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PAPER

Salinization and freshening by extracting fresh and brackish groundwater from transition zones: Insights from a field study in the Dutch coastal dunes and implications for freshwater extractability

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Abstract
Extracting brackish groundwater using scavenger wells beneath freshwater lenses can mitigate salinization of freshwater wells. However, disturbing the fresh–saline transition zone may induce losses from limited freshwater reserves through mixing and groundwater quality changes. A field study was conducted in the Dutch coastal dunes that combines geophysical and hydrogeochemical analyses to examine disturbances from well installation, salinity dynamics during fresh and brackish groundwater extraction, and mixing and ion-exchange processes affecting extracted groundwater quality. Fresh drilling fluid introduced during well installation primarily freshened deeper, more saline groundwater. Residual drilling fluid persisted mainly in clay seals after well development, affecting geophysical measurements. Nevertheless, applying fresh drilling fluid and clay seals improved long-term representativeness of groundwater quality monitoring by limiting ion exchange and vertical mixing within the borehole. Extracting brackish groundwater in addition to freshwater nearly tripled the 4-month freshwater extractability (from 48,000 to 142,000 m^3) at the pilot site, with limited losses owing to freshwater mixing in the brackish scavenger well (19,000 m^3). Alternatively, when extracting brackish groundwater only, the local expansion of the freshwater lens was limited relative to the estimated losses by mixing in the brackish well. Freshwater extraction triggered salinization-induced mobilization of freshwater cations (ammonium, barium, calcium, iron, and manganese). Concurrent brackish groundwater extraction stabilized extracted freshwater quality, but instead triggered ion exchange in extracted brackish groundwater. Overall, this study identifies freshwater losses and water quality changes as key design constraints for optimizing scavenger well installation and operation, aiming to increase coastal freshwater extractability.

Keywords Coastal aquifers · Drilling · Freshwater lens · Brackish groundwater extraction · Hydrochemistry

Introduction

Freshwater availability in coastal areas is often limited to fresh groundwater lenses that are replenished by natural recharge (Stoeckl et al. 2015; Tang et al. 2021). The recharged freshwater floats on denser ambient saline groundwater, with a brackish mixing zone in between. Excessive extraction of fresh groundwater from coastal aquifers results in shrinkage of freshwater lenses and may lead to salinization of wells by upconing (e.g., Reilly and Goodman 1987; Werner et al. 2009). This often leads to the abandonment of wells, as it takes a long time for wells to be reusable after salinization (Zhou et al. 2005; Van Camp et al. 2014). The vulnerability of coastal regions to saltwater intrusion is further amplified by sea-level rise and changes in natural recharge patterns (Ferguson and Gleeson 2012; Fahs et al. 2022; Zamrsky et al. 2024). Simultaneously, freshwater demands increase as coastal urban areas continue to experience rapid population growth and economic development (Vörösmarty et al. 2000).

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Various managed aquifer recharge (MAR) techniques have been applied for decades to prevent or halt salinization of aquifers and increase freshwater availability. These include infiltration of freshwater via surface spreading basins (e.g., Vandenbohede et al. 2008) and direct injection of freshwater through wells (e.g., Roosma and Stakelbeek 1990; Ortuño et al. 2012). However, even with a long-term balance between freshwater replenishment and extraction, temporary mismatches, such as recharge interruptions (e.g., Stuyfzand and Van der Schans 2018), can still trigger upconing and well salinization. This risk can be mitigated by installing a scavenger well (Fig. 1), i.e., a deeper extraction well that creates a hydraulic barrier and intercepts upconing brackish or saline groundwater before it reaches freshwater well screens (e.g., Alam and Olsthoorn 2014; Khadra et al. 2017).

Scavenger wells are installed to increase freshwater extractability, and may also reduce lateral outflow of freshwater at the boundaries of the freshwater lens (Fig. 1) by lowering the seaward gradient of freshwater heads (Gao et al. 2024). However, their installation and operation may disturb the fresh–saline transition zone, causing unintended volumetric freshwater losses through mixing. Drilling wells across a transition zone already disrupts the local native salinity profile, especially when uncased drilling techniques are applied and drilling fluids are introduced into the aquifer (Nienhuis et al. 2010). These drilling-induced disturbances are well recognized, but the influence of drilling fluid composition on the extent and persistence of these disturbances are not fully understood. Subsequently, groundwater extraction within or near a transition zone alters the distribution of fresh, brackish, and saline groundwater (Stein et al. 2019, 2020), with increased mixing of freshwater either in the aquifer or well. Disturbances across the fresh–saline transition zone may alter the groundwater composition beyond conservative mixing by triggering ion exchange (e.g., Russak et al. 2016; Sola and Vallejos 2022) and increase the risk of aquifer or well clogging (e.g., Goldenberg et al. 1983).

Previous studies on brackish or saline groundwater extraction focused on the potential to protect freshwater extraction wells (e.g., Saravanan et al. 2014) without considering the associated unintended losses of freshwater by water quality changes due to mixing or cation exchange. These losses are particularly critical in systems with limited freshwater replenishment, like freshwater lenses. Moreover, earlier research has explored hydrogeochemical dynamics of brackish transition zones in relation to long-term freshwater infiltration (Stuyfzand 1993) and to temporal variations in recharge and saline seepage (Eeman et al. 2017). However, the hydrogeochemical impacts of installing and operating wells in fresh–saline transition zones remain underexplored, particularly in relation to mixing losses and extracted groundwater quality. Prior to this study, the effects of drilling-induced disturbances, extraction-driven salinity dynamics, and hydrogeochemical processes were not jointly

