km distribution loop connecting all water to with the ASR-Coastal scheme that stores and recovers the water between autumn and spring/summer. Eventually, more than 200.000 m^3 of wastewater is effectively stored and reused each year. The system is a perfect example of hybrid grey and green infrastructure. It is collectively owned by the greenhouse owners and costs are covered by a pay-per-use system.

Key to the success of the Dinteloord system is the recently subsurface water solution ASR-Coastal. Eight innovative, dedicated ASR-Coastal wells with different levels for water infiltration and recovery were implemented to cope with unfavourable buoyancy effects (i.e. upward movement of ‘light’ stored freshwater in the native brackish groundwater). Thereby, the fully automated scheme enables unmixed recovery of >90% of the reused water. Total costs per m^3 of water supplied are less than 50% of the costs for the alternative aboveground (reservoir) storage. Other advantages of the ASR-Coastal system include an extremely low spatial footprint, preservation of water quality (e.g. no algal blooms), protection from potential sabotage, and the possibility of stepwise upscaling.

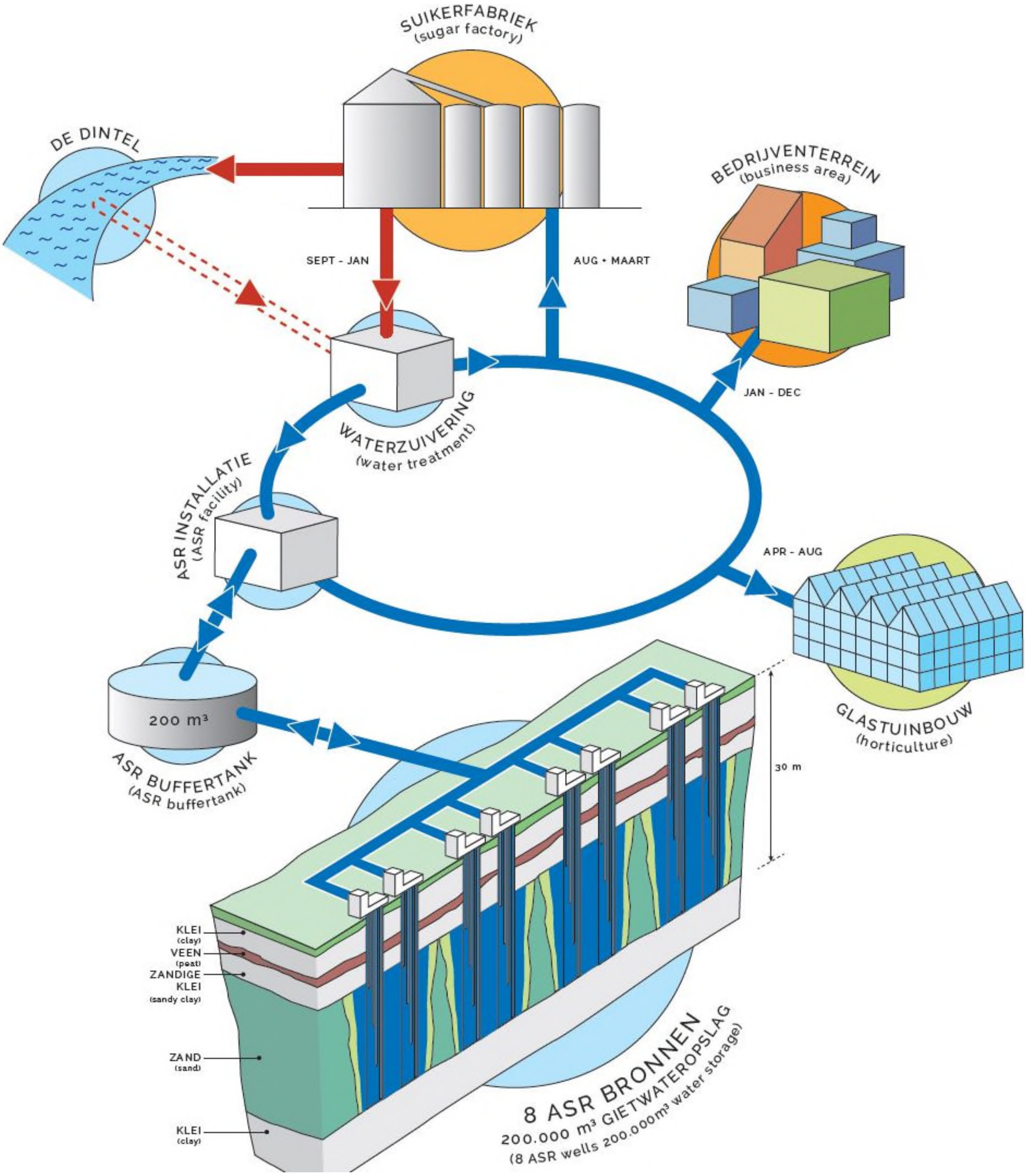


Figure 1: **The Dinteloord sustainable water supply system**

Realization

The realization of the Dinteloord water supply system took place in a close cooperation between end users (the horticultural cooperation 'Nieuw-Prinsenland', represented by TOM), researchers (KWR), an SME (Codema), and local authorities (Province, Water Authority, Municipality). The research and supervision of the implementation and operation was supported by the Dutch TKI-funding from the Topconsortia for Knowledge & Innovation (TKI's) of the Ministry of Economic Affairs and the EU Horizon 2020 project 'Subsol' (Grant Agreement no. 642228). All investments in the infrastructure and the well-field were done by the horticultural cooperation.

Aims (this report)

The aim is to demonstrate the use of ASR-Coastal for storage of reused effluent in Dinteloord at TRL7. This level was achieved in 2016 by realisation of the ASR facility, a first ASR-well, and a pilot (storing 8.500 m^3 for 6 months). Together, this provided a proof-of-concept.

The Dinteloord ASR scheme

The ASR-facility

The Dinteloord ASR facility was realized in an existing building bought by TOM. A connection was made to the distribution loop in order to receive and supply treated effluent from / to the water system (Figure 2). An aboveground buffer (200 m^3; Figure 3) was realized in order:

- receive the treated effluent from the distribution loop smoothly and deal with potential variation in the supply;
- to store the recovered water from the ASR well(s) before distribution to the loop with a booster pump. This means the submersible pumps do not need to deliver directly to the distribution loop and are independent of variations in water use from the distribution loop. The booster pump (Figure 4) ensures a constant pressure on the distribution loop.

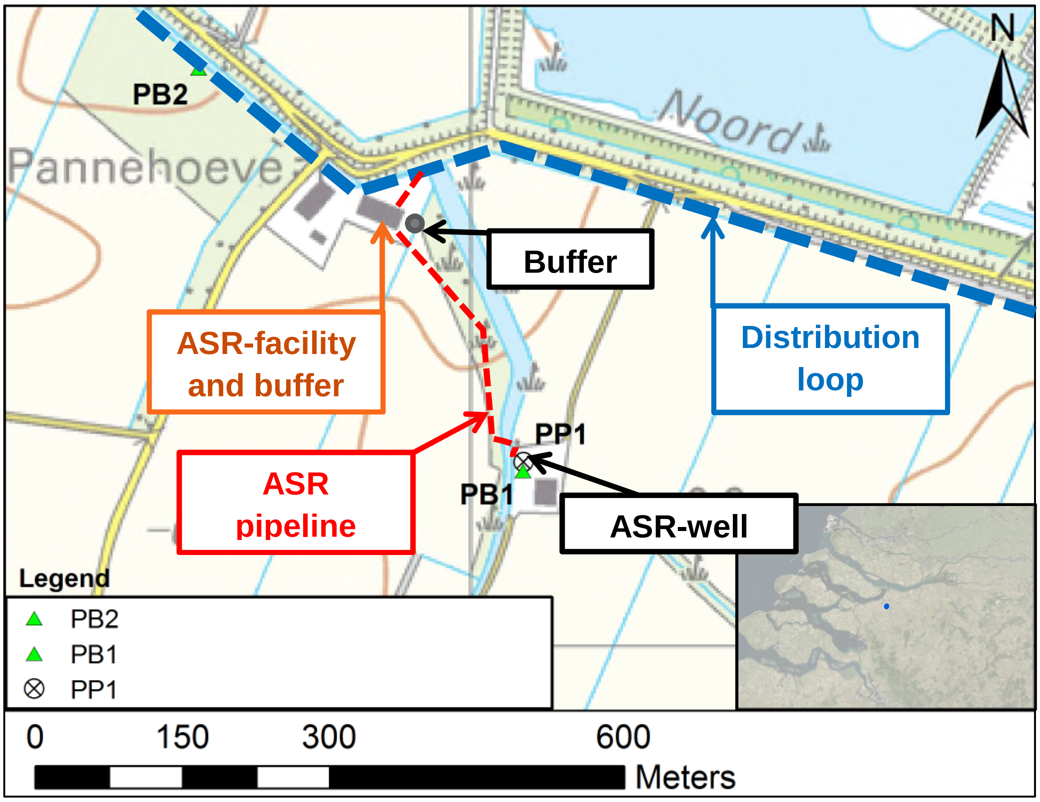


Figure 2: Locations of monitoring wells (PB1, PB2), the ASR-well (PP1), and infrastructure.

A 5 m high standpipe (Figure 3) was used to provide the infiltration pressure on the ASR pipeline. This way, a maximum infiltration pressure is ensured in order to prevent bursting of the covering clay layer at the ASR well, while release of any water bubbles in the infiltration water is also provided. The whole process of effluent receipt, infiltration, recovery and supply was automated and electronically logged via a central control unit with a programmable logical controller, which could be operated using a touch screen and via a internet connection. This control unit was based on the control unit at the Westland reference site.

Figure 3: Standpipe to provide infiltration pressure (left) and buffer (right)

Figure 4: Topview of the Dinteloord ASR-facility and close-up of the boosterpump for supply to the distribution loop.

