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How Subsurface Water Technologies (SWT) can Provide Robust, Effective, and Cost-Efficient Solutions for Freshwater Management in Coastal Zones

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Abstract Freshwater resources in coastal zones are limited while demands are high, resulting in problems like seasonal water shortage, overexploitation of freshwater aquifers, and seawater intrusion. Three subsurface water technologies (SWT) that can provide robust, effective, and cost-efficient solutions to manage freshwater resources in the subsurface are evaluated using groundwater modelling and validation at field-scale: (1) ASR-coastal to store freshwater surpluses in confined brackish-saline aquifers for recovery in times of demand, (2) the Freshkeeper to counteract salinization of well fields by interception and desalination of upconing brackish groundwater, and (3) the Freshmaker to combine ASR and Freshkeeper to enlarge the volume of natural freshwater lenses for later abstraction. The evaluation indicates that SWT can be used in various hydrogeological settings for various hydrogeological problems like seawater intrusion, upconing, and bubble drift during ASR and have significant economic benefits. Although only sporadically applied to date, we foresee that SWT will stimulate (cost-)efficient and sustainable exploitation of various freshwater sources (like groundwater, rainwater, treated waste water, surface water) in coastal zones. Prolonged SWT testing in the current pilots, replication of SWT in other areas worldwide, and the development of technical and non-technical support tools are required to facilitate potential end-users in investment decision making and SWT implementation.

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1 Introduction

Coastal zones are the most densely populated, productive, and economically dominant regions of the world. About half of the world's population lives within 200 km of a coastline (United Nations 2010), and while this produces many economic benefits, the associated high water demand puts tremendous pressure on the freshwater resources and the coastal ecosystems. This leads to problems like seasonal water shortage (Fig. 1), overexploitation of groundwater resources, saltwater intrusion, and disappearance of wetlands. Further economic growth, population increase, and climate change will intensify these problems, ultimately blocking the sustainable development of coastal zones in industrial, emerging, and developing countries (European Commission 2012). In 2015, water crises were identified as the main global risk in terms of impact (World Economic Forum 2015).

Traditionally, aboveground solutions are sought for these problems, such as construction of reservoirs or saltwater desalination. However, the subsurface may provide more robust, effective, sustainable, and cost-efficient freshwater management solutions due to a better water conservation and limited space requirements aboveground. For instance, the concept of subsurface storage and/or treatment known as managed aquifer recharge (MAR) is increasingly applied worldwide for water storage and treatment (Dillon et al. 2010). In coastal zones, however, the abstraction of (stored) freshwater is generally hampered by saline groundwater, causing early salinization of simple abstraction wells due to buoyancy effects and upconing (Oude Essink 2001; Ward et al. 2009). This makes traditional well configurations vulnerable to salinization and thus application of MAR often inefficient. The same holds for exploitation of fresh groundwater lenses formed by natural recharge, which is difficult due to upconing of

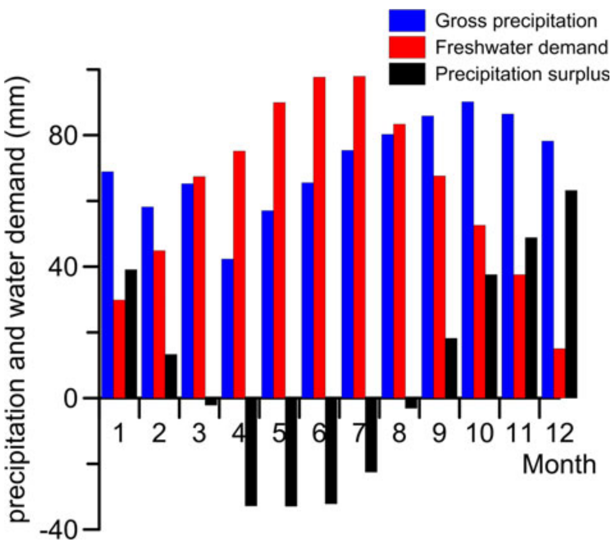

Fig. 1 Illustration of average freshwater availability and demand in a coastal area: mean gross monthly precipitation (1980–2010), estimated monthly water demand of an intensive greenhouse horticulture area (Greenport Westland-Oostland) in the Province of Zuid-Holland in The Netherlands (Paalman et al. 2012), and resulting freshwater surplus/deficit. Source: Zuurbier et al. (2013)

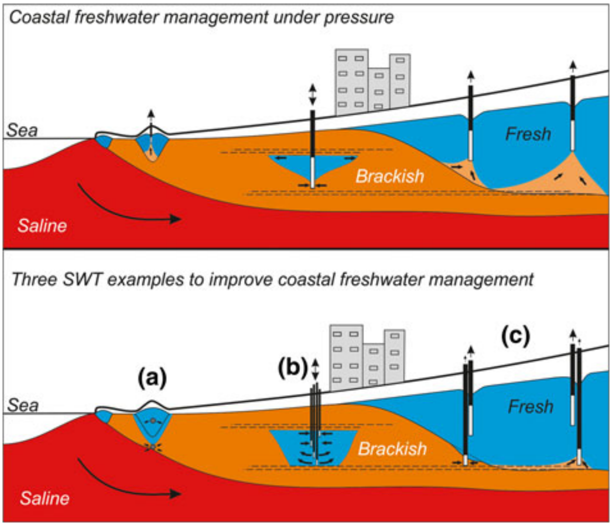

Fig. 2 Three examples of subsurface water technologies to overcome common freshwater issues in coastal aquifers, field-tested in the last 5 years. **a** = Freshmaker (horizontal wells to infiltrate in and recover from shallow freshwater lenses), **b** = ASR-coastal (deep injection, shallow recovery in brackish aquifers), **c** = Freshkeeper (interception of upconing brackish groundwater)

deeper saltwater (Fig. 2). The challenge is, therefore, to optimize the management of natural freshwater sources in the subsurface for drinking and irrigation water, thereby creating a valuable ecosystem service in coastal zones.