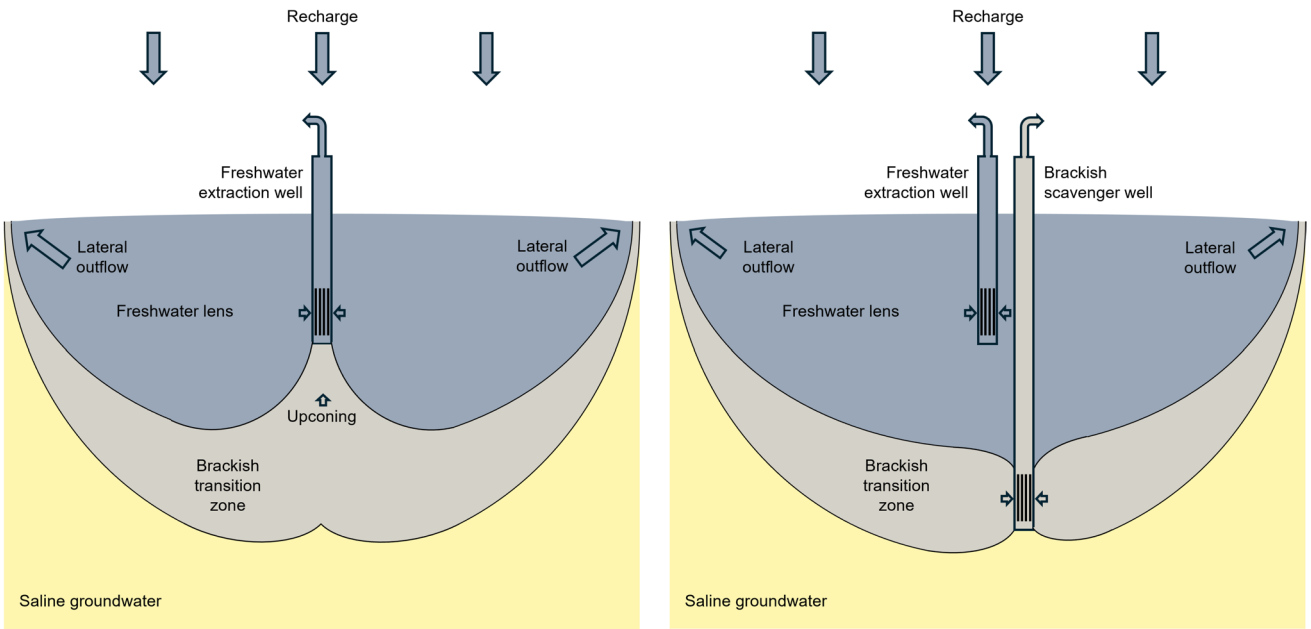


Fig. 1 Conceptual schematic of a recharge-fed coastal freshwater lens with **a** only a freshwater extraction well and **b** a combined system with a freshwater extraction well and a deeper brackish scavenger well, illustrating the impact of both pumping strategies on the distribution of fresh, brackish, and saline groundwater

evaluated, nor their combined implications for scavenger well design and operation.

This study is based on a field pilot conducted to investigate groundwater extraction from a fresh–saline transition zone beneath the Dutch coastal dunes, and uses both geophysical and hydrogeochemical analyses to address three objectives:

1. Assess the disturbances of the native salinity distribution introduced during the installation of extraction wells across the fresh–saline transition zone, including lingering effects of drilling fluid intrusion and implications for groundwater quality monitoring.
2. Evaluate the salinity dynamics induced by different extraction scenarios for fresh and brackish groundwater, and determine their consequences for freshwater extractability and mixing losses.
3. Characterize mixing and ion-exchange processes, and assess their effects on the quality of both fresh and brackish groundwater extracted with wells.

Materials and methods

Hydrogeological setting

Drinking water utilities in the Dutch coastal dunes have recharged pretreated river water through infiltration ponds since the 1950s. This approach was adopted to recover from overexploitation, but is now used to sustain the freshwater volume stored in the unconsolidated aquifer system and to prevent future salinization of fresh groundwater extraction wells (Stuyfzand 1993). The recharged water is extracted with shallow wells for drinking water production after aquifer passage. Maintaining an annual water balance between replenished and extracted volumes is generally achievable by the drinking water utilities; yet, replenishment may be interrupted temporarily, e.g., when the river water quality is inadequate for infiltration (Stuyfzand and Van der Schans 2018). The lowering of phreatic groundwater levels caused by continued extraction can be mitigated by shifting to deeper wells, which are more susceptible to salinization. This study examines whether brackish groundwater extraction can mitigate the risk of well salinization. A field pilot was conducted at the primary production location of drinking water utility Dunea in Scheveningen, near The Hague (The Netherlands) (Fig. 2).

At the pilot site, the aquifer system consists of unconsolidated Pleistocene and Holocene sediments (Fig. 3). The phreatic aquifer comprises the first 15 m of the subsurface, overlying two clay layers that form the first aquitard. Coarse sands form the second aquifer at depths between 25 and 40 m below sea level (m bsl). Both this aquifer and the phreatic aquifer contain freshwater and are used for drinking water production. The underlying 5–10-m-thick aquitard consists of dense clays and fine sands. A third aquifer is present from ca. 50 to 105 m bsl with a few intermittent

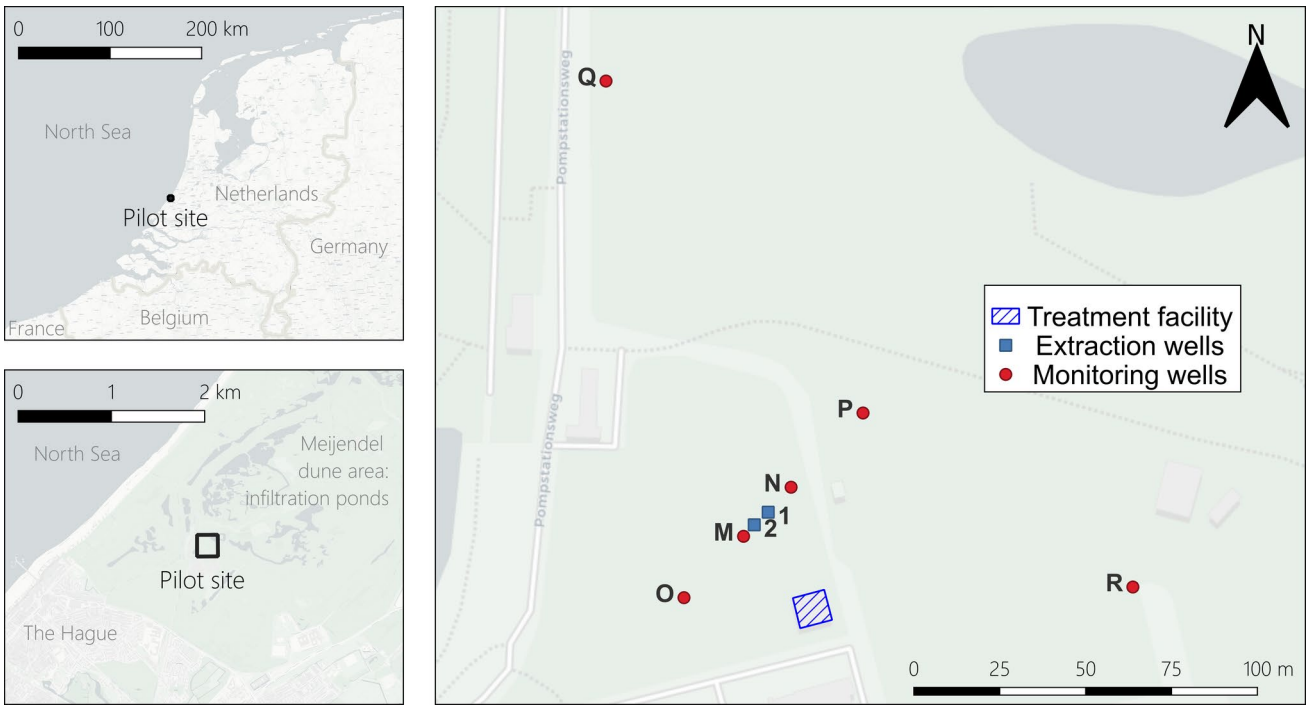


Fig. 2 Map of the well field installed for the extraction pilot near the city of The Hague and the infiltration ponds in the Meijendel dune area (the Netherlands), including two central extraction wells (1 and 2) and six surrounding monitoring wells (M–R)

