The Freshmaker: enabling aquifer storage and recovery (ASR) of freshwater using horizontal directional drilled wells (HDDWs) in coastal areas

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INTRODUCTION

Freshwater supply in coastal areas worldwide is under pressure due to salinization, increasing droughts, and/or increasing freshwater demands. With drinking, industrial, and agricultural water supply at stake, efficient exploitation of any available freshwater surplus is essential to avoid serious shortages. Seasonal aquifer storage and recovery (ASR) of any freshwater surplus (for instance, rain, surface or treated water) is an efficient technique to bridge periods of surplus and drought, without claiming large surface areas aboveground. ASR is defined as 'the injection of water surpluses by a well and recovery by the same well in times of demand' (Pyne, 2005).

ASR is successfully applied in freshwater aquifers, but storage of freshwater in saline aquifers is troublesome, however, mainly due to buoyancy effects. In such case, the density-difference between injected freshwater (low density) and ambient saline groundwater (high density) will induce upward movement of freshwater. The conventional ASR set-up, which uses a single vertical well for injection and recovery, will therefore generally fail in saline coastal aquifers, as the lower part rapidly extracts ambient saline groundwater (e.g., Esmail and Kimbler, 1967). Use of upscaling or multiple partially penetrating wells may counteract this effect in brackish, confined aquifers (Zuurbier et al., 2013; Zuurbier et al., submitted), but is presumably insufficient for small-scale ASR in saline aquifers, especially when they are thick and unconfined.

Recent development of horizontal directional drilled wells (HDDWs) may initiate successful ASR developments in saline aquifers. By spreading shallow extraction over a large area, for instance by HDDWs, a larger volume of freshwater can be recovered from natural freshwater lenses without salinization (Oude Essink, 2001). A new development is the use of a HDDW pair to enable injection, recovery, and interception at different depths within the aquifer to further manage fresh-salt interfaces. This way, thin, natural fresh groundwater lenses can be enlarged by shallow injection of freshwater and deep interception of upconing saline water (the 'Freshmaker' concept). The first Freshmaker prototype is installed early 2013 in the coastal province of Zeeland (The Netherlands, Figure 1). Here, a successful seasonal freshwater storage using the Freshmaker is predicted by preliminary SEAWAT modelling, which is to be verified in the summer of 2013.

METHODS

The Ovezande Freshmaker trial

In the study area, freshwater is scarce due to the surrounding Scheldt estuaries. Current freshwater resources are therefore limited to rainwater, local fresh groundwater lenses in higher lying paleocreek ridges (forming 'inverted landscapes'), and some river water transported by a pipeline. Due to the limited supply in (dry) summers, freshwater shortages occur in the local agri- and horticultural sector, causing considerable loss of revenue in especially the fruit production sector. On the other hand, large freshwater volumes are drained to sea in winters, when precipitation rates are high and water use and evapotranspiration are low. This fresh surface water is stored underground by the Freshmaker in a first field trial, in order to prevent summer shortages.

The field site is situated on a sandy, relatively young, 5 km wide former creek ridge near the village of Ovezande (Figure 1). The ridge reaches 0 to +2 m-sea level and is surrounded by (older) peat and clay deposits (0 to -1.5 m-sea level). Draining water courses are deep, and have controlled water levels generally of -0.6 to -0.7 m-sea level. They salinize during summers. Thickness of local fresh groundwater lenses is dependent on surface elevations and the surrounding drainage level (de Louw et al., 2011). Generally, their thickness is less than 15 m, which legally prohibits extraction from these reserves for irrigation purposes in order to prevent salinization.