In the past decade, a set of practical tools and concepts that may have the ability to improve freshwater management in coastal-zone aquifers was proposed to solve irrigation and drinking water shortages in The Netherlands. The common feature of these subsurface water technologies (SWT) is to protect, enlarge, and utilize fresh groundwater resources in coastal zones through advanced groundwater management (Fig. 2). Sophisticated and dedicated new well designs, configurations, and management strategies were designed to obtain maximum control over the water resources, and go far beyond the levels of control provided by standard water management techniques. The aim of this study is to report and evaluate the efficiency of three SWT examples (summarized in Table 1) recently applied in the Netherlands, and explore their potential for solving typical freshwater management problems in other coastal zones worldwide. In a first step, the most relevant outcomes of three recently extensively studied SWT

Table 1 Typical characteristics of the different subsurface water technologies (SWT) discussed

SWT	Aim	Target conditions	Artificial recharge	Saltwater interception	Well type	Water treatment
ASR-coastal	Temporal storage	Brackish aquifers	yes	no	MPPW	Pre-treatment
Freshkeeper	Protect wellfields	Stratified groundwater quality	no	yes	PP, MPPW	Optional post-treatment
Freshmaker	Temporal storage	Freshwater lenses	yes	yes	HDDW	Pre-treatment

MPPW multiple partially penetrating wells; *PP* partially penetrating well; *HDDW* horizontal directional drilled well examples for freshwater management were presented. Secondly, common freshwater management problems in coastal areas were identified in scientific literature. Finally, the ability of SWT to counteract these typical coastal freshwater management problems was analysed and discussed.

2 Materials and Methods

2.1 Field-Testing of Subsurface Water Technologies (SWT)

2.1.1 ASR-Coastal

Aquifer storage and recovery (ASR) of freshwater using wells in coastal zones may not recover sufficient freshwater to meet the demands due to the mentioned losses by buoyancy effects. With ASR-coastal, multiple partially penetrating wells in a single borehole (MPPW, Fig. 3) are introduced, enabling injection at the base of the aquifer and recovery at the top. An ASR-coastal system with MPPW was successfully applied in a Dutch coastal greenhouse horticulture area (Nootdorp, Province of Zuid-Holland, 12 km from the North Sea coast) and reported by Zuurbier et al. (2014). Here, a brackish (chloride concentration: 150–1100 mg/l) aquifer at 13–41 m below sea level and confined by clay layers was targeted for ASR. The operation of the ASR system, the injected and recovered water quality, and the water quality changes in the aquifer were extensively monitored (Fig. 4) to provide the data to set up a calibrated, density-dependent groundwater transport model (SEAWAT; Langevin et al. 2007) and use this to compare the performance of this advanced configuration with a 'conventional' ASR configuration (Zuurbier et al. 2014). The ASR-system was monitored from January 2012 untill September 2013.

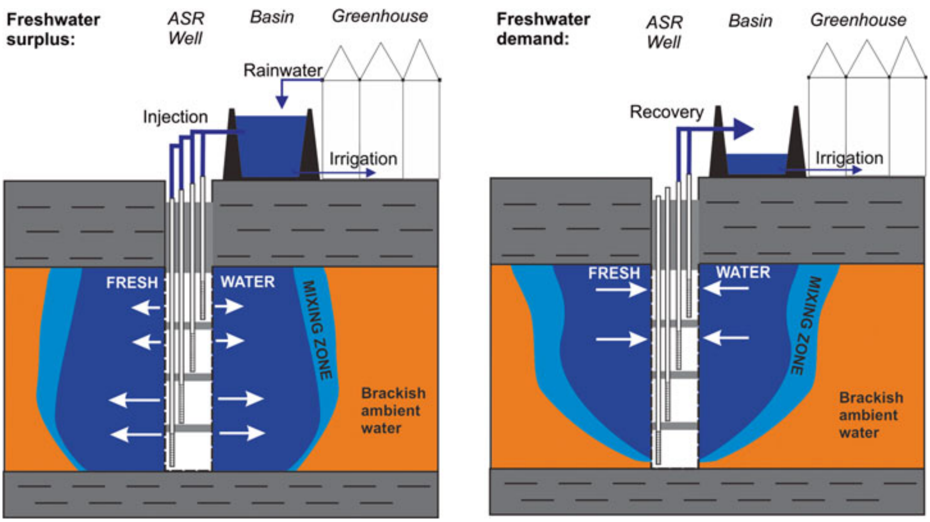

Fig. 3 Use of multiple partially penetrating wells (MPPW) for improvement of freshwater recovery of coastal ASR systems storing rainwater harvested from greenhouse roofs