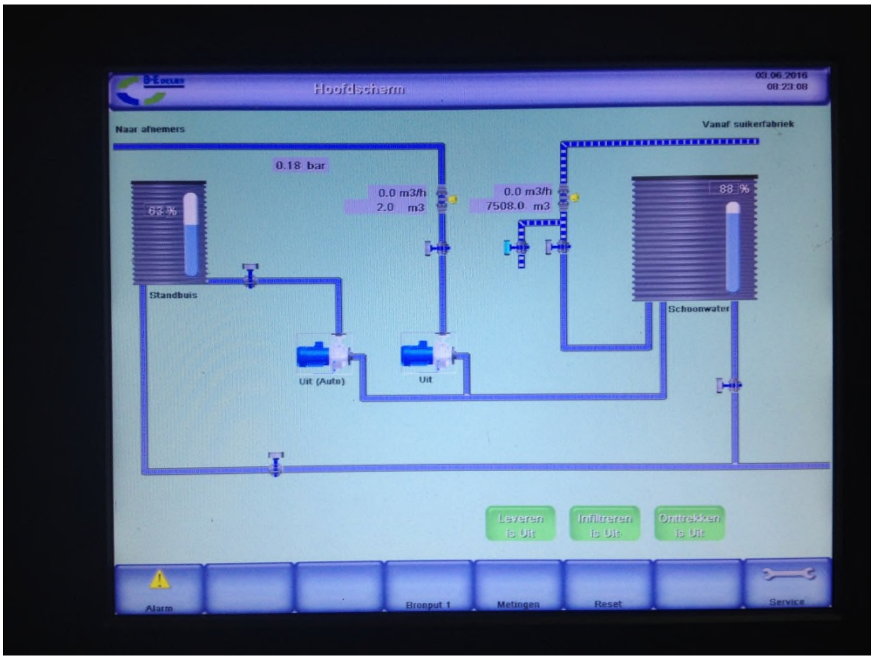


Figure 5: Digital interface of the central control unit.

The first ASR well (PP1) and the surrounding monitoring network

The first ASR well was drilled in September 2015 using reverse rotary drilling. The diameter of the borehole was 500 mm and the ASR-Coastal strategy of deep infiltration and shallow recovery was provided by placing four separate well screens in the target aquifer.

Observation wells were installed in PP1 itself (4), at 10 m from the ASR well (PB1: 5) and at 525 m from PP1 in a former pilot borehole (7). PB1.1, PB1.5, and PB2.2 were equipped with an electrical conductivity, temperature, and pressure transducer (CTD diver bij Van Essen, The Netherlands), recording every 1 hour. Observation wells PB1.2 to PB1.5 and the ASR well was sampled throughout the infiltration, storage, and recovery stages in 2016 and analyzed on physical parameters (EC, pH, temperature, DO) and macrochemistry of the dissolved solutes. The sampling dates are listed in Table 1.

Table 1: Water sampling during ASR cycle 1 (2016). 'IN' = injection water.

Date	Sampled locations
23-10-2015	PP1.1-1.4; PB1.2-1.5
12-2-2016	IN; PB1.2-1.5
21-3-2016	IN; PB1.2-1.5
28-4-2016	PP1.1-1.3; PB1.2-1.3
9-6-2016	PP1.1-1.4; PB1.2-1.5
9-8-2016	PP1.1-1.4; PB1.2-1.5
18-8-2016	PP1.1-1.4; PB1.2-1.5
25-8-2016	PP1.1-1.4; PB1.2-1.5

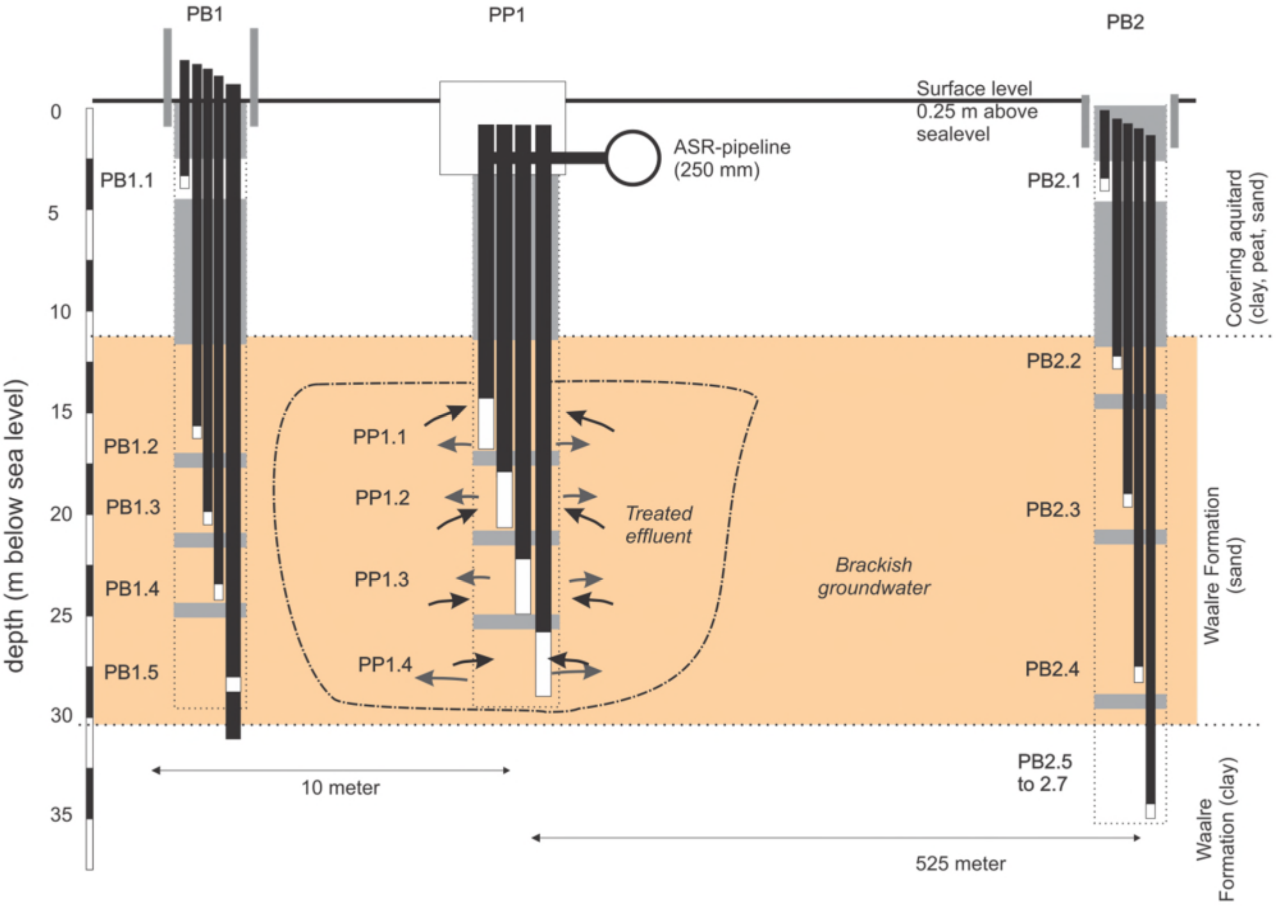


Figure 6: Depths of ASR wells screens and the nearby observation wells.

Figure 7: The first ASR-well (PP1) in the well field in Dinteloord (left) and its well completion including control valves in the well house (right)

Characterization of the target aquifer

Approach

A detailed characterization of the target aquifer was obtained by:

- Sieving the sand samples from PB1;
- A borehole logging using the Robertson DIL-38 probe (March 23, 2016);
- Taking samples of 1 kg from the targeted intervals of the aquifer for geochemical analyses;
- A pumping test in April 2016: in this test, wells F1 to F4 were switched on one-after-the other and eventually shut down simultaneously while monitoring the heads in all observation wells with pressure transducers. The results were reproduced by automatic optimization of a MODFLOW-2000 groundwater model. In this 3-D, half-domain model (5 x 10 km), a cell size of 1x1x1 m was assigned to cells in the vicinity (100 x 100 m) of the ASR well. Further away, a cell size of 5 x 5 m to 250 x 250 m (thickness: 1 m) was assigned. MODFLOW's well package was used the simulate the ASR wells. Constant heads were assigned at the side and top boundaries of the model and were based on the observed heads before introduction of the ASR scheme (side boundaries) and the drainage levels maintained by the water authorities (top level). A detailed hydrogeological parameterisation can be found in Table 4.

Results

The top 10 m consists of fine sand, clay, and peat and provide a cover for the confined aquifer (Table 2). The aquifer itself is around 18 m thick and consists of fine to medium fine sand, with a thin clay layer in the middle, as also indicated by borehole logging (Figure 8). The EC of the formation at the depth of the ASR well screens is 0 ms/m, since the treated effluent (very low EC: <50 µS/cm) was already injected at the time of the logging.

Table 2: Lithology based on PB1. mASL = meters above sea level

From mASL	To mASL	Formation	Lithology	Mean grain size
0,0	-10,0	Naaldwijk	Clay, fine sand, peat	-
-10,0	-20,0	Waalre (sand)	Fine sand, clay layer at the base	150
-20,0	-28,0	Waalre (sand)	Medium fine sand	215
-28,0	-32,0	Waalre (clay)	Sandy clay	-

The geochemical results indicate that the target aquifer will be most reactive at interval F2, followed by F1. Here, highest contents of SOM, calcite, siderite, and various metals were observed. However, the highest pyrite content (with potentially Zn, Ni, Co, As) was observed at F4. The high contents of Mg suggest that the carbonates may be present as dolomite ($(Ca, Mg)CO_3$).