At the field site, a 70 m long HDDW was installed at 14 m depth (Figure 2), forming the 'interception well'. A second, shallow HDDW ('ASR well') was installed right above the interception well for artificial recharge and recovery of freshwater surpluses at 7 m depth. The injected freshwater by this well should enlarge the 9 m thick, natural fresh groundwater lens and enable freshwater recovery for crop irrigation in the growing season. With the construction of the HDDWs, horizontal directional drilling (applied since the sixties) was used to insert a long horizontal well screen into an aquifer. A bentonite SW drilling fluid (HDD Drilling Fluids, Schoonebeek, The Netherlands) was used to lubricate the drilling, to dispose the cuttings and to provide borehole stability. Once the well screen was in place, a dispersant was used to remove the drilling fluid. The upper HDDW was provided with four rows having 10 mm open holes every 10 cm and was wrapped with geotextile. At the deeper, similar HDDW, an additional perforated 'lost casing' was left to protect the inner HDDW during installation at this depth.

An extensive monitoring network was established at the field site, consisting of 6 piezometer nests and three transects used for regular continuous vertical electrical soundings (CVES). Freshwater surpluses from the water course nearby were stored in a ~4,000 m^3 basin during the winter of 2012/2013. In the spring of 2013, the drilling operation was completed and all pipelines, pumps, and a pre-treatment installation were completed. On the same watercourse, extracted saltwater from the deep HDDW is disposed in dry periods when surface water is saline and intake is ceased (Figure 3).

<u>Conceptual modelling of Freshmaker benefits</u>
A SEAWAT (Langevin et al., 2008) model was built prior to installation to analyse the efficiency of the Freshmaker principle and estimate the required pumping rates. A simple slice consisting of only one row comprising 10 m of the HDDW pair was taken to control model runtimes. Edge effects on the outer ends of the HDDWs were thereby neglected. Hydraulic conductivities were estimated based on the grain size analyses and matched typical values for creek ridge sediments (~5 to 10 m/d). A small water course close by the Freshmaker set-up was added using MODFLOW's River package. Topography was taken from local height measurements. At 850 m from the Freshmaker a constant head boundary was placed. The initial chloride concentration was produced by simulating 100 year with a realistic recharge of 200 mm/yr (Royal Netherlands Meteorological Institute). This gave a salinity distribution very comparable to the reference CVES results (Figure 4) after adjusting the conductance of the beds of the different water courses. A low dispersivity (0.1 m) was chosen to reproduce the relatively thin mixing zone observed in the field.

The outcomes of the initial model were used to set the initial conditions prior to the installation of the Freshmaker HDDW pair. The HDDWs were simulated by normal single-cell wells in the slice at 7 and 14 m depth. Discharge of each well during 5 years (conform Table 1) was based on the estimated water availability and the well capacity. In total, five stress periods were calculated: an injection phase, a first recovery phase (sprinkling against frost damage), a storage phase, a second recovery phase (drought irrigation), and an idle period awaiting new freshwater surpluses.

RESULTS
The modelled chloride concentrations in different phases of the first ASR cycle are shown in Figure 5. Clearly, the Freshmaker is able to lower the fresh-salt interface to the level of the deep HDDW, thereby storing the targeted freshwater volume of 4,200 m^3. Due to the simultaneous injection of freshwater and extraction of deeper saline groundwater, the effects on the phreatic groundwater level were less than 5 cm. During recovery phases, the fresh-salt interface moved up again, however, not threatening the recovery of freshwater at the upper HDDW. A maximum phreatic drawdown of 7 cm was observed above the HDDW pair,

indicating that the hydrological effect remained limited. When only the deepest HDDW was actively intercepting saline water (storage periods), the fresh-salt interface was lowered and stabilized.

In comparison, when only a single HDDW (scenario ‘no deep HDDW’) was installed at a depth of 7 m, significantly less freshwater was found recoverable. This was evidenced by a firm increase in chloride concentration during both recovery phases, exceeding the local maximum chloride concentration for irrigation water. When a Freshmaker was installed, but no water was injected (scenario ‘no injection’), a satisfying volume of freshwater could be recovered from cycle 5 onwards, due to the almost continuous interception of saltwater by the deep HDDW, increasing freshwater infiltration and decreasing seepage to the surface water. However, a larger drawdown (13 cm) was observed, which might locally cause drought damage.