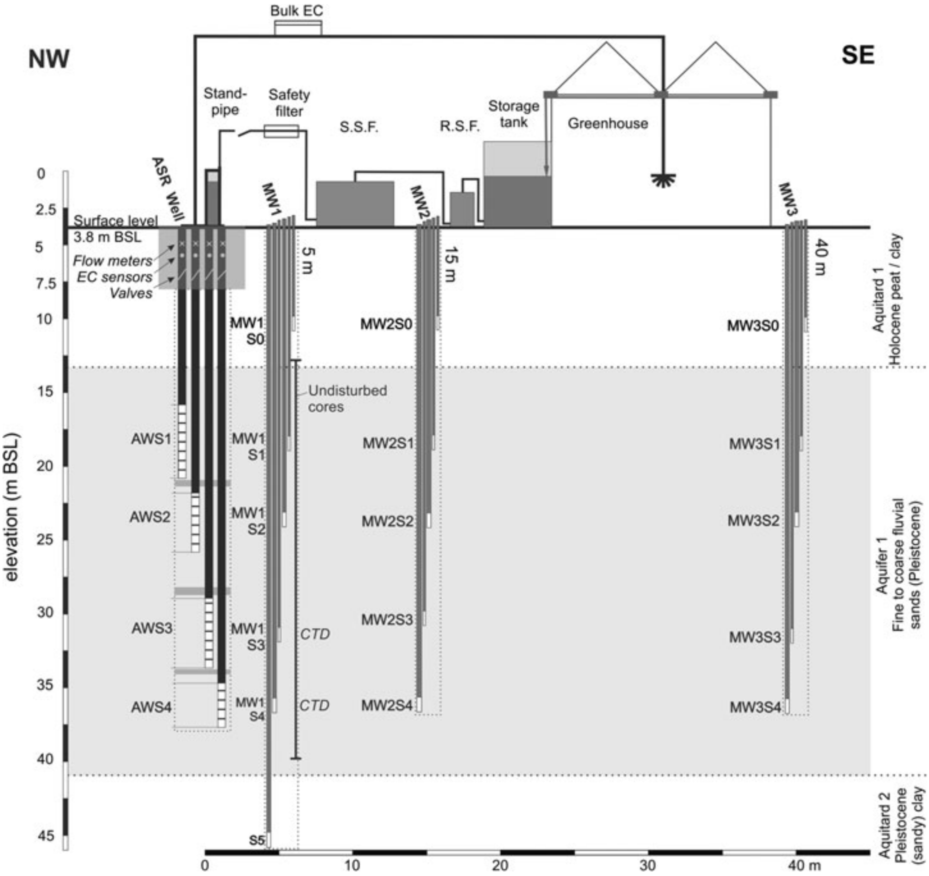

Fig. 4 Cross-section of the Nootdorp ASR system as presented in Zuurbier et al. (2014). Water from the greenhouse is first pre-treated by rapid sand filtration (R.S.F.) and slow sand filtration (S.S.F) and then injected mainly by deeper wells in the aquifer, whereas recovery occurs from the shallow wells

2.1.2 Freshkeeper

The Freshkeeper (Fig. 5) aims to safeguard the water supply from abstraction wells at risk of salinization. The concept follows a three-step approach: (1) intercept upconing brackish groundwater by abstracting freshwater from the top of the aquifer, while pumping intruding brackish water from the lower part of the aquifer; (2) use the intercepted brackish water as an additional water source by desalination through reverse osmosis; and (3) dispose of the RO membrane concentrate by deep-well injection into a confined, more saline aquifer. This 3-way approach was successfully applied in a pilot conducted at the Noardburgum well field (Province of Friesland, The Netherlands) by Vitens Water Supply (Oosterhof et al. 2013), at a well field that was abandoned in 1993 because of salinization. Shallow fresh and deeper brackish groundwater were extracted within a multiple partially penetrating well equipped with two separate well screens, at a rate of 50 m^3/h each. The focus of this pilot was on the management of the freshwater-brackish water interface and the injectivity of the RO-concentrate.

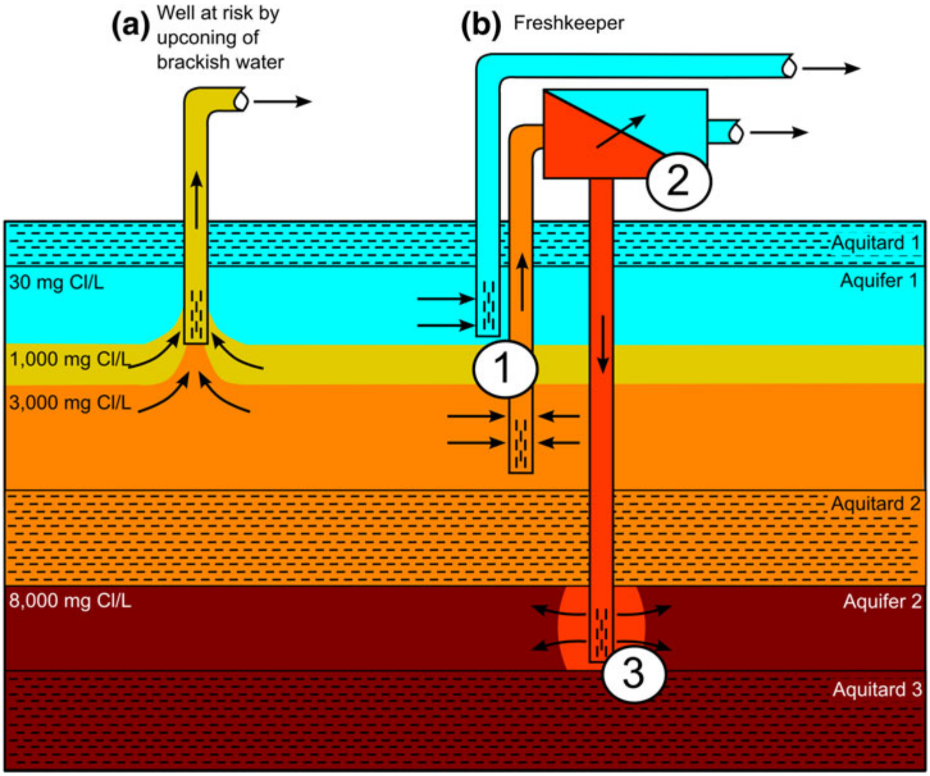

Fig. 5 Water well prone to salinization (**a**) and the Freshkeeper solution (**b**)

2.1.3 Freshmaker

It was reasoned that ASR-coastal is inefficient when target aquifers are shallow, saline, and unconfined because of severe buoyancy effects and the risk of unwanted hydrological effects. The Freshmaker technology therefore combines the ASR and Freshkeeper concepts with the use of recently developed horizontal directional drilled wells (HDDWs; Cirkel et al. 2010). With this HDDW-technology, long horizontal wells can be installed at any desired depth in shallow coastal aquifers. The horizontal wells allow for the depth-controlled injection and recovery of large volumes of freshwater and was named the ‘Freshmaker’. A shallow HDDW (the actual ‘ASR well’) is used for artificial recharge and recovery of freshwater surpluses, while buoyancy effects and upconing of saline water are prevented by the use of a deep interception HDDW (Fig. 6). The injected freshwater enlarges the natural freshwater lens along the HDDWs in periods with a freshwater surplus, and this stored water is available for recovery in periods of demand. The first Freshmaker was installed in 2013 in the coastal Province of Zeeland to supply a local fruit grower with irrigation water in Ovezande. Its efficiency was evaluated by 2-D groundwater transport modelling (using SEAWAT) and subsequently using geophysical field measurements (EM-39 borehole logging; McNeill et al. 1990), EC-sensors, and hydrochemical analyses during operation of the Ovezande field pilot. For more information on the modelling approach, the reader is referred to Zuurbier et al. (2015).