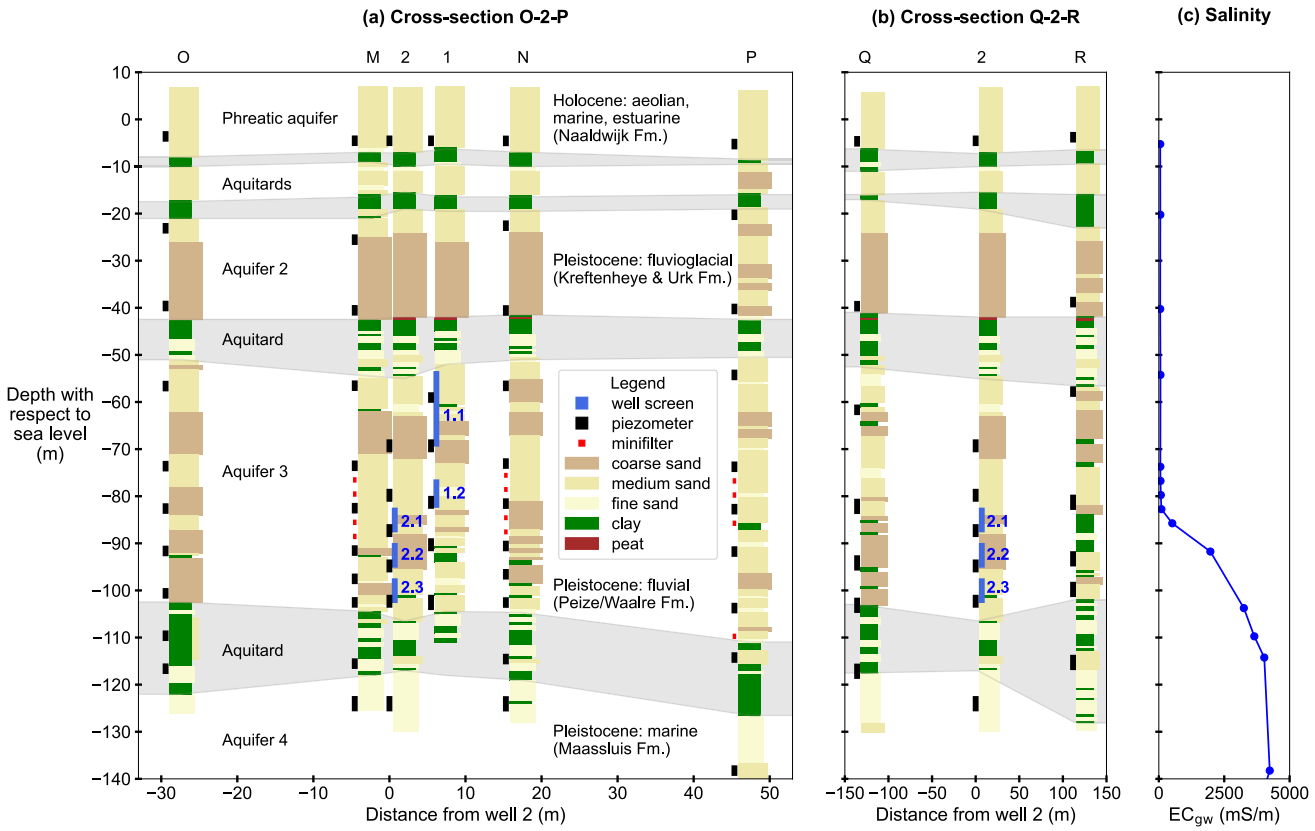


Fig. 3 Hydrogeological setting at the pilot site along cross-sections through wells O, M, 2, 1, N, and P (**a**) and Q, 2, and R (**b**) (Fig. 2), and electrical conductivity of groundwater (EC_{gw}) observed in well P in September 2021 (**c**). Extraction well screens 1.1, 1.2, 2.1, 2.2, and 2.3 are indicated in blue (**a**–**b**)

discontinuous clay layers. The top part of this aquifer contains freshwater, followed by a brackish transition zone from ca. 83 to 102 m bsl. Groundwater is saline at greater depths. An aquitard located between ca. 105 and 120 m bsl forms the bottom of the third aquifer and consists of an alternation of clays and fine sands with shell fragments.

Well field

The pilot well field consists of two extraction wells (1 and 2) surrounded by six monitoring wells (M–R; Fig. 2). All extraction and monitoring wells were equipped with multiple piezometers with 1- to 2-m-long screens at different depths for multilevel sampling (Fig. 3). The piezometers were installed with internal diameters of 36–57 mm, except for the deepest piezometer of each well, which was installed with a diameter of 68 mm to allow for periodic geophysical logging. Four additional monitoring screens (0.3 m long, 36 mm in diameter) were installed in wells M, N, and P for more specific water quality analyses. These 'minifilters' were fitted with 4-mm-diameter risers, which limited the potential for their development after installation and flushing prior to sampling. Each monitoring well was equipped with a single electrode cable for geoelectrical resistivity measurements (GEM), containing 13 electrode pairs spaced 3 m apart along the cable, with 20 cm between the electrodes of each pair. These cables were installed to cover the complete transition zone for electrical resistivity measurements. The extraction wells were equipped with two GEM-cables to double the vertical resolution.

Extraction well 1 was equipped with two well screens (1.1 and 1.2) in the fresh part of the third aquifer (Fig. 3). Well screen 1.1 was screened from 54 to 69 m bsl, with an unscreened section between 59.5 and 64 m bsl to cover a local clay layer, while 1.2 was screened from 77 to 82 m bsl. Extraction well 2 was equipped with three 4-m-long partially penetrating well screens (2.1, 2.2 and 2.3) in the brackish transition zone from 83 to 102 m bsl (Fig. 3). The extraction screens were backfilled with 1.0–1.6 mm sand and separated by 1-m-thick clay seals. Each well screen was equipped with a frequency-controlled pump (Grundfos) and connected to a treatment facility through separate pipelines for desalination by reverse osmosis. Each pipeline was equipped with sensors for flow (Endress + Hauser Proline Promag W 400 HART) and electrical conductivity (Endress + Hauser Memosens

CLS82D) to monitor the extraction rate and salinity of the extracted groundwater continuously.