Discussion and conclusions

High ASR recovery efficiencies are generally not feasible in coastal aquifers. The Freshmaker principle enlarges thin fresh groundwater lenses in shallow aquifers by the use of two horizontal directional drilled wells (HDDWs). An upper, shallow HDDW injects freshwater surpluses and a deeper HDDW extracts and intercepts saline groundwater. Freshwater stored in this process, can be efficiently recovered again using the upper HDDW, even after periods of storage. SEAWAT transport modelling shows that a recovery efficiency of 100% is feasible. A prerequisite is continuous interception of deeper saline groundwater by the deeper HDDW. Due to the use of long horizontal wells, regional hydrological effects are limited.

A first prototype of the Freshmaker was installed in Ovezande (Province of Zeeland, The Netherlands) and is extensively monitored during its first ASR cycle during the spring and summer of 2013. Key research topics are the calibration of the SEAWAT model, groundwater quality development in the reactive aquifer, and the effect of the disposal of saline groundwater on a nearby water course. In the following years, more cycles are planned to study the most efficient pumping scheme, potential well clogging, and regional potential for large-scale implementation of this ASR technique.

When the Freshmaker principle proves feasible in practice, a robust ASR technique is at hand in coastal areas with similar hydrological settings worldwide. This means valuable freshwater surpluses can be stored in these areas, without claiming large surface areas aboveground. With this increased freshwater availability, coastal areas can remain (or become) interesting for agriculture and industries.

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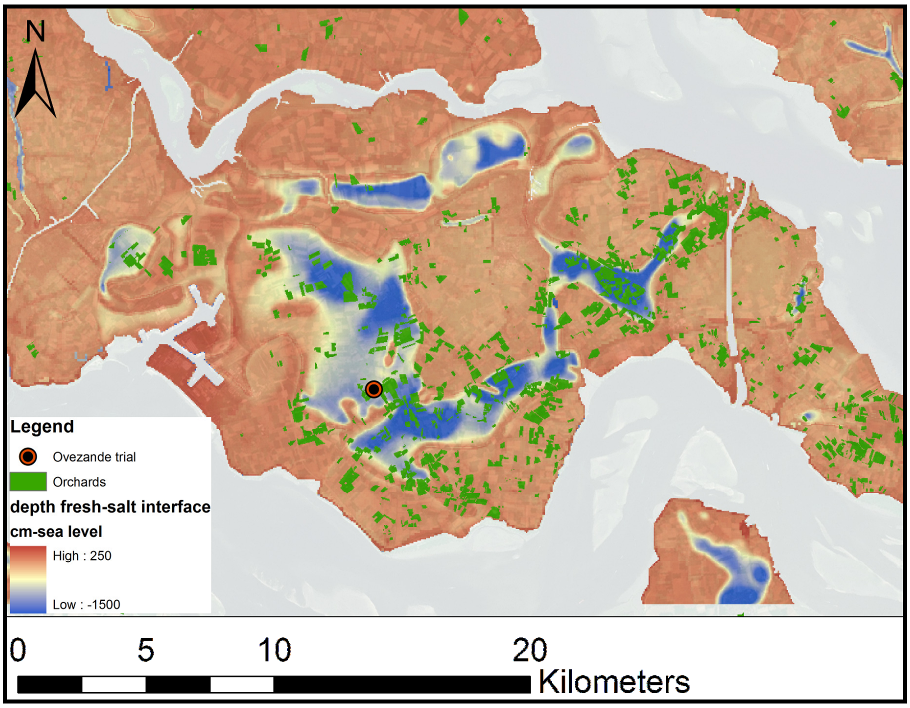


Figure 1: Depth of fresh-salt interface indicating natural freshwater lenses found at the island of Zuid-Beveland (Zeeland, The Netherlands) and the location of the Ovezande Freshmaker trial.