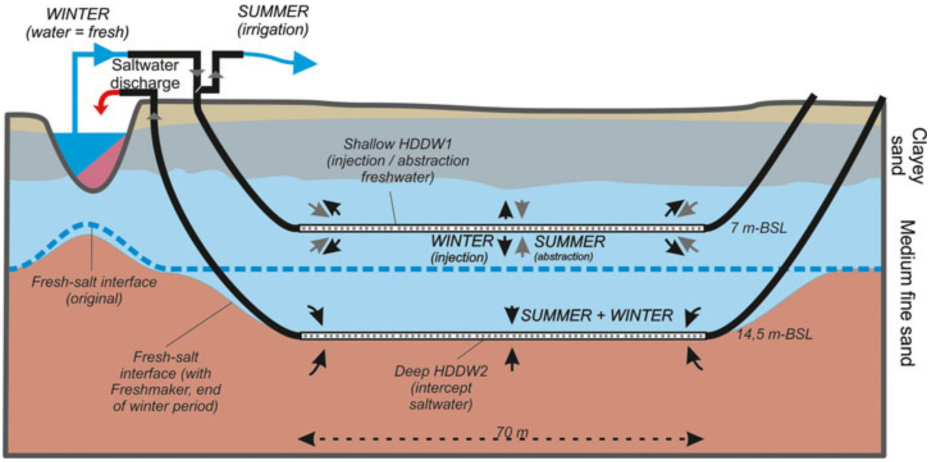

Fig. 6 Use of the Freshmaker principle to enlarge freshwater lenses. Side-view at the HDDWs. Set-up as installed at the Ovezande field-trial. m-BSL = meters below sea-level

2.2 Broader Evaluation of the Efficiency of Subsurface Water Technologies (SWT) to Improve Freshwater Management

In order to explore the (broader) applicability of SWT for freshwater management in coastal zones, its efficiency to solve five common hydrogeological problems in these areas was assessed:

- *Brackish water upconing* (Reilly and Goodman 1987): resorting from shallow abstraction from a stratified aquifer (i.e., freshwater overlying brackish/saline water);
- *Seawater intrusion* (*SWI;* Werner et al. (2013): 'the landward incursion of seawater' via the subsurface;
- *Bubble drift during aquifer storage and recovery* (Ward et al. 2009): 'injected freshwater trying to "float" upwards through the aquifer while the denser native groundwater sinks down and inwards, contaminating the well at the bottom';
- *Thin target aquifer for abstraction / storage*: this may imply a low yield per well, requiring placement of expensive well galleries with many wells and pumps;
- *Saline seepage in deep polder areas* (de Louw et al. 2010): with ongoing land subsidence, sea-level rise, and occasionally (former) peat excavations, saline seepage is a increasing problem in delta areas as it causes salinization of inland surface waters.

3 Results

3.1 Field-Testing of Subsurface Water Technologies (SWT)

3.1.1 ASR-Coastal

The Nootdorp field trial obtained satisfying results, with more than 40 % of the injected freshwater (13,700 m^3) recovered practically unmixed in the first cycle in 2012. A calibrated SEAWAT model was able to reproduce this performance, and predicted even better performance in subsequent cycles, with recovery efficiencies approaching almost 60 % (Fig. 7). This proved to be more than sufficient to guarantee freshwater availability for the greenhouse, even during long periods of drought. Alternatively, without the advanced MPPW set-up, less than 20 % was found recoverable by conventional ASR wells, according to the SEAWAT model (Zuurbier et al. 2014), which would have led to frequent freshwater shortages throughout the summer season. Compared to a situation without buoyancy effects, however, the recovery will always be lower as the formation of a stable, protecting mixing zone is absent in the lower half of the aquifer. The estimated cost price for water supplied by this ASR concept is 0.17 to 1.58 €/m^3 (Zuurbier et al. 2012), depending on the scale and recovery efficiency achieved. This makes the concept competitive with less-sustainable, alternative water sources in the area (drinking water, desalinated water: ~1 €/m^3).

3.1.2 Freshkeeper

At the Noardburgum field site, the abstracted freshwater as well as the brackish abstraction water freshened upon dual zone Freshkeeper abstraction. Chloride concentrations of the abstracted fresh and brackish water decreased in the first months of the pilot, from 45 to 35 and 1000 to 600 mg/L, respectively. Freshening not only occurred in the near surrounding of the abstracting well screens, but also in observation wells at greater distance (Fig. 8). Only the observation well screen just above the confining clay layer did not show any freshening; chloride concentrations remained stable there due to the lateral inflow of brackish groundwater.

While the goal was to stabilize the fresh-brackish water interface, the chosen operation (fresh and brackish water abstraction rates of 50 m^3/h) even provoked downconing of brackish water, which was confirmed by SEAWAT modelling (Van der Valk 2011). In the same study,

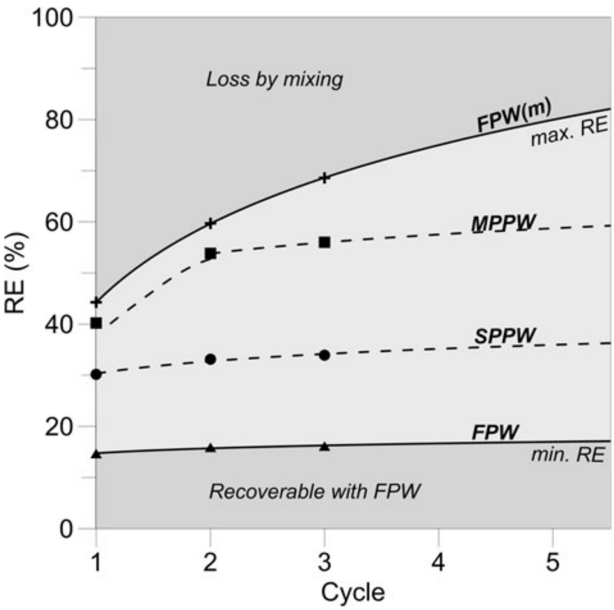

Fig. 7 Modelled RE per cycle versus cycle number for four scenarios. FPW (m) = scenario with only mixing and a fully penetrating ASR well, but no buoyancy. The other scenarios take into account mixing, seepage, and buoyancy for multiple partially penetrating wells (MPPW), a single partially penetrating well in the upper half of the aquifer (SPPW), and a fully penetrating well (FPW). Cycles 1-3 were modelled, cycle 4 and 5 were extrapolated from the modelled cycles. Data from: Zuurbier et al. (2014)