Drilling, backfilling, and developing wells

The wells were installed by uncased rotary circulation drilling to accommodate the relatively large borehole diameters (500–1000 mm) and depths (120–140 m) required for the desired monitoring equipment. Borehole diameters were tapered to 400–500 mm at depth while drilling. First, an exploratory well was drilled in February 2020 to a depth of 204 m bsl (well P; Figs. 2 and 3). Monitoring results obtained from this well guided the installation of the remaining wells about 1.5 years later.

For drilling, aboveground containers were filled with 27 m^3 of drinking water as initial drilling fluid (Fig. 4). The drilling fluid mixed with the drilled sediments and groundwater from the borehole and was recirculated through a 127-mm-diameter drilling string back into the containers, allowing suspended solids to settle. This sediment was regularly removed from the containers. Borehole stability was ensured by maintaining a borehole pressure roughly 1 m above the land surface and adding drinking water to the containers to compensate for the loss of drilling fluid to the aquifer, which amounted to 150–690 m^3 for each well. The electrical conductivity of the drilling fluid (EC_{df}) was monitored at the entrance to the borehole (Hanna Instruments HI 98195), along with the electrical conductivity and volume of the drinking water (EC_{dw} and V_{dw}) added to the containers (Fig. 4), to track the position of the fresh–saline transition zone during drilling.

After drilling, the boreholes were backfilled and equipped with monitoring tools. Bentonite clay seals were applied at clay layers and between piezometer and well screens to prevent short-circuiting. The electrical conductivity, pH, temperature (Hanna Instruments HI 98195), and volume of the water extracted from individual piezometers were monitored during subsequent well development. Development continued until the salinity and turbidity of the extracted groundwater stabilized. Approximately twice the volume of water was extracted from each well during development of piezometers compared to the total volume of drilling fluid that had entered the borehole.

Groundwater extraction

After establishing the well field, two extraction experiments were conducted (Fig. 5). The first experiment aimed to increase the fresh–saline transition zone depth by extracting brackish groundwater continuously for 1.5 years with the three well screens in well 2 (Fig. 3). The relative contribution of each well screen was adjusted periodically to increase the flow-average extraction depth. In total, 586,000 m^3 of brackish groundwater was extracted during this experiment. The second experiment evaluated the potential of brackish groundwater extraction as a strategy to protect freshwater extraction wells. Fresh groundwater was first extracted with well screen 1.1 for 4 months after a 3-month idle period to assess how much freshwater can be extracted without salinization (Figs. 3 and 5). The extraction rate was stepwise increased to a rate that was still only about 0.5% of the water utility's total freshwater extraction in the coastal dunes. Brackish groundwater was subsequently extracted for

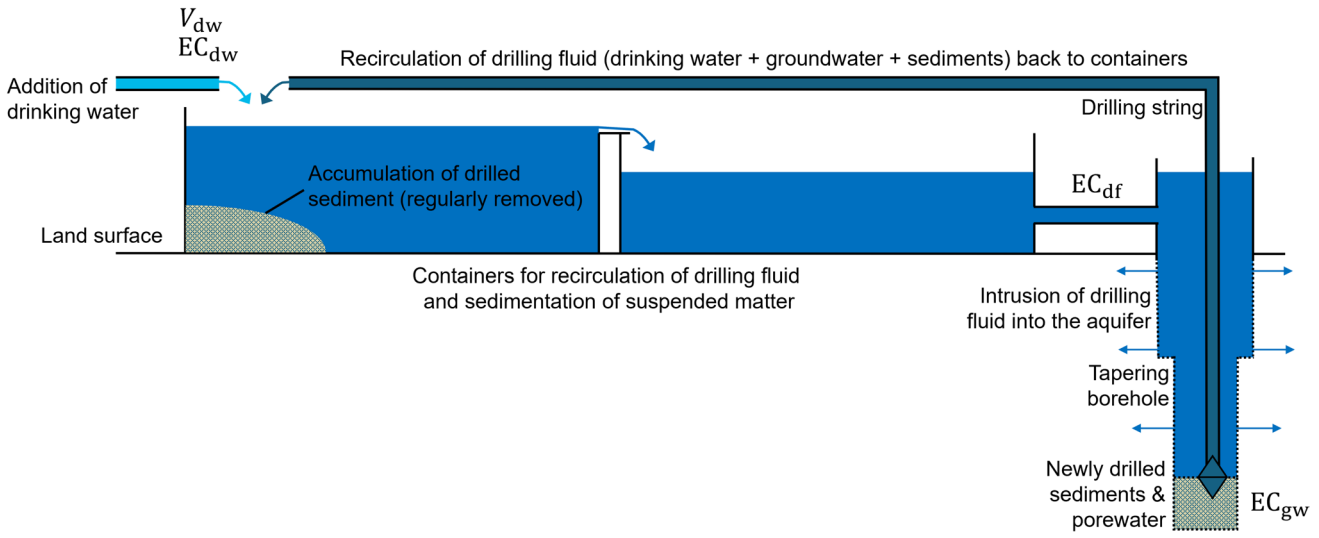


Fig. 4 Schematic overview of the application and recirculation of drilling fluid during well installation, with V_{dw} and EC_{dw} representing the volume and electrical conductivity of drinking water added to the containers, EC_{df} representing the electrical conductivity of recirculating drilling fluid measured right before entering the borehole, and EC_{gw} representing the electrical conductivity of ambient groundwater

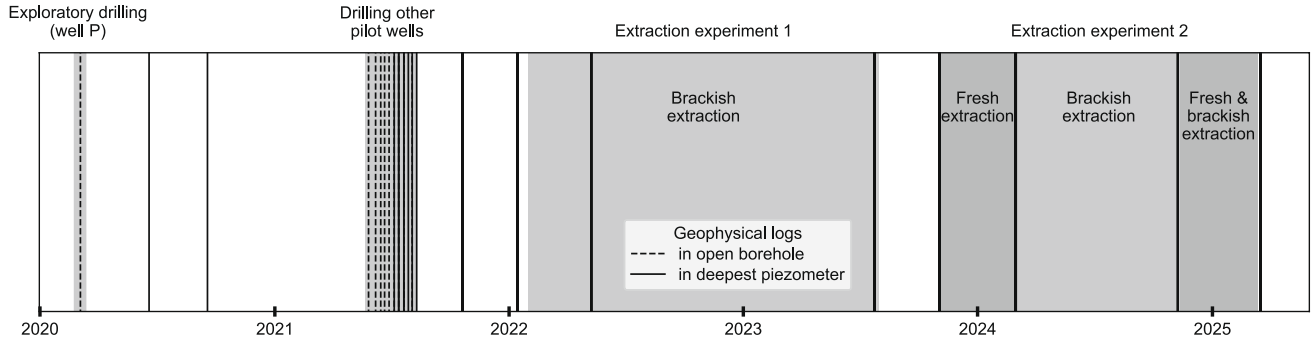


Fig. 5 Timeline of well installation, extraction experiments, and geophysical borehole logging