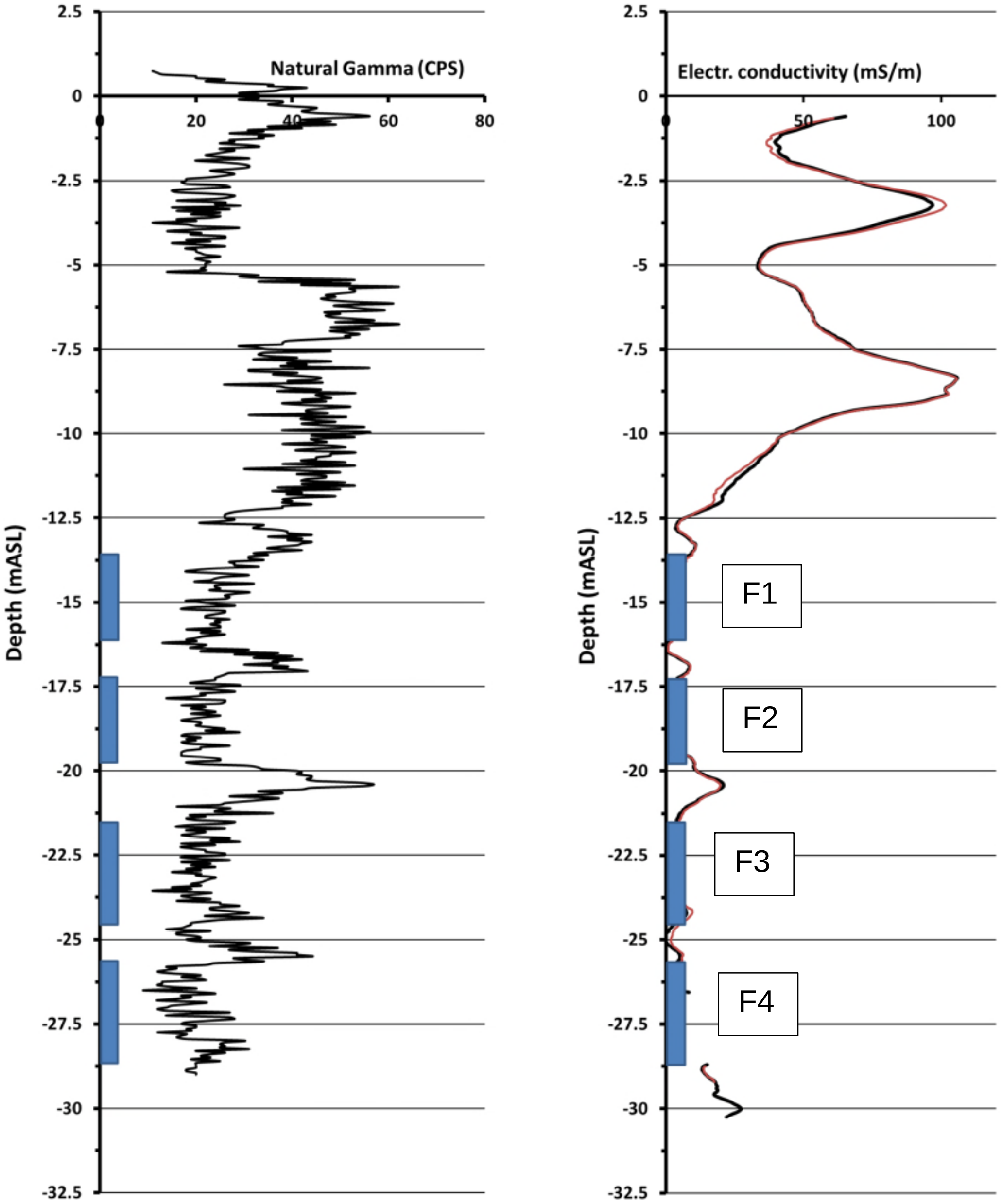


Figure 8: Natural gamma log and electrical conductivity at PB1 (March 2016).

Table 3: Geochemical results based on mixed samples from PB1 at the depth of the ASR well screens

	Interval:	***F1***	***F2***	***F3***	***F4***
Parameter					
Dry residue 105˚C (g/g)	%	81.0	81.8	80.8	85.0
Loss on ignition 550˚C (g/g)	%	79.1	80.1	80.2	84.7
Residue 1000˚C (g/g)	%	78.1	78.8	79.6	84.3
Potassium upon HNO3 destruction	mg/kg dw	935	1100	500	250
Magnesium upon HNO3 destruction	mg/kg dw	2460	4190	2050	430
Manganese upon HNO3 destruction	mg/kg dw	165	380	77	15
Nickel upon HNO3 destruction	mg/kg dw	13	9.3	6.6	4.4
Aluminium upon HNO3 destruction	mg/kg dw	6820	7285	2980	1470
Arsenic upon HNO3 destruction	mg/kg dw	2.8	3.8	2.1	18
Calcium upon HNO3 destruction	mg/kg dw	3170	6575	2330	465
Cobalt upon HNO3 destruction	mg/kg dw	4.8	3.7	2.2	4.2
Chromium upon HNO3 destruction	mg/kg dw	12	14	7.9	3.2
Iron upon HNO3 destruction	mg/kg dw	15855	28755	6515	4045
Silica upon HNO3 destruction*	mg/kg dw	2195	2625	1780	1615
Sodium upon HNO3 destruction	mg/kg dw	100	120	88	53
Barium upon HNO3 destruction	mg/kg dw	15	16	7.9	4.5
Zinc upon HNO3 destruction	mg/kg dw	17	14	9.6	4.7
Titan upon HNO3 destruction	mg/kg dw	32	45	43	22
C	%	0.31	1.09	0.18	0.07
S	%	0.05	0.06	0.02	0.16
SOM (calculated using C)	%	0.62	2.18	0.36	0.14
$CaCO_3$ (calculated using Ca)	%	0.79	1.64	0.58	0.12
Pyrite (calculated using S)	%	0.09	0.10	0.04	0.30
$FeCO_3$ (calculated using Fe)	%	3.29	5.97	1.35	0.84
Mg/Ca		1.28	1.05	1.45	1.52
K/Al		0.09	0.10	0.12	0.12

** Not reliable upon HNO_3 destruction*

Parameterisation based on pumping test

Based on the pumping test, different hydraulic conductivities (K_{hor}) were assigned to several intervals of the target aquifer. The intervals were determined based on the grain size analysis and borehole logging. A best-fit (Figure 9) was attained with the results reported in Table 1. The results indicate that the highest conductivity is found in the lower half of the aquifer, whereas the conductivity in the upper half is limited to around 6 m/d.

Table 4: Hydrogeological parameters based on pumping test.

Geological unit	Depth (mASL)	Model layers (thickness)	Eff. porosity (-)	K_{hor} (m/d)	K_{hor} / K_{vert} (-)	Storativity (S) (-)
Top layer	1 - 0	1 (1 m)	0,3	5	3	0.1
Phreatic layer	0 - -4	4 (1 m)	0,3	5	3	1.0E-04
Clay cap	-4 - -11	7 (1 m)	0,2	0,1	10	1.0E-04
Aquifer 1a	-11 - -19	8 (1 m)	0,35	6	1	5.0E-05
Aquitard 1a	-19 - -20	1 (1 m)	0,2	0,4	10	1.0E-04
Aquifer 1b	-20 - -24	4 (1 m)	0,35	6	3	1.0E-04
Aquitard 1b	-24 - -25	1 (1 m)	0,2	3	10	1.0E-04
Aquifer 1c	-25 - -29	4 (1 m)	0,35	18	3	1.0E-04
Aquitard 1c	-29 - -36	7 (1 m)	0,2	0,14	10	1.0E-04
Aquifer 2	-36 - -39	3 (1 m)	0,35	10	3	1.0E-05
Aquitard 2	-39 - -49	10 (1 m)	0,2	0,02	10	1.0E-05
Aquifer 3	-49 - -69	20 (1 m)	0,35	15	3	1.0E-06

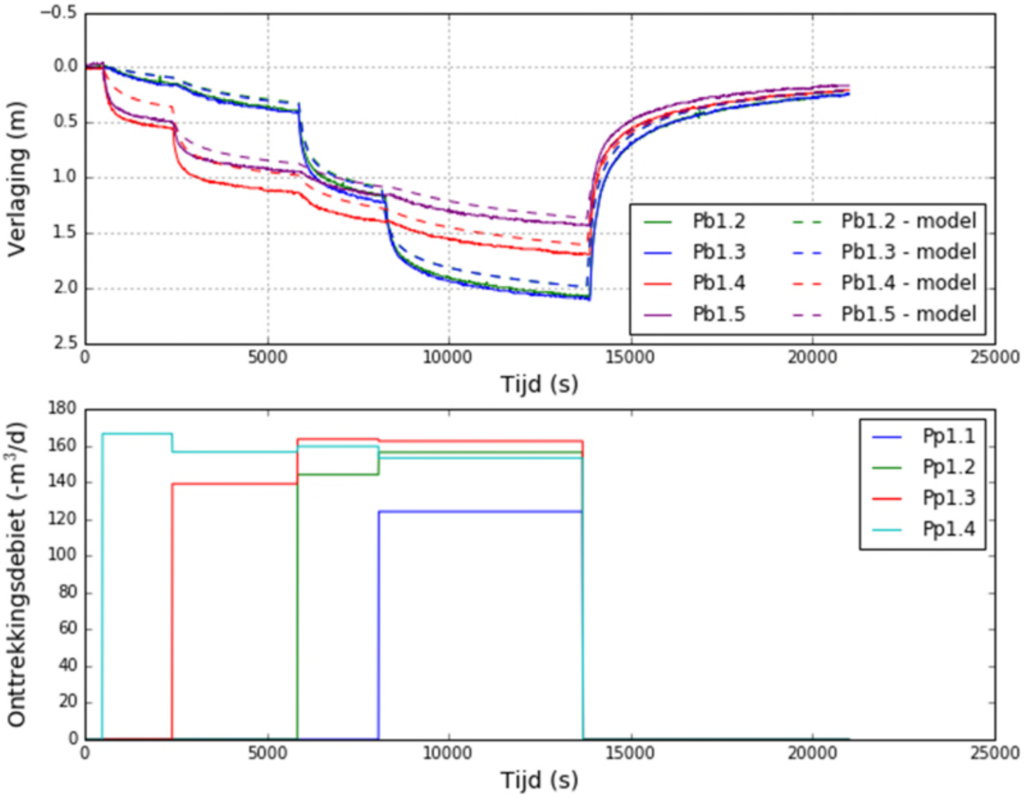


Figure 9: Drawdown (’verlaging’) and discharge (’onttrekkingsdebiet’) versus time (’tijd’): observed versus modelled results.

Characterization of the native groundwater at the ASR site

The native groundwater (Table 5) is relatively fresh (Cl: 15 – 54 mg/l) compared to the groundwater observed at PB2 in 2014 (approximately 700 mgl/ Cl). Relatively high Na concentrations (22 – 41 mg/l) with respect to Cl indicate freshening of the aquifer. The water has high concentration of Fe and Mn, which might also be a consequence of the drilling performed for the borehole. The water is presumable anoxic based on the absence of NO_3.