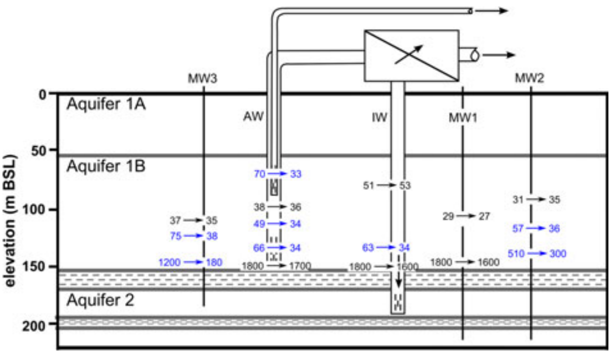

Fig. 8 Changes in chloride concentrations (in mg/l) in the source aquifer, after 8 months of simultaneous abstraction of fresh and brackish groundwater. In blue: freshening; in black: no change in chloride. AW = dual zone Freshkeeper abstraction well; IW = RO concentrate injection well; MW = monitoring well. m BSL = meters below sea-level

SEAWAT modelling suggested that the brackish water abstraction rate can be lowered to 16 m^3/h to keep chloride concentrations in the abstracted freshwater well constant at 45 mg/L.

A reverse osmosis recovery level of 70 % was attained, which was accompanied by a waste stream of 30 % containing the dissolved solids from the brackish groundwater and requiring re-injection. Although anti-scalants were not applied in the brackish water desalination process, clogging was not observed during injection of the RO concentrate in a deeper, unconsolidated, sandy aquifer. Production of calcite precipitates was not observed, which was explained by the high iron(II) levels in the feed water, inhibiting calcite precipitation (Wolthek et al. 2012). In a parallel concentrate injection experiment conducted at Zevenbergen, the Netherlands (Brabant Water Water Supply), calcite precipitation caused injection well clogging, which was later prevented by dosing CO_2 to the concentrate.

Following the successful pilot, Vitens Water Supply sees opportunities to apply the Freshkeeper at full-scale and to reopen the abandoned well field. A circular setup of six Freshkeeper wells appears to be the most effective in preventing salinization of the wells and of the central part of the well field (Van der Valk 2011). In this study, the fresh to brackish abstraction ratio was more than 3:1, i.e. for every 3 m^3 of fresh water less than 1 m^3 of brackish water needs to be abstracted. Using a RO recovery of 50 %, this would result in a yearly, sustainable production of 3 Mm^3 of drinking water (abstracted fresh water and RO permeate), while 0.43 Mm^3 concentrate is to be disposed of by deep-well injection (Oosterhof et al. 2013).

3.1.3 Freshmaker

Model Results SEAWAT modelling results suggest that the modelled Freshmaker at Ovezande should be able to keep the targeted freshwater volume of 4200 m^3 available for abstraction during at least 6 months (Zuurbier et al. 2015). In the simulation, the deepest HDDW was actively intercepting saline groundwater to lower and stabilize the freshwater-saltwater interface. The modelled chloride concentrations in the abstracted water at the shallowest HDDW (HDDW1), used for injection and recovery of freshwater, indicated that injected surface water will be abstracted in spring. Abstracted water will be mainly native groundwater from the natural freshwater lens in late summers, which is mixed with upconing saltwater at the end of Cycle 1 (Fig. 9; Scenario D). In Cycle 2–5 this simulated upconing was limited and did not impose a

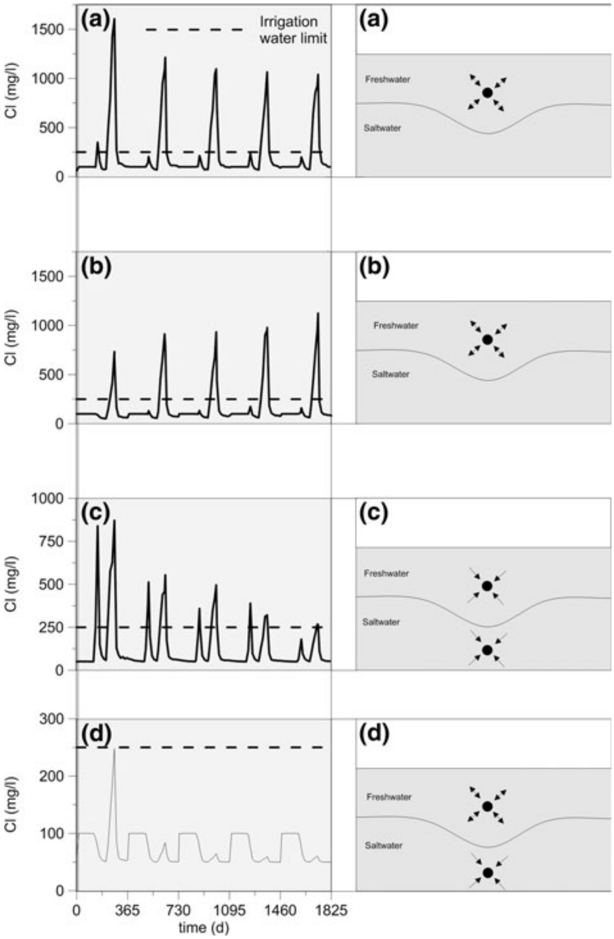

Fig. 9 Modelled chloride concentrations at the upper HDDW for upon yearly injection and abstraction of 4500 m^3 of freshwater without the interception of saline groundwater by a deep HDDW (**a**), same as (**a**), but after 1 year without recovery (**b**), with interception of deep saline groundwater but without injection (**c**), and with a complete Freshmaker (**d**). Source: Zuurbier et al. (2015)

risk for the salinity of the abstracted water. The simulation results show the upper part of the aquifer will gradually freshen, which will result in a decrease in saline seepage towards a local water course and eventually even local infiltration via the water course during freshwater recovery.