8 months to restore the aquifer's salinity distribution, preparing for a 4-month phase of concurrent fresh and brackish groundwater extraction. In this last phase, freshwater extraction was identical to the previous phase, while progressively shallower screens (2.3, 2.2, 2.1, and 1.2; Fig. 3) were used for concurrent brackish groundwater extraction to improve protection against salinization of well screen 1.1.

Geophysical measurements

After each drilling, the natural gamma radiation and bulk electrical conductivity (EC_{bulk}) of the surrounding sediment and groundwater were logged from the open borehole (9512 Slim Hole Induction Tool, Century) to infer the lithology and salinity distribution and to determine suitable placement of piezometer and well screens. The bulk electrical conductivity was also logged repeatedly in the deepest piezometers after well completion. Wells 1, 2, M, and N were logged both before and immediately after well development to determine the impact of well development on the salinity distribution (Fig. 5). All pilot wells were logged just before extraction started, again after 3.5 and 18 months of the first extraction experiment, and at the end of the three phases of the second extraction experiment to determine the effect of groundwater extraction on the salinity distribution (Fig. 5).

Geoelectrical resistivity measurements (GEM) were conducted at least once every 2 weeks with the electrode cables. The measured resistivity (ρ_{GEM} in Ω m) was corrected from the groundwater temperature ($T_{gw} \approx 12$ °C) to a reference temperature ($T_{ref} = 20$ °C) using a temperature constant (α_T) of 0.02 1/°C, and converted to bulk electrical conductivity (EC_{bulk} in S/m) following Hayashi (2004):

$$EC_{bulk} = \frac{1}{\rho_{GEM}\left(1 + \alpha\left(T_{gw} - T_{ref}\right)\right)} \quad (1)$$

Several electrode pairs of the GEM-cables were positioned adjacent to piezometer screens, allowing the bulk electrical conductivity (EC_{bulk}) to be compared with the electrical conductivity of simultaneously sampled groundwater (EC_{gw}). These pair-specific relationships (formation factors) were subsequently used to estimate groundwater electrical conductivity (EC_{gw}) from resistivity data (ρ_{GEM}) at times without available water quality analyses. The average correlation determined for electrode pairs within 0.25 m of piezometer screen centers was used for electrode pairs lacking nearby piezometers or having only a single corresponding water quality sample. This methodology provided a high temporal and spatial resolution of the electrical conductivity in the well field.

In total, 24,869 resistivity measurements were conducted since completion of the well field, using two Chauvin Arnoux CA 6460 Earth Testers (0.5–2000 Ω), modified to enable selection among 13 different electrode configurations. A low battery value during eight measurement rounds potentially affected 936 recordings. In addition, 88 measurements were reported as negative or zero, 59 measurements yielded implausible values of 1 or 2, and 92 individual measurements exhibited abrupt changes by a factor of at least 1.5 compared to the preceding and subsequent round for the same electrode pair, which were not related to operational changes. These anomalies were potentially due to manual transcription errors or improper connection of the GEM-cable to the device. These 1175 measurements (~5%) were therefore excluded from further analysis.

Water quality analysis

The piezometers in well P were sampled monthly for chemical analysis before the installation of the other wells to assess the impact of the exploratory drilling on the groundwater quality. All piezometers were sampled after installation of the complete well field and right before the onset of the extraction. Selected piezometers, primarily in the central wells 1, 2, M, and N (Fig. 3), were sampled during and after each extraction phase to evaluate induced water quality changes. Groundwater extracted with the individual well screens was also sampled frequently.

Each piezometer was purged with 3 times the combined volume of the riser and screen before sampling. Most piezometers required a submersible pump for sampling because hydraulic heads were low (< 8 m). The sampling flow rate remained below 500 mL/min. A flow-through cell was used for field measurements of electrical conductivity (WTW Cond 3110), pH (WTW SenTix 41 or 81), temperature (TLC 1598, Testo 104, Testo 106, or TFX 410), and dissolved oxygen (Hach HQ30D). Water for laboratory analyses was collected without filtration and cooled directly to 5 ± 3 °C.

Laboratory analyses included electrical conductivity (500 mL, WTW Cond 7310), chloride concentration (100 mL, Thermo Fisher Gallery plus discrete analyzer), and turbidity (500 mL, Hach TU5200). More detailed water quality analyses were conducted on selected samples only. Alkalinity was determined by titration (500 mL, Metrohm 848 Titrino Plus). The concentrations of ammonium, silicate, orthophosphate, and sulphate were determined with a spectrophotometer (100 mL, Thermo Fisher Gallery Plus Discrete Analyzer). Total metal concentrations were analyzed using ICP-MS (Thermo Fisher iCAP RQ ICP-MS) after acidifying 100-mL samples with 0.55 mL of 22% nitric acid (pH ≤ 2). Dissolved organic carbon (DOC) was measured with a total organic carbon analyzer (Shimadzu TOC-LCPH) after acidifying 250-mL samples with 1 mL of sulfuric acid (2 mol/L). Samples with elevated salinity required dilution prior to analysis of sulphate, DOC, and metals.

Salinity was determined from 788 samples, and more detailed analyses were conducted on 451 of them. Ionic balance errors greater than 15% occurred in 13 out of 451 samples, associated primarily with inconsistent concentrations of sodium and magnesium in brackish and saline groundwater. In addition, one sample obtained on 28 November 2023 and 14 samples obtained between 24 and 30 April 2024 were concluded to have been insufficiently acidified after possible contact with air. All analyses of these 28 samples (~ 6%) were therefore excluded from further analysis.

Determination of the deviation from conservative mixing

Conservative mixing between fresh and saline groundwater was the primary process considered for observed water quality changes, with chloride transport assumed to be conservative. Samples taken from piezometers 5 (ca. 73 m bsl) and 17 (ca. 138 m bsl) of the exploratory well (P) at the end of the brackish groundwater extraction were selected to represent the fresh and saline endmembers (Appendix Table 1), with corresponding chloride concentrations of 1.29 mmol/L ($[Cl^-]_{fw}$) and 467 mmol/L ($[Cl^-]_{sw}$). This well had the most time to equilibrate after installation and the salinity at these piezometer screens remained fairly constant during groundwater extraction. The water quality of the selected saline endmember is representative of diluted seawater with respect to most major ions (chloride, calcium, magnesium, potassium, sodium, and sulphate).