Table 5: Native groundwater quality observed at PB1

Sample code	**PB1.2**	**PB1.3**	**PB1.4**	**PB1.5**
Depth (mASL)	-16.00	-19.50	-24.00	-28.50
Date	23/10/2015	23/10/2015	23/10/2015	23/10/2015
EC-25 Lab (uS/cm)	691	691	671	730
Temp (˚C)	12.4	11.7	11.7	11.8
pH (Field)	7.9	7.8	7.8	7.7
Turbidity (NTU)	3.0	1.2	11.4	8.5
DO (mg/L)	1.1	0.5	0.8	1.3
Na (mg/L)	40	41	29	35
K (mg/L)	3.4	3.4	3.5	2.4
Ca (mg/L)	92	91	100	110
Mg (mg/L)	10.0	10.0	11.0	8.6
Fe (mg/L)	0.4	0.4	0.7	1.1
Mn (mg/L)	2.7	2.4	2.2	0.2
NH_4 (mg NH_4/L)	1.7	1.9	1.7	0.5
Cl (mg/L)	32	28	29	54
SO4 (mg/L)	<30	<30	<30	<30
HCO3 (mg/L)	380	390	370	350
NO3 (mg N/L)	<3	<3	<3	<3
PO4-t (mg P/L)	<1	<1	<1	<1
As (ug/L)	6.9	6.6	5.6	<5
IBAL %	2.2	1.8	3.9	3.9
□EC-meas %	-22	-10	13	6
BEX (meq/L) excl. dolomite	1.7	1.9	1.4	0.7
BEX (meq/L) incl dolomite	1.0	1.2	0.6	0.3
Watertype	F3CaHCO3+	g3CaHCO3+	g3CaHCO3+	F3CaHCO3
Ca/Mg	9.2	9.1	9.1	12.8
HCO3/S A meq/L	1.0	0.9	0.9	0.8
Fe/Mn	0.1	0.2	0.3	7.3
TDS (mg/L)	562	568	547	562
Density	1000.2	1000.2	1000.2	1000.2

ASR Cycle 1 (2016)

Infiltration water quality

The treated effluent used for infiltration is extremely fresh (Table 6), anoxic, and sub saturated for calcite. Based on the ionic balance, there is a lack of anions measured. The water is quality before infiltration complies with the limits for high-class irrigation water, as set by TOM.

Table 6: Observed injection water quality in 2016

Sample code	**IN_12-2-16**	**IN_21-3-16**	**IN_4-10-16**	**Quality limit TOM**
Date	12/02/2016	21/03/2016	4/10/2016	21/03/2016
EC-25 Lab (uS/cm)	13	14	19	300
Temp (˚C)	11.4	10.2	14.5	-
pH (Field)	6.8	7.2	5.7	6.5
Turbidity (NTU)	4.1	0.8		-
DO-calc (mg/L)	0.8	0.7	0.8	-
Na (mg/L)	1.5	1.2	2.0	2.3
K (mg/L)	0.5	0.6	1.2	46.9
Ca (mg/L)	<0,5	<0,5	<1.2	32.1
Mg (mg/L)	<0,5	<0,5	<0.15	4.9
Fe (mg/L)	<0,01	<0,01	<0.09	0.25
Mn (mg/L)	<0,002	0.0	<0.01	0.25
NH_4 (mg NH_4/L)	0.2	0.1	<0.05	0.4
Cl (mg/L)	7.3	<1	1	17.7
SO_4 (mg/L)	5.3	<1	<0.6	28.8
HCO_3 (mg/L)	25	16	7.6	91.5
NO_3 (mg N/L)	<3	<3	<0.1	217
PO_4-t (mg P/L)	<1	<1	<0.06	27
As (ug/L)	<5	<5	0.08	-
Zn (ug/L)			375	196
DOC	<5		0.1	-
IBAL %	-78.2	-56.7	-13.8	
TDS (mg/L)	40	18		
Density	999.8	999.8	999.8	

ASR operation

From January 28 to March 4, a total volume of 8,300 m^3 was infiltrated using all well screens (F1 – F4). The infiltration rate remained extremely stable at a constant infiltration pressure, indicating that clogging was not occurring. Most water was infiltrated via PP1.3. From August 15 – 20, about 1,000 m^3 was recovered for the pilot.

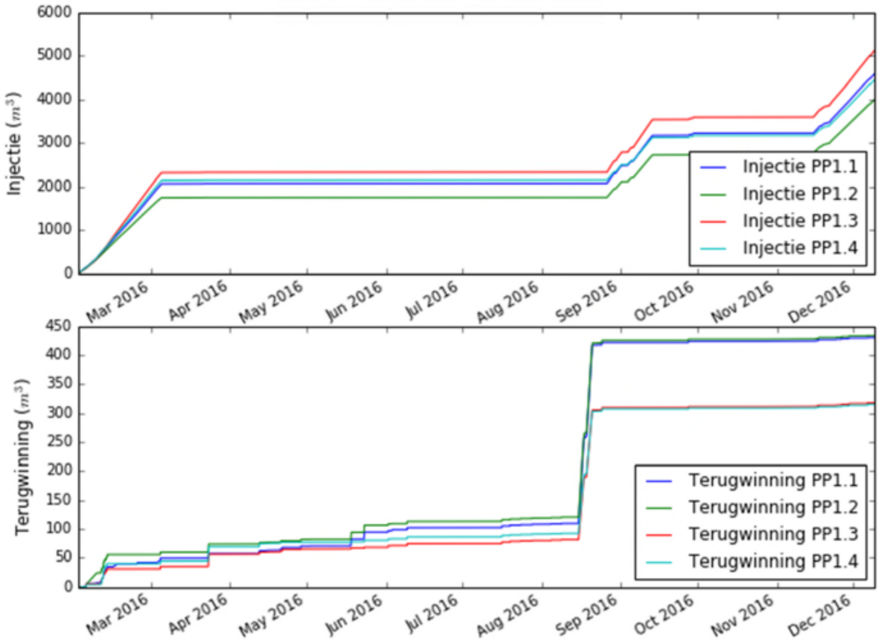


Figure 10: Pumping during the ASR pilot in Dinteloord in 2016 ('injectie' = injection; 'terugwinning' = recovery).

Modelling results

With the MODFLOW model built for the pumping test, a SEAWAT model was set up to model the test cycle (Figure 11, Figure 12). Based on the modelling results, buoyancy and mixing at the Dinteloord ASR site will be limited, which will positively affect the recoverability of the stored water.

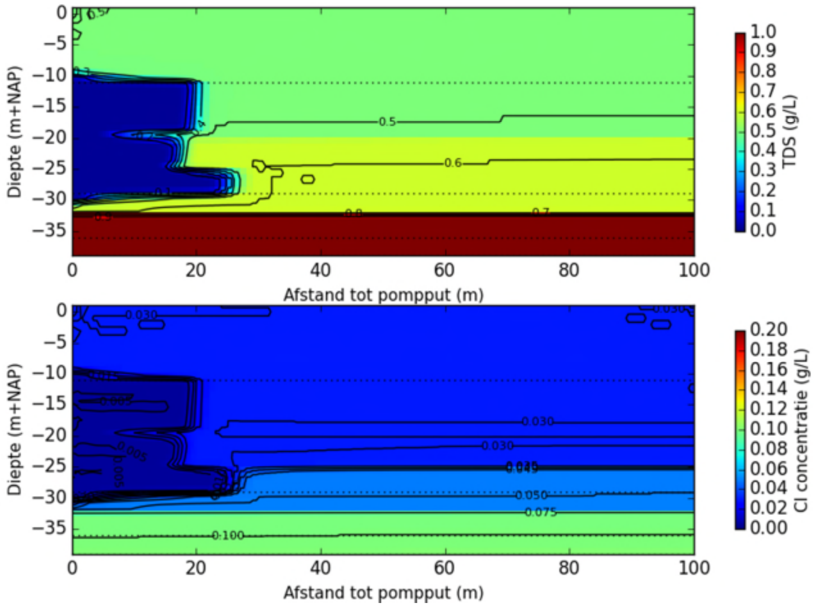


Figure 11: TDS and Cl concentrations in the aquifer during storage (June 3, 2016). Depth is in m-ASL, horizontal distance is the distance from the ASR wells (in m)

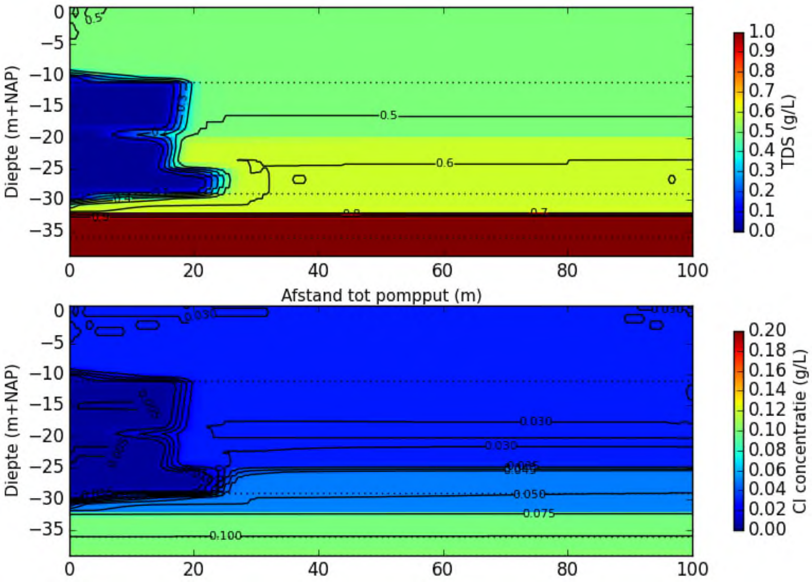
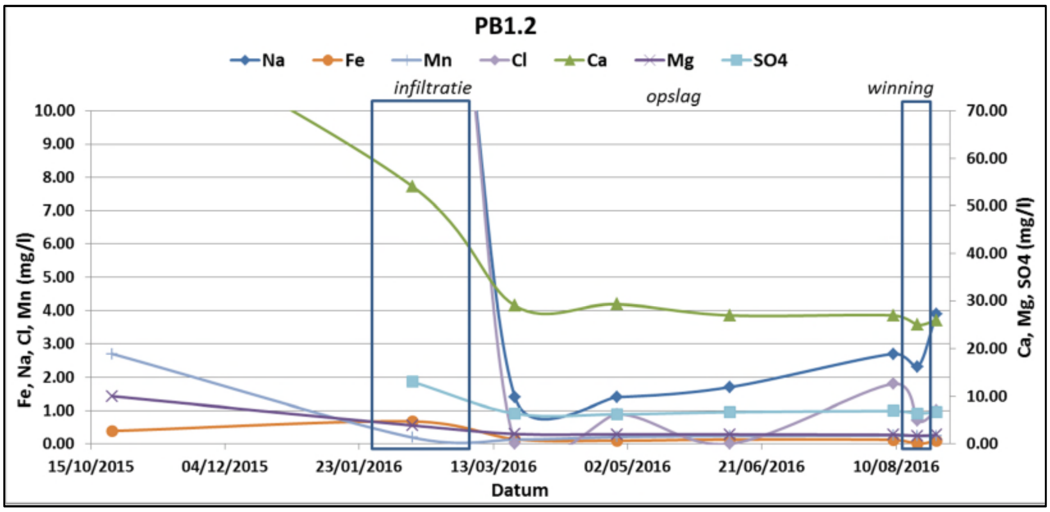