Significantly less freshwater was found to be attainable when only a shallow single HDDW is used (Scenario A), even when excessive infiltration was applied to form a 'buffer zone' of unrecovered infiltration water (Scenario B). The maximum chloride concentration for irrigation water would be exceeded after abstraction of a volume which was ~50 % of the injected volume. When a Freshmaker was installed, but no water was injected (like a Freshkeeper, Scenario C), a satisfying volume of freshwater could be abstracted from Cycle 5 onwards, due to the almost continuous interception of saltwater by the deep HDDW (HDDW2). This indicates that active injection of freshwater at this location (having a natural recharge of approximately 0.75 mm/d) is not a requirement for the abstraction of a same volume of freshwater, and that continuous interception of saltwater preceding freshwater abstraction can be sufficient.

Field Results The Freshmaker Ovezande field pilot is being executed since 2013. In Cycle 1 (June – September 2013), 1700 m^3 was injected and a same freshwater volume was successfully abstracted. In Cycle 2 (November 2013 – September 2014) 4450 m^3 was injected, and 4.400 m^3 of freshwater was abstracted by September 2014. The geophysical EM-39 measurements show that the Freshmaker indeed enlarged the freshwater lens during injection (3 to 4 m, Fig. 10), kept the freshwater at its place during storage (Cycle 1 and 2), and is able to recover a freshwater volume equal to the injected volume. The estimated cost-price for the water supplied by the Freshmaker is 0.35 €/m^3, which is less than the local alternative (piped water: 0.70 €/m^3).

3.2 Broader Evaluation of the Efficiency of Subsurface Water Technologies (SWT) to Improve Freshwater Management

Based on the outcomes and insights of the SWT field and modelling studies, the applicability of SWT to solve common hydrogeological problems and improve freshwater supply in coastal zones was evaluated. The outcomes are summarized in Table 2 and discussed below.

- *Brackish water upconing*: this process can be delayed by ASR-coastal, but full elimination cannot be guaranteed as upconing may still occur during recovery, especially when storage periods are long and deeper water is saline, which is similar to scenario A and B of the Freshmaker in Section 3.1.3. When brackish water is not desalinated or discharged from the groundwater system but only re-injected, upconing may also still threaten shallow abstraction wells in the Freshkeeper case, as recently demonstrated by Alam and Olsthoorn (2014). The Freshkeeper and Freshmaker in their presented form (injecting membrane concentrate in a deeper confined aquifer or discharging abstracted saltwater to sea) can sufficiently eliminate upconing, as demonstrated by field monitoring (Section 3.1.2) and model scenarios C and D (Section 4.1.3). For both the Freshkeeper and Freshmaker it is

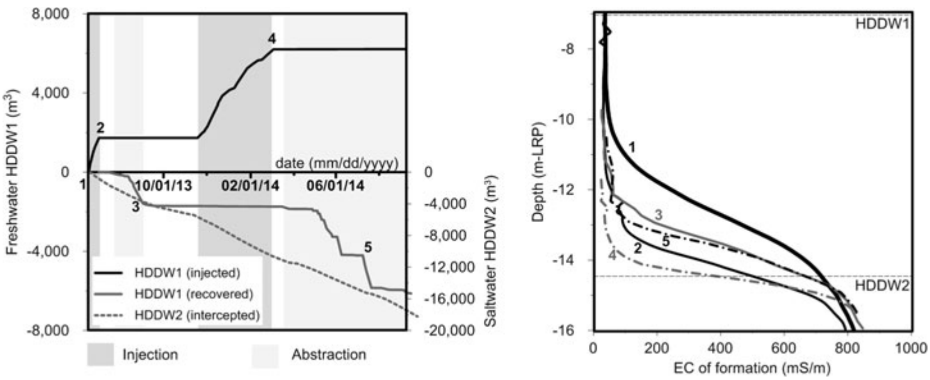

Fig. 10 Pumping by the Freshmaker (positive = injection, negative = abstraction). Changes in the electrical conductivity of the formation in the target aquifer measured by EM-39 demonstrating freshening (EC decrease) and salinization (EC increase) at the centre of the Freshmaker (halfway the HDDW well screens). Black arrows indicate the shift of the freshwater-saltwater interface over time. *m-LRP* = meters below local reference point, which is at approximately 0.4 m above sea-level. *Numbers* 1–5 indicate the moments at which EM-39 recordings were performed

Table 2 Evaluation of the efficiency of SWT concepts to counteract common hydrogeological problems

Hydrological problem	ASR-coastal	Freshkeeper	Freshmaker
Brackish water upconing	+/-	+	+
Seawater intrusion	+/-	+	+
Bubble drift during ASR	+/-	+/-	+
Thin target aquifer for abstraction / storage	-	-	+
Saline seepage	+/-	+	+

+*: Counteracting the hydrological problem*

+/-*: May counteract when boundary conditions are met*

-*: No positive effect, or even negative effect*

required that freshwater abstraction rates and saltwater interception rates are coupled: overabstraction of freshwater during limited interception of saltwater will result in upconing;