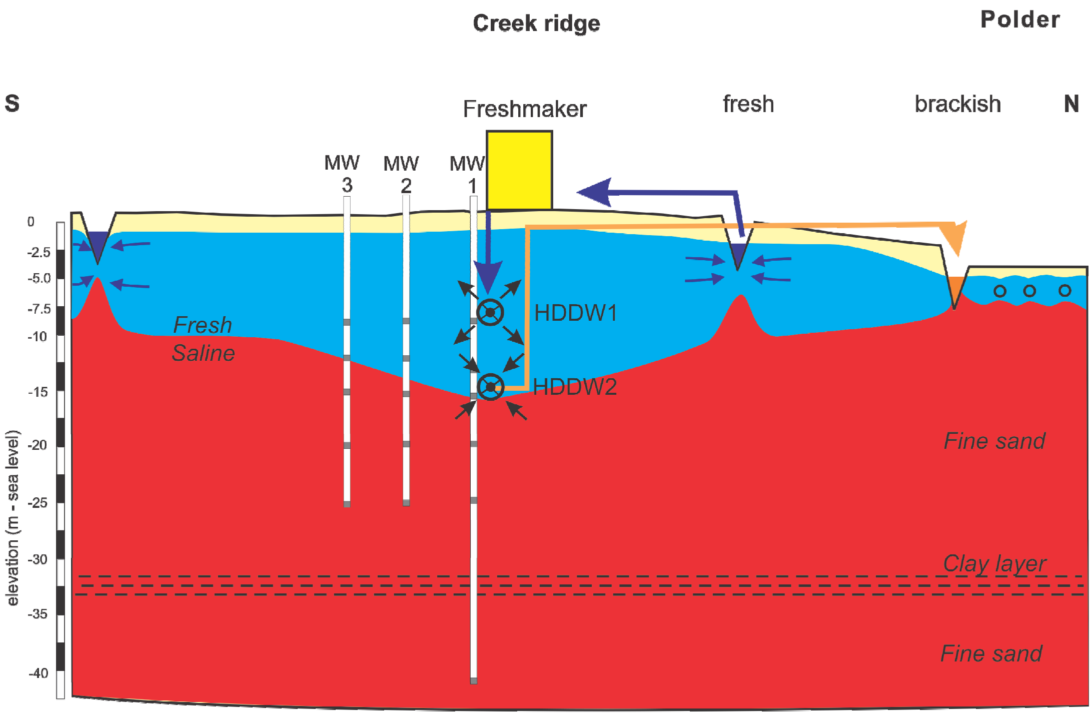


Figure 2: Cross section of the Freshmaker set-up at the Ovezande trial. *MW = monitoring well, HDDW=horizontal directional drilled well.*