Deviations in parameter concentrations relative to conservative mixing between the fresh and saline endmembers were attributed to additional hydrogeochemical processes. The deviation (Δm) of the concentration of a specific parameter in any given sample relative to the concentration expected from conservative freshwater–saltwater mixing was determined as (Appelo and Postma 2004; Sola and Vallejos 2022):

$$\Delta m = m_{sample} - m_{mix} = m_{sample} - \left(m_{sw} - (m_{sw} - m_{fw}) \frac{[Cl^-]_{sw} - [Cl^-]_{sample}}{[Cl^-]_{sw} - [Cl^-]_{fw}} \right) \quad (2)$$

where $[Cl^-]_{sample}$ is the chloride concentration in the sample and m_{mix} the expected concentration of parameter m based on conservative mixing. The actual concentrations of parameter m in the sample, the freshwater endmember and the saltwater endmember are denoted as m_{sample}, m_{fw} and m_{sw}, respectively. All concentrations are expressed in mmol/L. A negative Δm indicates a deficit (i.e., removal from solution), while a positive Δm indicates a surplus (i.e., mobilization) of the parameter relative to the concentration expected from conservative mixing. The relative deviation (Δm_{rel}) was used to compare deviations of different parameters with each other:

$$\Delta m_{rel} = \frac{\Delta m}{m_{mix}} \quad (3)$$

The relative contribution of a parameter to the total composition of a sample (f_m) was characterized by its concentration (m_{sample}) in mmol/L relative to the total concentration of measured cations and anions in mmol/L:

$$f_m = \frac{m_{sample}}{\sum \text{cations} + \sum \text{anions}} \quad (4)$$

Results

The installation and operation of the pilot wells resulted in various intended and unintended disturbances of the salinity profile and groundwater quality. The different aspects and parameters that were affected are described here.

Disturbance of the salinity profile during drilling and restoration following well development

The electrical conductivity of the recirculating drilling fluid (EC_{df}) remained low and fairly stable while drilling through the top two aquifers, as the electrical conductivity of the added drinking water (EC_{dw}; 51–56 mS/m) was similar to that

of ambient fresh groundwater (EC_{gw}; Fig. 6). The electrical conductivity of the drilling fluid (EC_{df}) gradually increased below a drilling depth of about 105 m bsl, up to approximately 100–150 mS/m at 130 m bsl. This maximum electrical conductivity was about 40 times lower than that of the ambient groundwater ($EC_{gw} \approx 4000$ mS/m at 110–130 m bsl; Fig. 6c) owing to mixing with the relatively large volume of fresh drilling fluid already within the borehole and containers. In addition, the increase occurred about 30 m deeper than the actual steep salinity increase at 80 m bsl in the ambient groundwater (EC_{gw}; Fig. 6a, c). The ambient electrical conductivity profile (ECgw) was used as a reference in an attempt to reconstruct the observed electrical conductivity of the drilling fluid (EC_{df}). For this, transport of groundwater and sediment via the drilling string to the containers (Fig. 4) was modeled with a depth-dependent time lag using plug flow (EC_{gw+lag}). Moreover, water mixed instantaneously with the drilling fluid and drinking water additions in the containers ($EC_{gw+lag+dil}$), with the mixing volume of the containers being corrected for sediment removal during drilling (Fig. 4). Based on this approach, about 10 m of the observed discrepancy between EC_{gw} and EC_{df} can be accounted for by the lag in the transport of sediments and porewater through the drilling string to the aboveground containers (Fig. 6a, c; EC_{gw+lag}). An additional discrepancy of 15 m can be attributed to the subsequent dilution of the porewater with the drilling fluid and drinking water additions in the containers (Fig. 6a; $EC_{gw+lag+dil}$). The amount of sediment removal from the containers mainly governed the extent of dilution (Fig. 6a). The remaining discrepancy of 5 m is most likely due to more gradual rather than instantaneous mixing in the containers and the borehole, as well as immediate mixing of porewater and drilling fluid in the borehole prior to entering the drilling string.

The relatively fresh drilling fluid intruded into the deeper, more saline parts of the subsurface, causing the bulk electrical conductivity (EC_{bulk}) observed right after well completion to be lower than that recorded in later borehole logs (Fig. 7a). The bulk electrical conductivity measured in the open borehole within the shallower fresh groundwater range