- *Seawater intrusion*: ASR-coastal may only prevent saltwater intrusion if the net injection exceeds the saltwater intrusion, making it a freshwater hydraulic barrier (e.g. Luyun et al. 2011; Mahesha 1996), with deep injection at the optimal aquifer interval (Abarca et al. 2006). One may expect, however, that the Freshkeeper and the Freshmaker can even prevent saltwater intrusion, provided that the well placement and their abstraction rates are such that the entire intruding saltwater wedge is intercepted and disposed of or desalinated. This was confirmed using density-dependent transport modelling in combination with an optimization model (Abd-Elhamid and Javadi 2011), which indicated that coupled interception and abstraction (ADR: abstraction, desalination, recharge) can then be considered most (cost-) efficient;
- *Bubble drift during aquifer storage and recovery*: ASR-coastal can reduce the freshwater during ASR, but it was shown by Zuurbier et al. (2014) that it will not lead to 100 % recovery of injected freshwater. Like for conventional ASR: the more saline the aquifer is, the lower the recovery efficiency will be. A Freshkeeper may help to recover a larger part of injected freshwater during ASR, but will also not make the system render 100 % recovery of injected freshwater (Van Ginkel et al. 2014). The Freshmaker concept appeared able to recover a volume equal to the injected freshwater volume in a saline environment (without depleting the natural freshwater lens), given that an existing freshwater lens is enlarged and natural recharge is occurring;
- *Thin target aquifer for abstraction / storage*: ASR-coastal and the Freshkeeper will be hard to apply in thin aquifers. However, the use of HDDWs in the Freshmaker case may make thin aquifers viable for abstraction/storage, since a single, high-capacity well is feasible. Approriate design of the HDDW (length, diameter, pumping rates, amongst others) is however crucial to attain a uniform distribution of the abstraction along the HDDW screen (Sun and Zhan 2006; Wang et al. 2014). At the Freshmaker trial, this was ensured by the relatively limited length of the HDDWs (70 m) and confirmed by the observed lowering of the freshwater-saltwater interface along full length the wells;
- *Saline seepage in deep polders*: ASR-coastal may freshen the diffusive seepage component sourced by shallow groundwater in the upper aquifer, but is less effective in counteracting seepage of deeper, saline groundwater via boils, which can be the largest salt contributor in polder areas (de Louw et al. 2010). The Freshkeeper concept was

previously suggested as a suitable technique to counteract saline seepage (Olsthoorn 2008; Stuyfzand and Raat 2010), although it was considered unviable when all abstracted water is directly re-injected in deeper aquifers (De Louw et al. 2007) because of hydrological effects in the surrounding areas and the required high pumping rates. This underlines that disposal or concentration of the abstracted brackish water is desirable. The Freshmaker can decrease the saline seepage in polder areas based on the modelling performed for the Ovezande field pilot (Section 3.1.3). The current set-up does not contribute to a reduction in salt load to the local surface water system, as the intercepted saltwater is disposed of at a local water course here,. Disposal of intercepted brackish-saline groundwater and membrane concentrate is therefore expected to be a key element in coastal freshwater management.

4 Discussion: Current State of Subsurface Water Technologies (SWT)

4.1 The Efficiency and Economics of the Demonstrated SWT

The presented subsurface water technologies (SWT) highlight a recent trend in hydrological engineering driven by new drilling techniques, water treatment, and automation of water supply facilities using sophisticated programming and sensors. The SWT-examples (ASR-coastal, Freshkeeper, and Freshmaker) show that despite the increasing complexity, these technologies can realize a significant increase in freshwater availability in coastal areas for a competitive cost price.

SWT will not fully overcome all the mentioned hydrological problems in all coastal zones, but can generally improve freshwater production, or as found in this study: a reduction of freshwater losses during storage of several tens of percents or the complete prevention of freshwater upconing. This has economical relevance. For instance, the greenhouse owner's water demand at the Nootdorp ASR-coastal field site requires an average recovery efficiency of approximately 40 % of the injected water. It was demonstrated that this was not feasible with a conventional ASR well (<20 %) or a shallow partially penetrating well (<35 %). The use of a MPPW at this site (with only minor additional costs for PVC pipelines, standpipes, and valves) boosted the freshwater recovery up to more than the owner's demand (55 %). Instead of investing in more expensive and less sustainable freshwater sources (in this case: desalinated or piped water), there is now a valuable freshwater surplus that can be sold to neighbouring companies with a higher demand.

In the case of the Freshkeeper (Noardburgum) an entire well field was closed and replaced following salinization in 1993. SEAWAT modelling scenarios suggest that installation of only six Freshkeeper wells in a circular set-up is sufficient to prevent salinization of the entire well-field in future (Oosterhof et al. 2013; Van der Valk 2011). Since Vitens Water Supply was looking for additional drinking water in this region, this is a cost-reducing outcome. A recent study has shown the potentials of Freshkeeper to abate salinization problems in Florida (USA), and to guarantee the long-term drinking water supply there (Ross et al. 2014). In the Florida case, a Freshkeeper was found economically much more feasible than alternative water supply options such as full-scale brackish water reverse osmosis. The exact economic benefits of SWT for other cases may vary and likewise for normal MAR-techniques, they are often hard to assess a priori due to feasibility uncertainties and the chance of under-performance (Arshad et al. 2014; Maliva 2014). However, the SWT ability to counteract reductions in freshwater production resulting from unsuitable aquifer conditions will mitigate the increase of operational expenditures, potentially compensating for higher capital expenditures.

4.2 Other SWT Examples

SWT are not limited to the field test examples presented in this paper. For instance, Van Ginkel et al. (2014) proposed an elegant concept to store freshwater in an Egyptian saline aquifer by combining freshwater storage with saltwater abstraction from below the injected freshwater, which has similarities with and can further improve the ASR-coastal concept. Alam and Olsthoorn (2014) proposed to discharge a part of the intercepted brackish water by deep Punjab scavenger wells to achieve a net freshening effect (comparable to elements of both the Freshkeeper and the Freshmaker). In 2013, the Baton Rouge Water Co. (U.S.A.) has installed a brackish water scavenger well that, similar to the Noardburgum Freshkeeper, should prevent brackish water upconing to the overlying freshwater production wells. The pumped brackish water is disposed of to the Mississippi river (Tsai 2011). Olsthoorn (2008) and Stuyfzand and Raat (2010) proposed a Freshkeeper at a polder scale, using the abstracted brackish water for drinking water production and simultaneously solving various environmental problems caused by upward seepage of nutrient-rich brackish groundwater at the same time. However, no Freshkeeper is currently operating for this purpose.