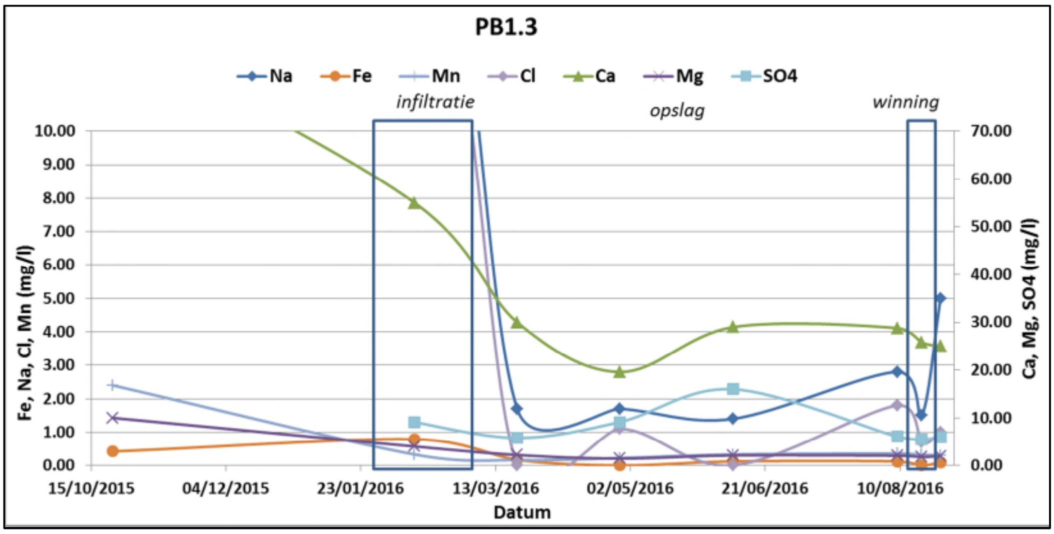
Figure 12: TDS and Cl concentrations at the end of recovery (August 21, 2016)

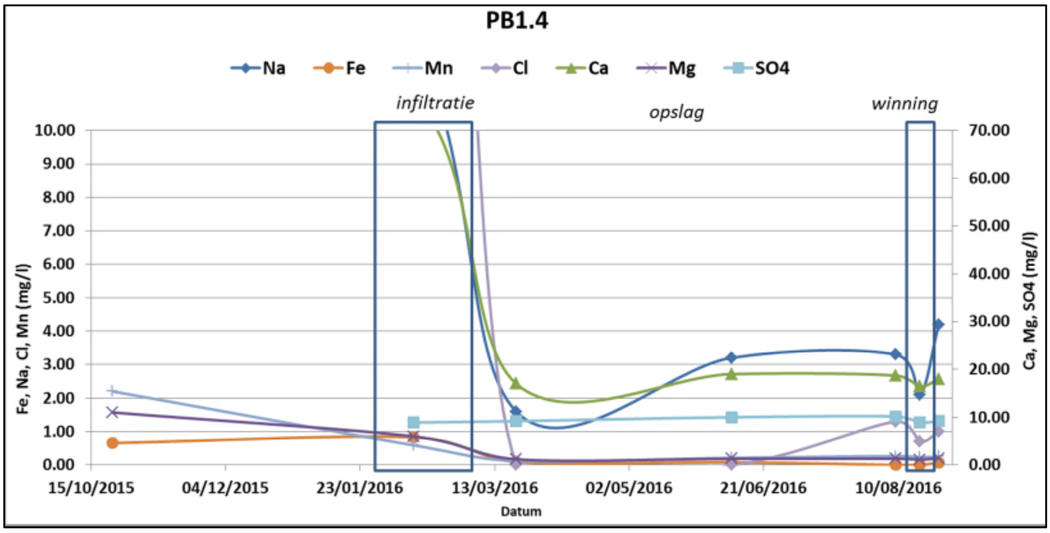
Water quality observations at PB1

Freshening occurred at PB1 after around 15 days of infiltration (infiltration of 2200 m^3), confirming the effective porosity of 0.3 to 0.35. The main observations were:

- Enrichment of Ca, Mg and HCO_3 as a consequence of calcite and dolomite dissolution;
- Early enrichment with Na and Cl at PB1.5, later enrichment with Na at all well screens;
- A slight enrichment with Fe, Mn, and SO_4' the latter indicating that some pyrite oxidation is occurring;
- An increase in pH to 8.


PB1.2
Na
Fe
Mn
Cl
Ca
Mg
SO4
infiltratie
opslag
winning
Fe, Na, Cl, Mn (mg/l)
Ca, Mg, SO4 (mg/l)
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
15/10/2015
04/12/2015
23/01/2016
13/03/2016
02/05/2016
21/06/2016
10/08/2016
Datum


PB1.3
Na
Fe
Mn
Cl
Ca
Mg
SO4
infiltratie
opslag
winning
Fe, Na, Cl, Mn (mg/l)
Ca, Mg, SO4 (mg/l)
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
15/10/2015
04/12/2015
23/01/2016
13/03/2016
02/05/2016
21/06/2016
10/08/2016
Datum


PB1.4
Na
Fe
Mn
Cl
Ca
Mg
SO4
infiltratie
opslag
winning
Fe, Na, Cl, Mn (mg/l)
Ca, Mg, SO4 (mg/l)
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
15/10/2015
04/12/2015
23/01/2016
13/03/2016
02/05/2016
21/06/2016
10/08/2016
Datum

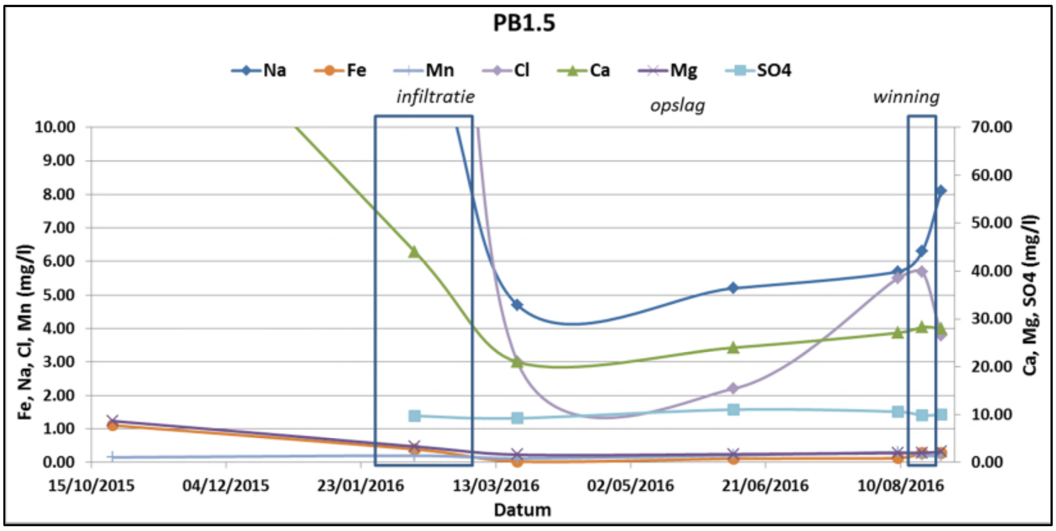


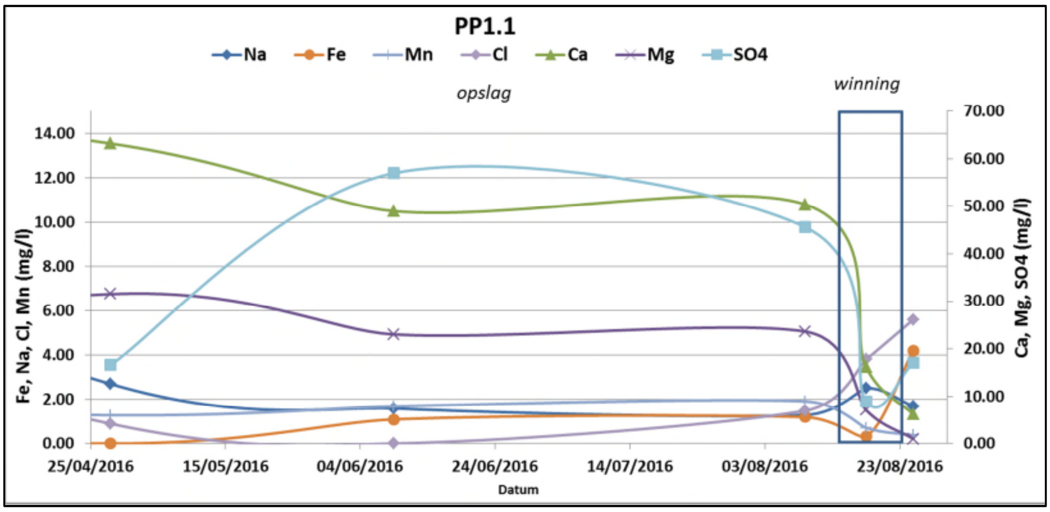
Figure 13: Macrochemical water quality changes at PB1