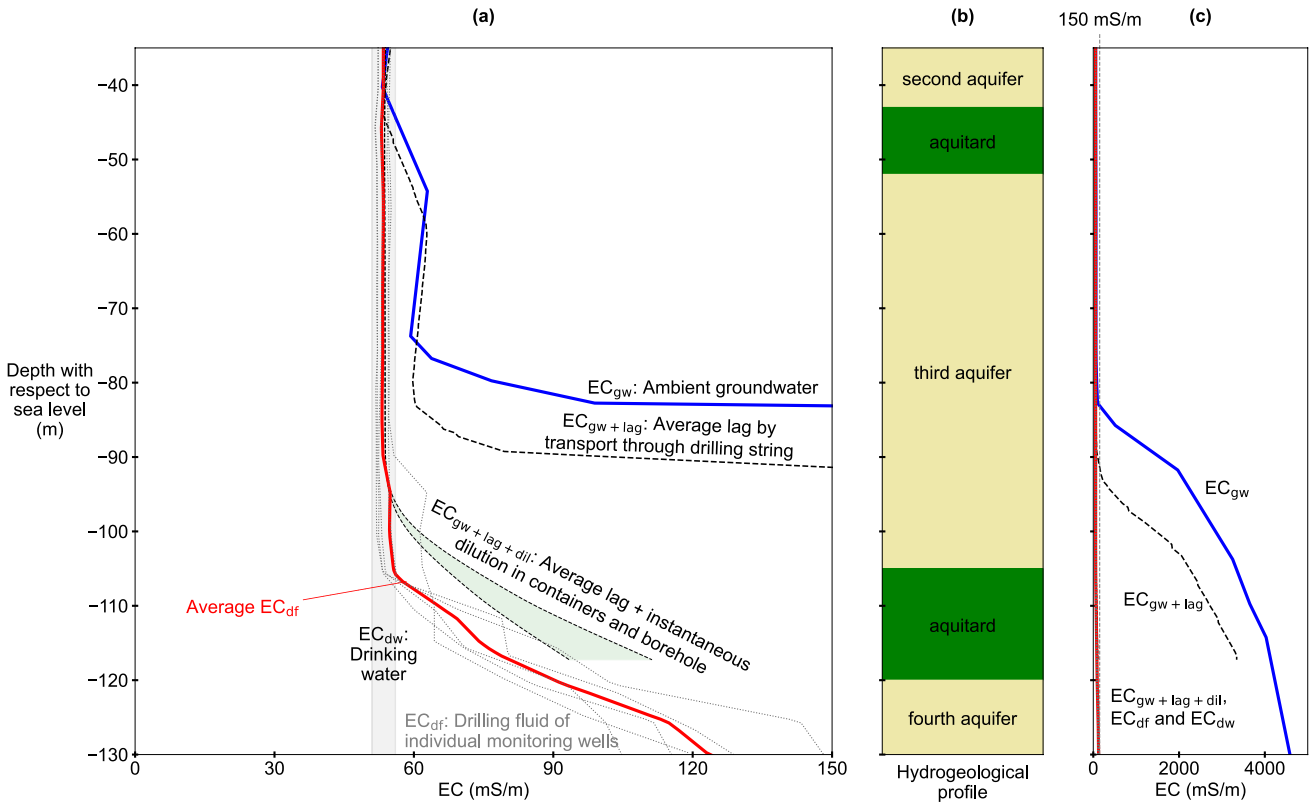


Fig. 6 **a** Depth profile of the electrical conductivity of recirculating drilling fluid (EC_{df}) observed in monitoring wells M, N, O, Q, and R (grey and red) and of ambient groundwater (EC_{gw}) observed in well P in September 2021 (blue). The profiles reconstructed from EC_{gw} accounting for the lag by transport through the drilling string (EC_{gw+lag}) and subsequent instantaneous dilution with the drilling fluid in the containers and the borehole ($EC_{gw+lag+dil}$) are shown with dashed lines. The green bandwidth represents the range reconstructed for direct and continuous sediment removal (left) to no sediment removal (right). **b** The hydrogeological profile for the deepest part of the drilling range (35–130 m bsl). **c** The full range of electrical conductivity measured in ambient groundwater (EC_{gw}) in reference to the drilling fluid (EC_{df}) that remained relatively fresh while drilling

(40–80 m bsl) was only slightly elevated with respect to later measurements in piezometers, owing to the limited salinization of the recirculating drilling fluid while drilling at these depths (EC_{df} in Fig. 6) as well as the formation of a firm borehole skin that prevented the later intrusion of more saline drilling fluid at these depths. Consequently, well development predominantly resulted in a strong increase in electrical conductivity at greater depths, and only a minimal decrease at shallower depths (Fig. 7a). This restoration was particularly evident at the depths of piezometer screens, which were developed more easily than minifilters (Fig. 7a, d). Overall, the electrical conductivity values indicated that well development largely restored the original relatively sharp transition from fresh to brackish and saline groundwater at a depth of 83 m bsl (Fig. 7a).

Gradual restoration of the original salinity profile continued during the first extraction experiment at unscreened intervals below 102 m bsl (Fig. 7b). Here, residual borehole skin and the presence of fine clayey sediments (Fig. 7e) impeded mixing of residual drilling fluid with, and its displacement by, ambient more saline groundwater. The bulk electrical conductivity increased particularly slowly between 117 and 122 m bsl (Fig. 7b), where the relatively fresh drilling fluid likely became entrapped in the clay seals during backfilling of the borehole (Fig. 7d). Slow back-diffusion from these clay seals likely contributed to the continued salinization at the deepest piezometer (Fig. 7b), which was hydraulically isolated from the extraction. The bulk electrical conductivity at the clay seals below 102 m bsl stabilized only during the second extraction experiment (Fig. 7c), approximately 2 years after well installation.

Freshening during brackish groundwater extraction

In the first 1.5-year experiment, the variable extraction of brackish groundwater across the three well screens caused rapid local downconing of the fresh-brackish groundwater transition. The depth of this transition shifted from the initial 83 m bsl to eventually about 95 m bsl at the central wells (1, 2, M, and N), based on the bulk electrical conductivity profiles (Fig. 7b). In line with this transition, the 0.15 and 1 g/L isochlors (Fig. 8a, b), and the 500 mS/m EC_{gw}-contour determined from geoelectrical resistivity measurements (GEM) also followed the flow-averaged extraction depth (Fig. 9a). The more remote wells O and P also freshened, unlike the most distant wells Q and R, albeit more gradually and less extensively than the central wells (Figs. 8a, b and 9a). Meanwhile, the brackish to saline groundwater