4.3 Wider Scope of Application

The SWT development and studies mentioned above suggest that although the field-tested SWT are all situated in the Netherlands, they potentially have a much wider scope of application. This is underlined by the evaluation of the SWT in this study, which shows SWT can be used to reduce or overcome very common hydrological problems in coastal zones, which are amplified by an expected exacerbation of saltwater intrusion in coastal zones by sea-level rise and changes in both recharge and evaporation due to global climate change (Oude Essink et al. 2010), which will require a more enhanced management of coastal aquifers (Werner et al. 2013). SWT fulfills the demand for more advanced management tools to deal with coastal groundwater salinization and the demand for increased freshwater storage.

Elements of the SWT discussed in this paper may also be combined. For instance, a Freshkeeper was recently added to a new field ASR-coastal system to protect shallow recovery wells and produced additional freshwater via RO-treatment. In this field pilot, clogging of the RO-membranes is monitored with large interest, since these receive a feedwater, which is a mixture of infiltrated fresh, oxic rainwater with saline, anoxic groundwater. In general, abstracted water quality is a relevant aspect when RO-treatment is involved in SWT since the chemical and physical (suspended fines, temperature) quality of water used for RO, which is abstracted close to the freshwater–saltwater transitions may vary significantly over time due to freshening, salinization, and changes in redox conditions, especially upon artificial infiltration of fresh, oxic water. Membrane selection and prevention of membrane clogging are, therefore, critical aspects when desalination via RO is incorporated in the selected SWT.

It should be noted that all current SWT examples are being tested in sandy aquifers in The Netherlands, which are dominated by intergranular flow. However, limestone aquifers are also frequently found in coastal zones, and are targeted for freshwater supply worldwide. Transport processes may differ significantly in such aquifers due to dual-porosity (Bibby

1981). This can lead to underperforming ASR-systems due to early salinization via preferential flow paths (e.g., Maliva and Missimer 2010; Missimer et al. 2002; Pyne 2005). In the same way, this may reduce the effectiveness of SWT, since flow patterns are less predictable and preferential flow paths may hamper for instance the interception of brackish-saline water by the Freshkeeper and the Freshmaker.

Disposal of concentrate produced upon desalination as applied in the Freshkeeper example may be another obstacle, as this is often not allowed on surface waters or sewage systems. Re-injection in deeper aquifers on the other hand may induce (local) groundwater salinization and is therefore under discussion. Important prerequisites for this disposal are often the salinity of the receiving aquifer and the required separation of abstraction and injection well screens by aquitards because local salinization and short-circuiting must be prevented. Since desalination in combination with deep disposal of concentrate does not directly add an additional salt mass to the groundwater system, it may be more relevant to evaluate the regional consequences of this net abstraction of H_2O from the groundwater body. A key question is then if this net abstraction is compensated by either intrusion of more saline groundwater (negative) or by recharge of freshwater (naturally or artificially). The latter is often the case when inland brackish or saline groundwater originates from former transgressions in coastal zones that are currently recharged by freshwater, while seawater intrusion is generally limited to areas close to the shore.

4.4 The Future of SWT

SWT provide a coupled solution of a natural ecosystem service with a technological approach that allows for an enhanced protection and utilization of the freshwater resources in coastal areas. The SWT described in this paper have all been developed within public-private partnerships of innovators in the water market. SWT are gaining more-and-more interest from early adopters in the Netherlands. Following the pilot described in this paper, authorities in western Netherlands now consider ASR-Coastal as an important tool serving their regional water governance, and are stimulating greenhouse owners to increase their water self-supportiveness by applying this technique. Recently, a group of farmers in southwest Netherlands have inquired for a Freshmaker feasibility study to improve the irrigation water supply in their orchards. Vitens Water Supply in the North of the country just started a follow-up Freshkeeper pilot study that should be the final step towards full-scale application in the near future.

Despite the growing interest for SWT, further uptake inside and outside The Netherlands is slowed down by a number of non-technical barriers, including a lack of: (1) demonstration of long-term viability, (2) an analysis of their hydrological effects in their surroundings, (3) knowledge of new technologies and the ability to construct and operate them, (4) capabilities upon making investment decisions, and (5) inherent conservatism due to a lacking *local* track-record of successful implementation of SWT. As a consequence, more expensive and potentially unsustainable but proven technologies are chosen for freshwater management, such as seawater desalination or restrictions on water delivery. We plea for prolonged SWT testing in the current pilots, replication of SWT pilots in other areas worldwide, and the development of technical and non-technical support tools that can facilitate potential end-users in investment decision making and SWT implementation. Such an approach will accelerate acceptance and implementation of subsurface water technologies as robust answers to freshwater resources challenges in coastal areas.

5 Conclusions

Balancing freshwater availability and demand is a major challenge in especially coastal areas. Subsurface water technologies (SWT) have transformed from idea to proven-technology in the past decade to better manage subsurface freshwater volumes. Both groundwater transport modelling and extensive field operation and monitoring of three SWT examples (ASR-coastal, Freshkeeper, Freshmaker) underline that SWT can be used to protect, enlarge, and utilize fresh groundwater resources in coastal zones for use in times of demand. For this reason, coastal aquifers that have been considered to be or have become unsuitable for freshwater supply or storage have thus become 'instruments' for coastal freshwater management. Local natural freshwater sources such as rainwater can be utilized this way without claiming large areas aboveground and reduce the need for other less sustainable sources of freshwater. SWT can also combine innovations in drilling techniques, information and communications technology (ICT) and online sensoring, and water treatment to counteract very common coastal hydrological problems like saltwater upconing, seawater intrusion, and ASR bubble drift. SWT is not necessarily a freshwater management panacea for every hydrogeological setting, but the required (increase of) water supply may become technically and economically feasibile by SWT. Prolonged SWT testing in the current pilots, replication of SWT in other areas worldwide, and the development of technical and non-technical support tools are required to facilitate potential end-users in investment decision making and SWT implementation. Such an approach will accelerate acceptance of subsurface water technologies as robust answers to freshwater management challenges in coastal zones.

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