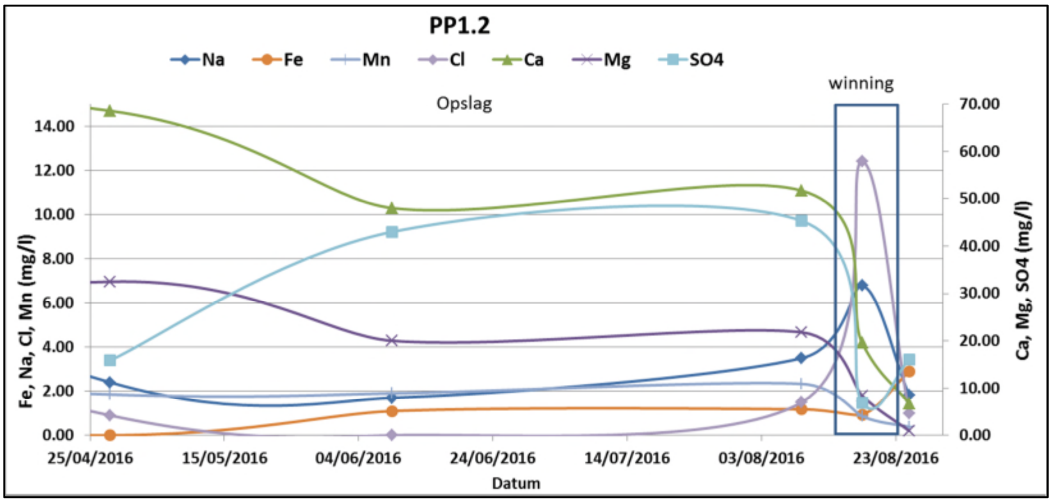
Water quality of the recovered water

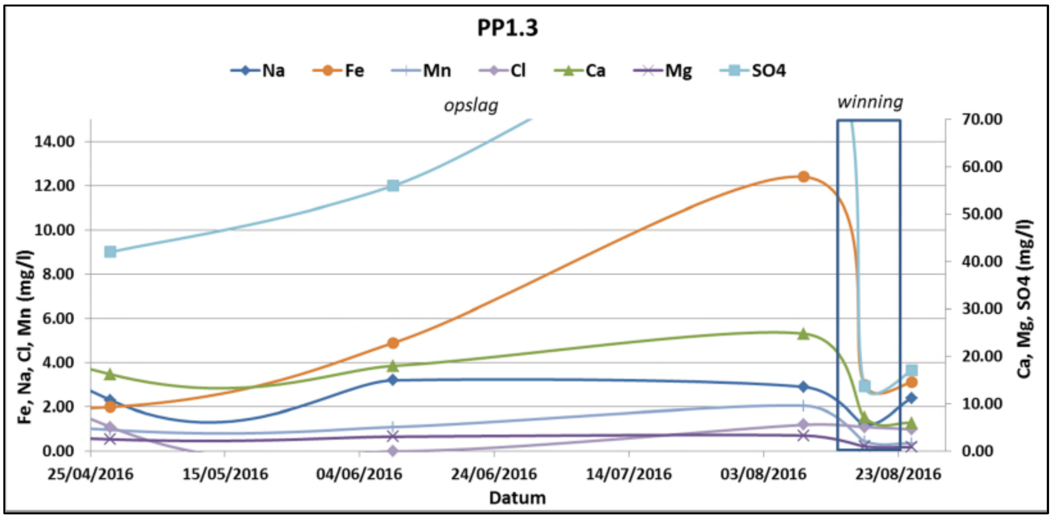
Water quality development during storage

During regular recovery of small freshwater volumes, it was found that the water around ASR well showed at steep rise in EC. At PP1.1 and 1.2 this was caused by increasing concentrations of Mg, Ca, HCO_3, and some SO_4 (Figure 14), which suggests a significant dissolution of dolomite. At PP1.3 and 1.4 this was mainly caused by an increase in SO_4, Ca, and Fe, which suggests that oxidation of pyrite (FeS_2) is occurring. All these intense dissolution processes were not observed at PB1 at 10 m from the ASR wells and are therefore related to the ASR well itself (probably distortion of the aquifer during drilling or introduction of air during storage via the air vents on the infiltration lines). The volume of this specific enriched water type is limited to tens of m^3 around the ASR well and relatively limited (Figure 15).

The water recovered later during the test cycle had a constant quality and very low EC (50 – 150 µS/cm), see Table 7. The water virtually met the quality limits set by TOM, except for pH, Fe, and Mn. As the water is first distributed to aboveground reservoirs, it is expected that Fe and Mn will precipitate and settle out. The Na limit is set very strict and a minor increase in Na concentration in the injected water is observed and attention is also required with respect to Na.


PP1.1
Na
Fe
Mn
Cl
Ca
Mg
SO4
opslag
winning
Fe, Na, Cl, Mn (mg/l)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
Ca, Mg, SO4 (mg/l)
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
25/04/2016
15/05/2016
04/06/2016
24/06/2016
14/07/2016
03/08/2016
23/08/2016
Datum


PP1.2
Na
Fe
Mn
Cl
Ca
Mg
SO4
Opslag
winning
Fe, Na, Cl, Mn (mg/l)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
Ca, Mg, SO4 (mg/l)
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
25/04/2016
15/05/2016
04/06/2016
24/06/2016
14/07/2016
03/08/2016
23/08/2016
Datum


PP1.3
Na
Fe
Mn
Cl
Ca
Mg
SO4
opslag
winning
Fe, Na, Cl, Mn (mg/l)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
Ca, Mg, SO4 (mg/l)
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
25/04/2016
15/05/2016
04/06/2016
24/06/2016
14/07/2016
03/08/2016
23/08/2016
Datum

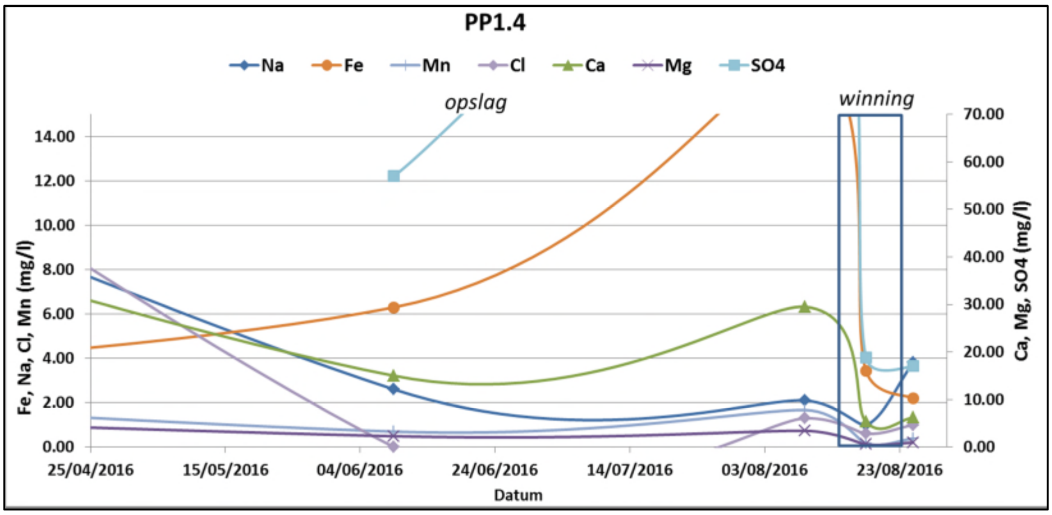


Figure 14: Macrochemical water quality development at PP1 (‘winning’ = recovery stage in August)

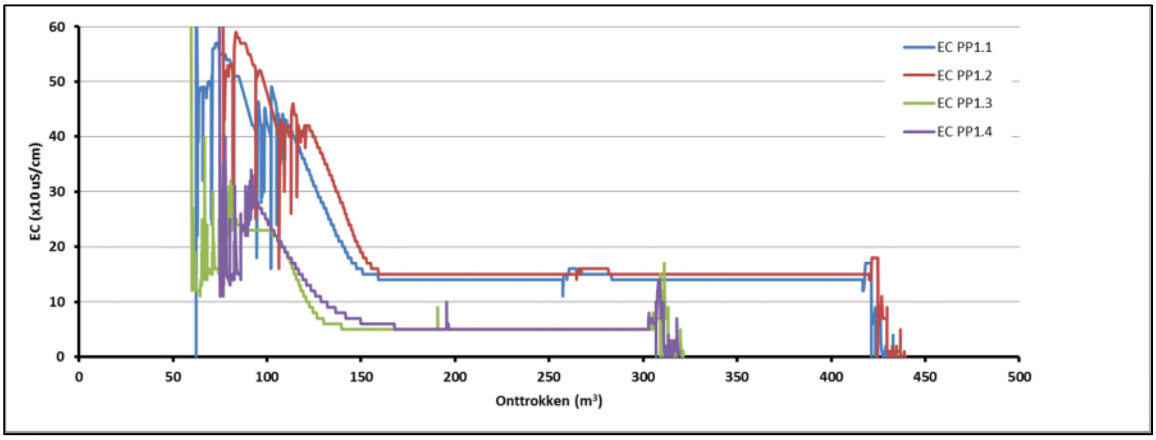


Figure 15: EC of the recovered (’onttrokken’) water during the ASR test cycle.

Table 7: Observed recovered water quality at the end of the test cycle in 2016

Sample:		**PP1.1**	**PP1.2**	**PP1.3**	**PP1.4**	**PP1**	**Limit TOM**
Date		25/08/2016	25/08/2016	25/08/2016	25/08/2016		
Infiltration	m³	2072.3	1751.5	2325.9	2146.9		
Recovery	m³	421.4	424.8	309.2	306.9		
O2	mg/l	0.1	0.1	0.1	0.1	0.1	
Turbidity	NTU	8	12	12	9	10.3	
EC-25	uS/cm	53	27	48	43	43	300
Temp	°C	13.1	13	12.9	13	13.0	
pH-Lab		8.4	7.9	7.4	7.1	7.7	6.5
pH-field		7.6	7.7	7.8	7.7	7.7	6.5
Na	mg/l	1.7	1.8	2.4	3.8	2.4	2.3
K	mg/l	0.9	0.9	0.8	0.8	0.8	46.9

Ca	mg/l	6.2	6.7	6	6.2	6.3	32.1
Mg	mg/l	1.0	0.9	0.9	1.0	0.9	4.9
Fe	mg/l	4.2	2.9	3.1	2.2	3.1*	0.25
Mn	mg/l	0.4	0.4	0.4	0.4	0.4*	0.3
NH_4	mg/l	0.1	0.1	0.1	0.1	0.1	0.4
Cl	mg/l	5.6	1	1	1	2	17.7
SO_4	mg/l	17	16	17	17	16.8	28.8
HCO_3	mg/l	16	20	18	27	20.3	91.5
$N0_3$	mg/l	0	0	0	0	0	217
PO_4-t	mg/l	0	0	0	0	0	27.0
As	mg/l	10	6	6	<5	7.1	-
Zn	ug/l	10	10	53	82	39	196

Long-term performance expectation

The recovery efficiency of the final well field (8 ASR wells) is analysed with the SEAWAT groundwater model. In this case, 25.000 m^3 of freshwater is infiltrated and recovered per ASR well to produce 200.000 m^3 per year.

Predicted performance based on Cl concentrations

Since Cl is the best indicator for salinization, it was first analysed when the wells would recover water with concentration above the TOM limit (17.7 mg/l). In the first 5 years, the recovery efficiency increases from 92.5 to >99% (Table 9). The results do show that concentration will increase in the final recovery stage, especially at the deepest well screens.