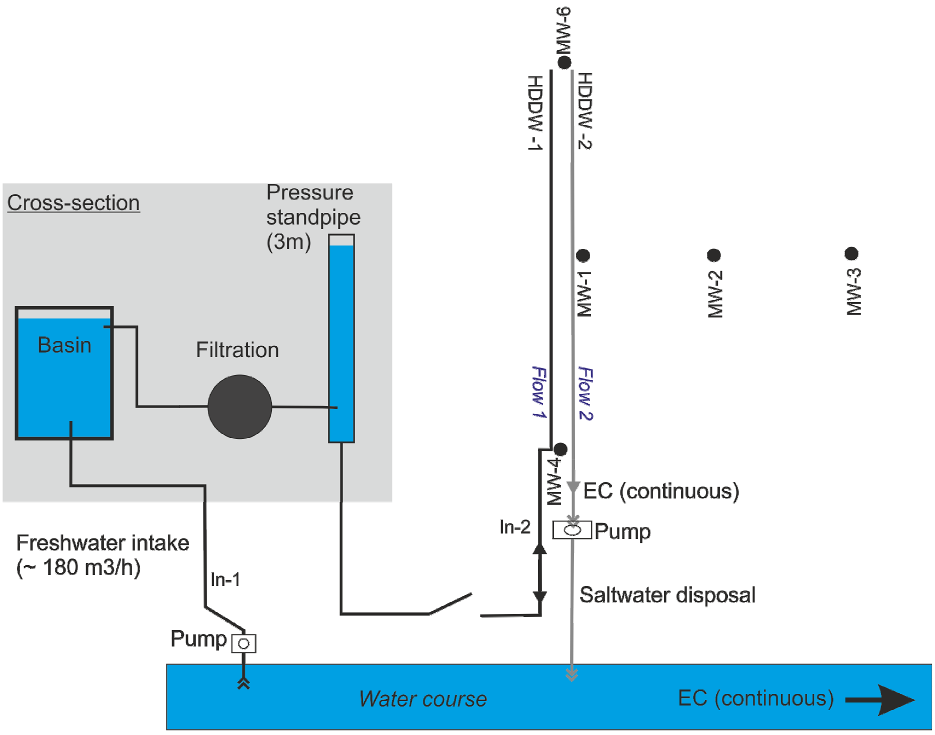


Figure 3: Plan view of the Freshmaker set-up at the Ovezande trial.

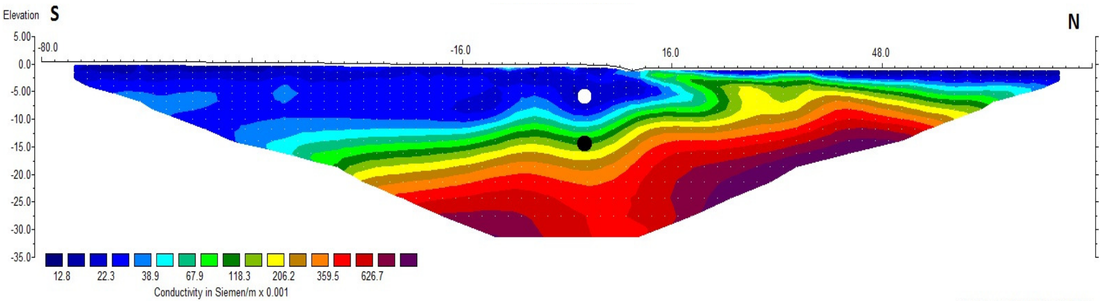
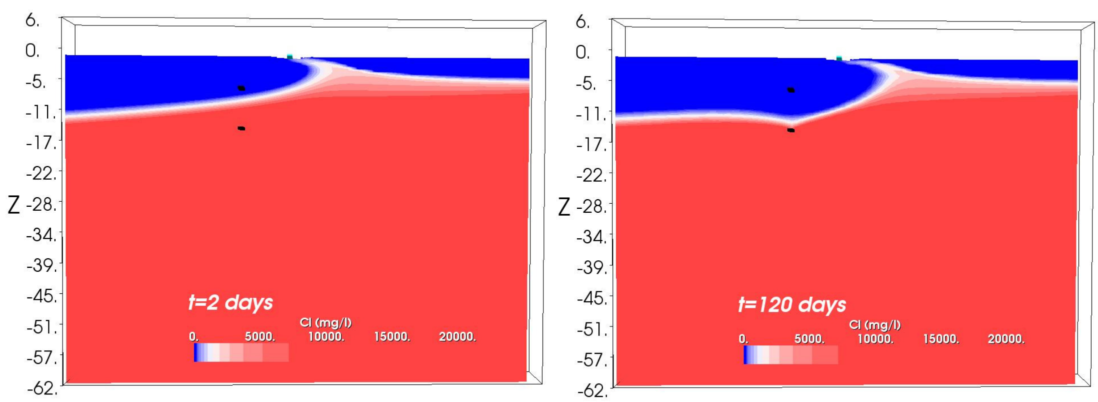


Figure 4: Continuous vertical electrical sounding (CVES) at the Ovezande field site. The positions of the HDDWs are marked white (upper) and black (deeper).