Table 8: Operational ASR scheme of the groundwater model

Phase	Duration (d)	Q (m3/d)	Volume (m3)	Q per well screen layer (%)
Injection	140	180	25.200	PPX.1: 25, PPX.2: 21, PPX.3: 28, PPX.4: 26
Storage	150	0	0	-
Recovery	40	-625	-25.000	PPX.1: 25, PPX.2: 21, PPX.3: 28, PPX.4: 26

Table 9: Recovery efficiency per cycle based on Cl

Cycle	Recovery Efficiency (%)
1	92,5
2	95,9
3	98,4
4	98,4
5	98,4
6 - 20	99,2

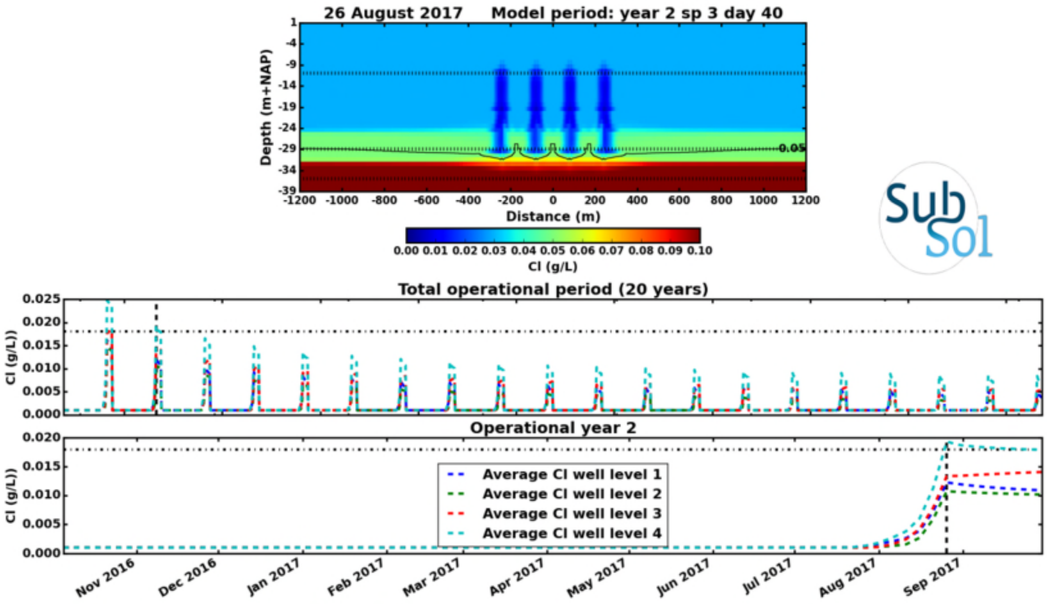


Figure 16: Modelled Cl concentrations (10 cycles: Cycle 2 is shown).

Predicted performance based on Na concentrations

The limit set for Na is relatively stricter that the limit for Cl, such that less mixing with brackish water can be allowed. Especially well layer 1 and 4 suffer from early admixing of Na by diffusion from the confining clay layers, limiting the recovery efficiency in the first cycles. However, as a consequence of ungoing freshening as a consequence of overinfiltration, the recovery efficiency increases to >80% after 5 years. When a somewhat higher salinity (e.g. 11 mg/l: generally accepted in modern greenhouse horticulture) is accepted, the recovery efficiency will be in line with the recovery efficiency based on Cl.

Table 10: Predicted recovery efficiency based on the TOM Na limit (2.4 mg/l)

Cycle	Recovery Efficiency (%)
1	33,8
2	59,7
3	70,5
4	75,9
5-6	80,3
7-8	82,6
9-10	83,5

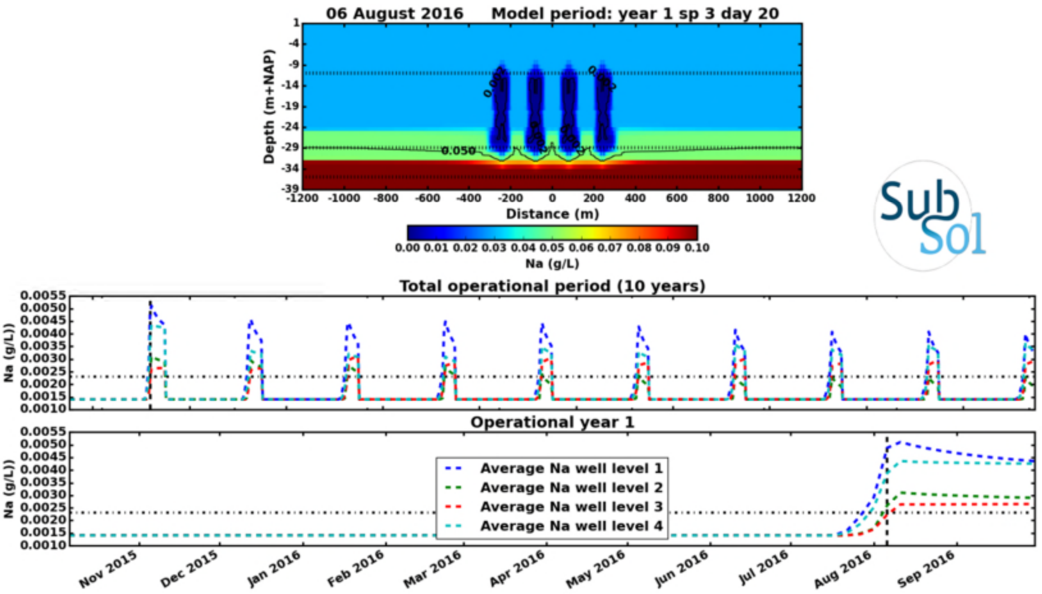


Figure 17:Simulated Na concentrations (10 cycles: Cycle 1 is shown)

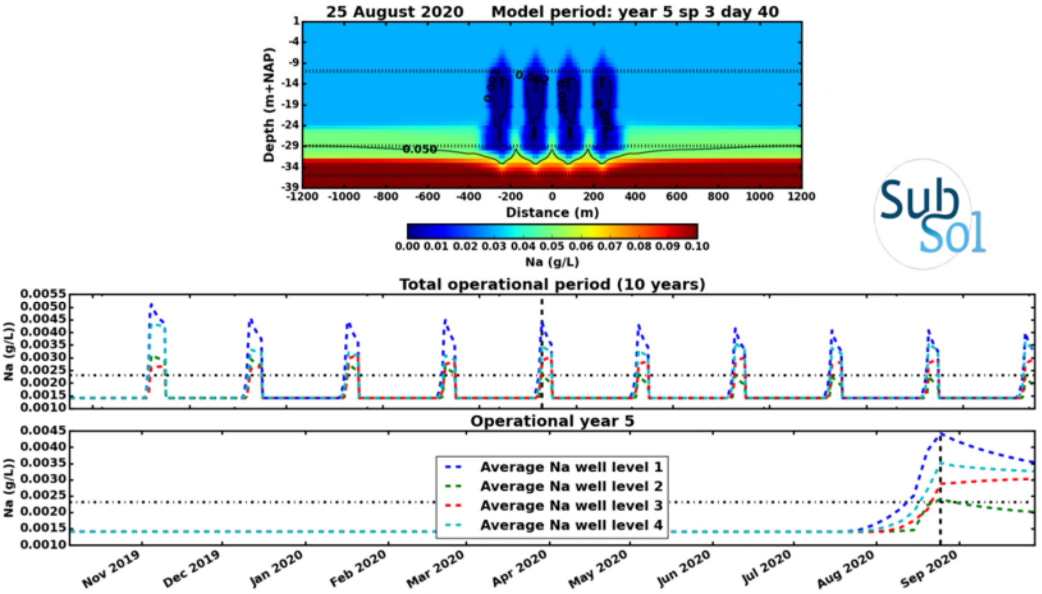


Figure 18: Simulated Na concentrations (10 cycles: Cycle 5 is shown)

Impact of Dinteloord ASR-Coastal on the surroundings

During the test cycle, the water level changes in the area were monitored with sensors. The observed changes could be reproduced by the groundwater transport model and were used to simulate the hydrological effects of the test cycle and the eventual full-scale ASR scheme. Although strong variations in the hydraulic head of Aquifer 1 are induced, the impact of these changes on the surroundings is limited thanks the covering clay/peat layer. Therefore, the water authority approved expansion of the well field to four wells in 2017.

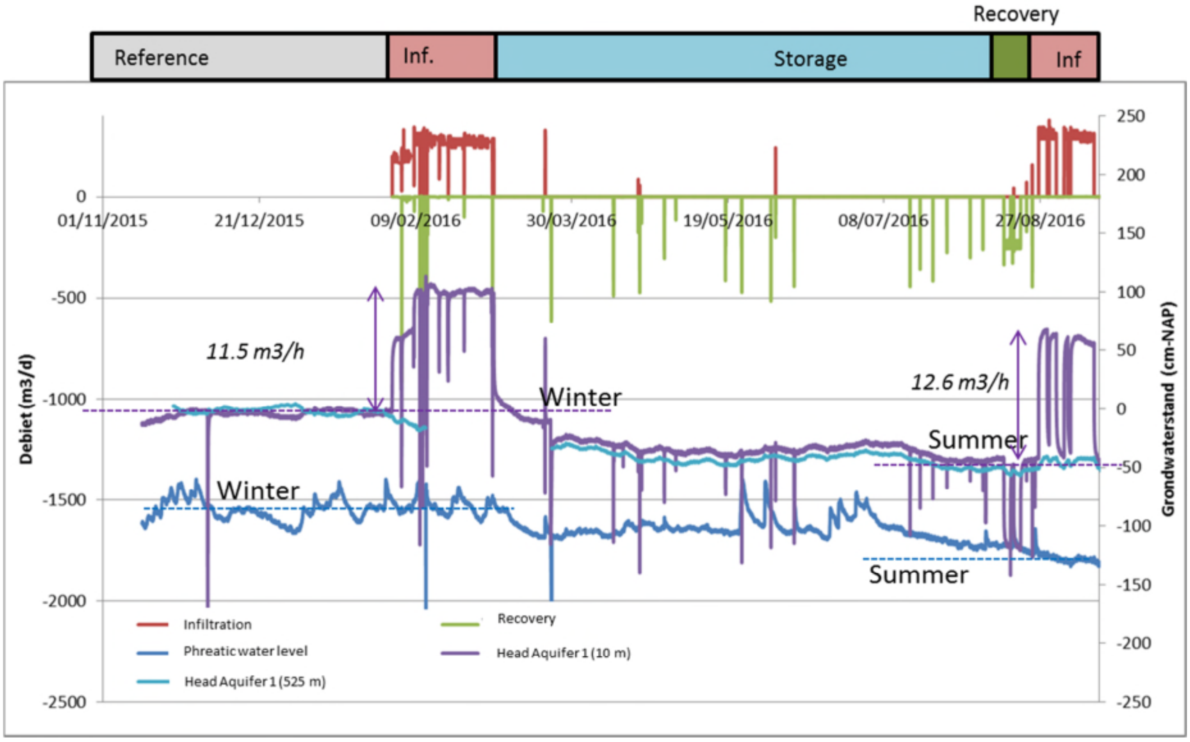


Figure 19: Pumping of the ASR system and reaction of the waterlevel in various piezometers in the area.

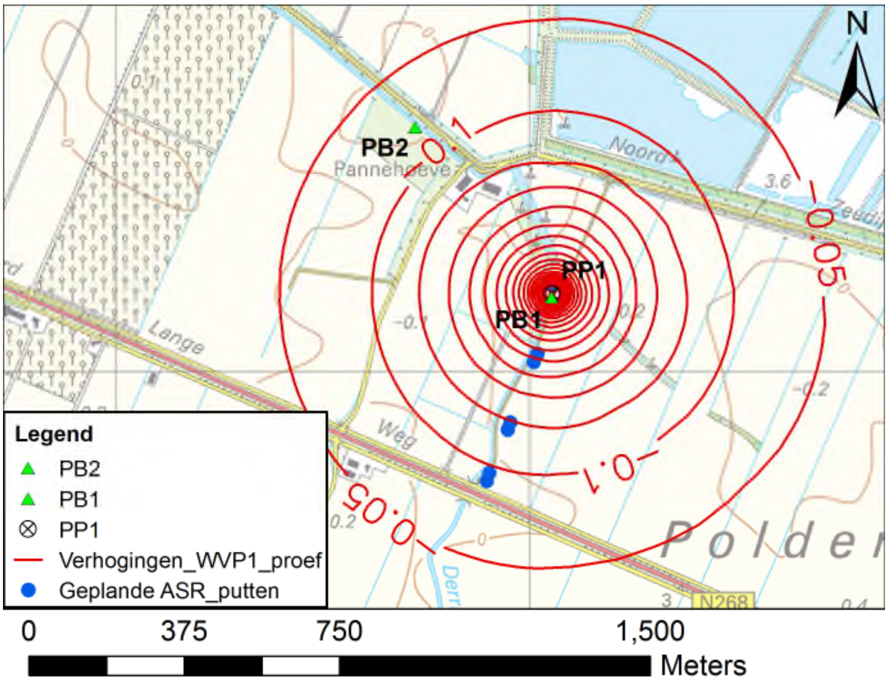


Figure 20: Increase in hydraulic head (Aquifer 1) during infiltration during the test cycle

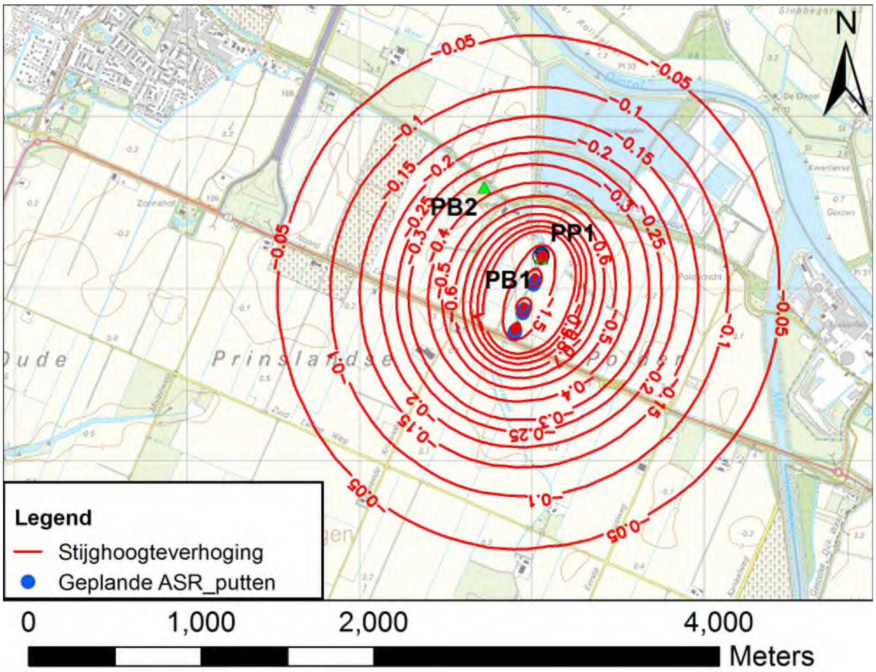


Figure 21: Increase in hydraulic head (Aquifer 1) during infiltration during full-scale application

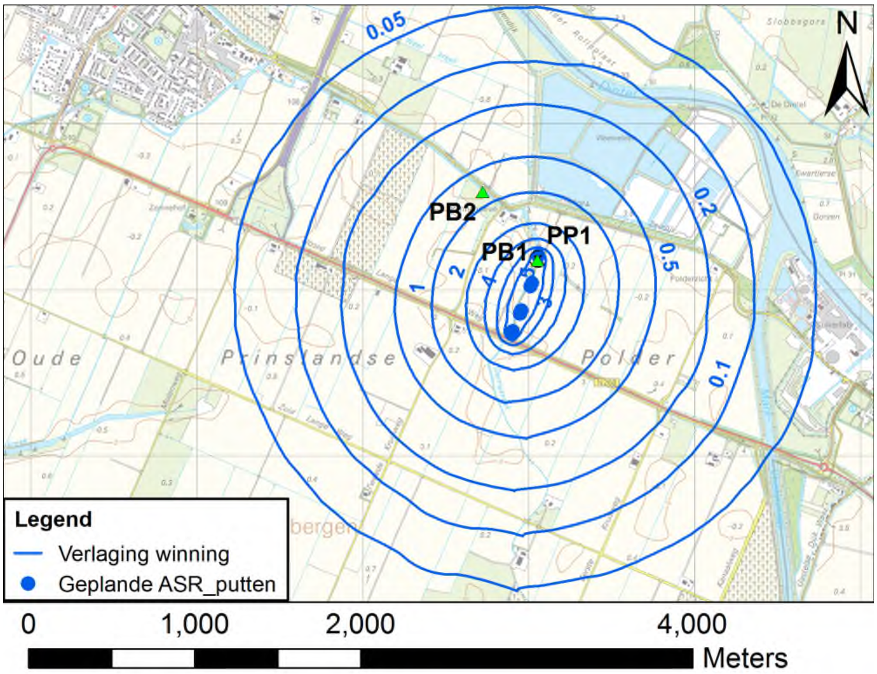


Figure 22: Decrease in hydraulic head (Aquifer 1) during recovery during full-scale application

Cost analysis of ASR and aboveground storage alternative

A comparison was made between the ASR-Coastal storage system and storage using a conventional basin (using dikes, covered by foil). As a consequence of a higher lifespan and lower investment costs, and especially much lower costs for aboveground land, a positive business case was attained for ASR. The cost for ASR are 0.37 euro/m^3, while the alternative above groundbasin would cost 0.99 euro/m^3. Additionally, a proper foil basin will require frequent and complete costly renovations, while the ASR well field and main infrastructure will last at least 50 years. Even if the aboveground basins would also last 50 years, the costs per m^3 would still be 0.53 euro due to the costs for land. Only the operational costs for ASR are higher due to the higher energy consumption and higher costs for maintenance.

The benefits for the project developer are estimated at 0.62 euro/m^3 based on

Table 11. For the developer this means that the total estimated benefits are 62.000 euro/year, based on an estimated average supply of 100.000 m^3/yr. Due to a lack of alternatives (use of groundwater and surface water during drought was prohibited and other storage option were not realistic), this is virtually the only alternative to be analysed.

Table 11: Costs of ASR and aboveground storage based on a maximum supply of 200,000 m^3 and an average supply of 100,000 m^3.

Costs of storage using ASR-Coastal		
Initial investment	630,783	euro
Re-investments	886,200	euro
Lifespan	50	yrs
CAPEX	0.30	euro/m^3
OPEX	0.07	euro/m^3
Interest (land)	0	euro/m^3
Costs of ASR	0.37	euro/m^3
Costs of storage in aboveground basin		
Investment basin	3.75	euro/m^3
Investment boosterpump	20,000	euro
Total volume to be realized	200,000	m^3
Claim on above ground land	50,000	m^2
Total investment	770,000	euro
Lifespan	12.5	yrs
CAPEX	0.62	euro/m^3
OPEX	0.01	euro/m^3
Interest (land)	0.36	euro/m^3
Costs of aboveground storage	0.99	euro/m^3

Conclusions

An ASR test cycle was run at the Dinteloord greenhouse cluster. The approximately 20 m thick target aquifer consisted of very fine to medium fine and was properly confined by clay and peat layers. The geochemical composition indicated potential calcite and dolomite dissolution, as well as pyrite oxidation. These processes were observed during the infiltration of 8,300 m^3 of high quality, virtually demineralized freshwater, but the impact on the stored water quality was acceptable for the current use as irrigation water after supplementation of aboveground rainwater reservoirs. The recovered water quality is clearly different from the infiltrated water quality. A core focus during future cycles with regards to the stability of the water quality should therefore be on:

1. Enrichment with sodium(Na): due the the mixing with ambient groundwater and diffusion from clayey interval in the target aquifer, the limit for Na set by the TOM may be the first to be reached during recovery. This can be enanced by potential dissolution of albite.
2. Around the ASR-well, a particular water quality evolves during storage upon ending the infiltration. This concerns around 200 m^3 of water with relatively high Ca, Mg, HCO_3, SO_4, Fe, Mn, and EC. After recovery of this part, only Fe, Mn, and pH threaten the recovered water quality. This enrichment may be induced by distortion by drilling (fluids) and potentially enhanced oxidation by air intrusion via air vents.

Groundwater modelling indicated that virtually all infiltrated water can be recovered with acceptable Cl concentrations after a few cycles. More cycles were required to attain a recovery of more than 80% with acceptable Na concentrations. The observed hydrological effects were in line with the predictions by the groundwater model. The model was therefore used to explore the effects of upscaling. Based on these results, it was found that hydrological effects were acceptable and did not hamper further expansion of the well field in 2017.

Based on a cost analysis, a positive business case for ASR-Coastal was found. The costs based on an average water use of 100,000 m^3/yr and a maximum capacity of 200,000 m^3 are estimated on 0.37 euro/m^3, versus 0.99 euro/m^3 for aboveground storage in foil basins. This results in a yearly benefit of 62,000 euro/yr. Further advantages of ASR were the limited claim on land (which can now be used for greenhouses) and protection from pollution (atmospheric deposition, sabotage, algae).