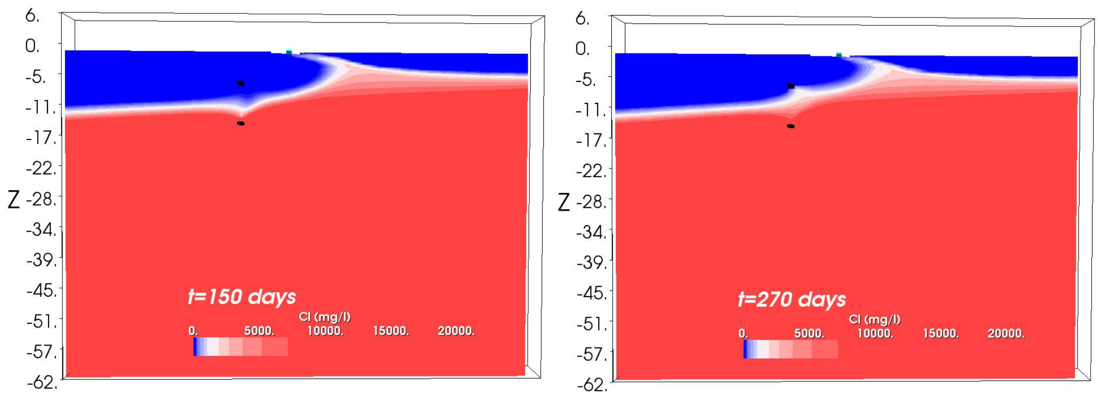


Figure 5: Results of SEAWAT modeling in a cross-section at the start and end of injection, and at the end of two recovery periods. The positions of the HDDWs are indicated by black rectangles.

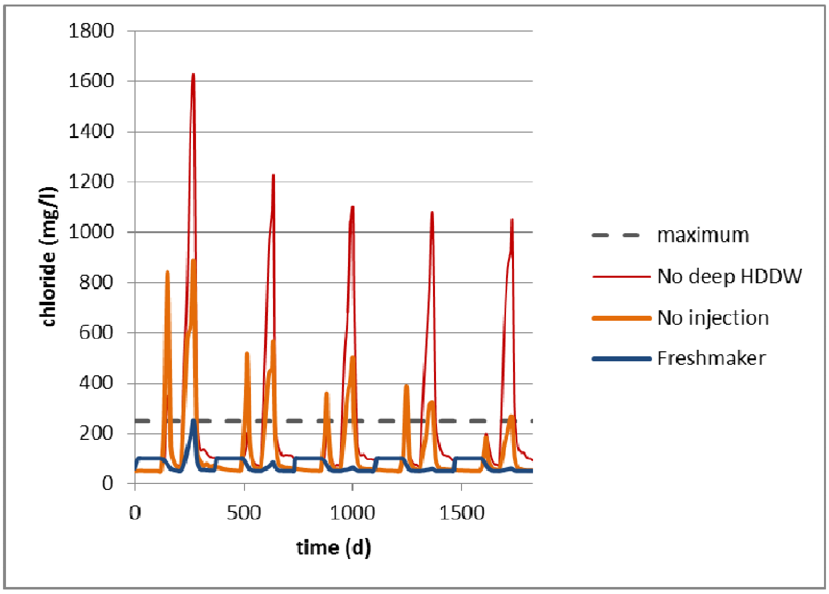


Figure 6: Chloride concentrations at the upper HDDW for the Freshmaker and scenario's without injection, or without the interception of saline groundwater by a deep HDDW.

Table 1: Modeled (yearly) ASR scheme for the Ovezande Freshmaker trial

Period	**t = (d)**	**Q_{in} (m^3/d) (HDDW1, fresh)**	**Q_{out} (m^3/d) (HDDW1, fresh)**	**Q_{out} (m^3/d) (HDDW2, saline)**
Winter (infiltration)	120	35	0	35
Spring (recovery 1)	30	0	70	35
Spring (storage)	60	0	0	35
Summer (recovery 2)	60	0	35	35
Idle	95	0	0	0
Total (m^3)		4200	4200	9450