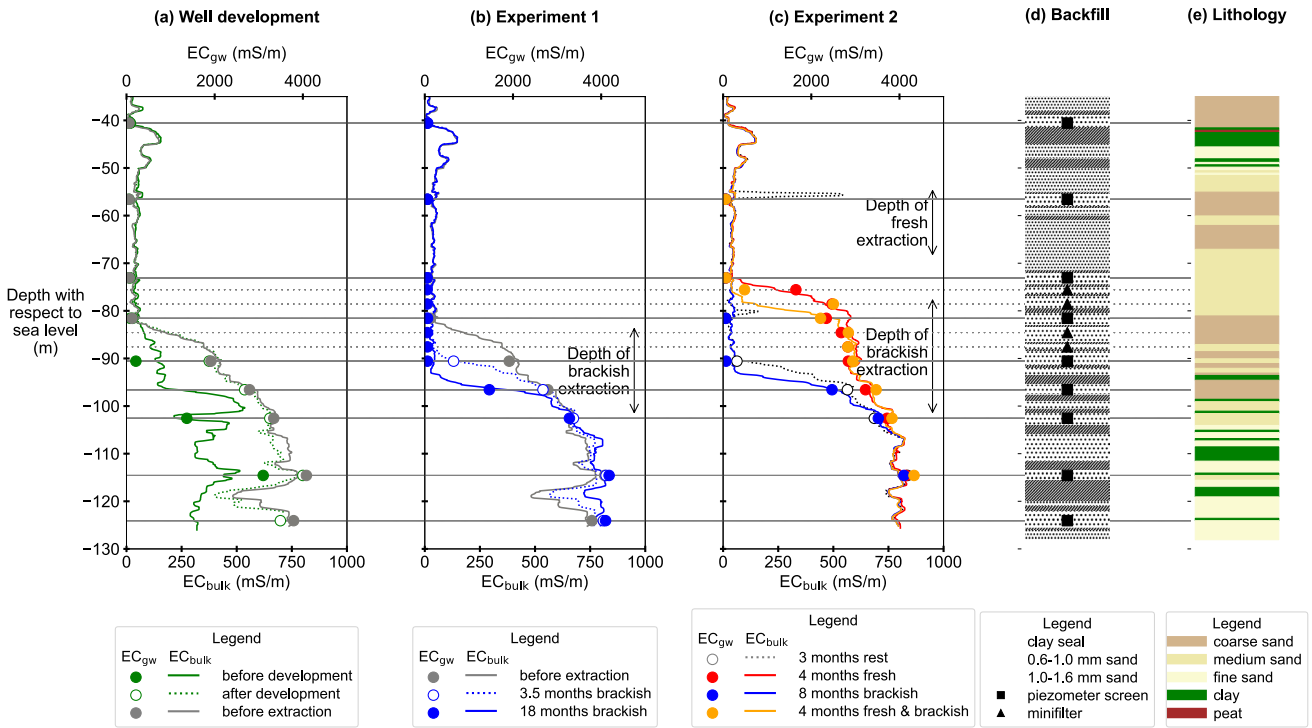


Fig. 7 Depth profiles of electrical conductivity measured in sampled groundwater (EC_{gw}) and in the geophysical borehole logs (EC_{bulk}, 1-m rolling median) from monitoring well N (Fig. 3), during well development (**a**), extraction experiment 1 (**b**; Fig. 5) and extraction experiment 2 (**c**; Fig. 5). The backfill of the borehole (**d**) and the lithological profile (**e**) are shown for reference. Double-headed arrows indicate the depth intervals of fresh and brackish groundwater extraction, and horizontal lines indicate the depths of piezometer screens (solid) and minifilters (dotted)

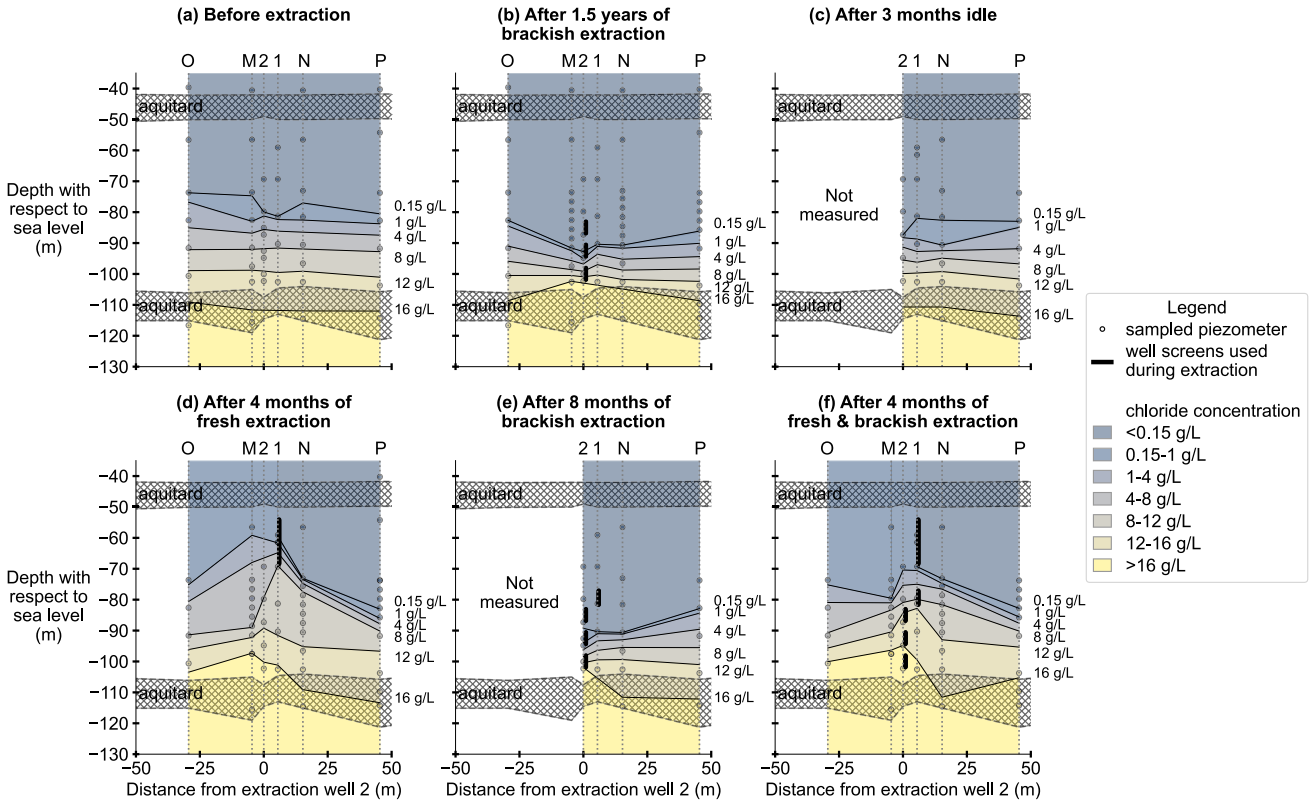


Fig. 8 Cross-sectional distribution of chloride concentrations (in g/L) before extraction (**a**), after 1.5 years of brackish groundwater extraction (**b**), after a 3-month idle period (**c**), after 4 months of fresh groundwater extraction (**d**), after 8 months of brackish groundwater extraction (**e**) and after 4 months of concurrent fresh and brackish groundwater extraction (**f**). Isochlors are linearly interpolated between the sampled piezometer screens of wells 1, 2, and M–P. Depths of piezometer screens and of well screens used during the extraction phase are indicated by open circles and black lines, respectively

(12 and 16 g/L isochlors; Fig. 8a, b) moved slightly upward at the central wells, narrowing the overall fresh–saline transition zone. Net freshening occurred because the upward movement of saline groundwater was likely impeded by the vertical resistance of the aquitard directly underneath.

The upper well screen (2.1) freshened completely within approximately 1 month, while it took 1.5 years for the middle screen (2.2) to freshen below 100 mS/m (~0.15 g/L chloride; Fig. 9b). This timing coincided with the GEM-determined 500 mS/m EC_{gw}-contour passing the bottom of these screens (Fig. 9a). Moreover, the salinity of groundwater extracted with each well screen closely matched the GEM-inferred salinity (Fig. 9b), particularly at lower salinities and even upon (re)activating well screens. This suggests relatively uniform mixing of groundwater across each well screen and supports the use of GEM to reliably predict the electrical conductivity of extracted groundwater (EC_{gw}). The peaks in the GEM-determined electrical conductivity of well screens 2.2 and 2.3 during the second experiment (Fig. 9b) are probably related to the use of two different measurement devices.

During the first year, brackish groundwater was extracted with three well screens at a total rate of 50 m^3/h (Fig. 9c). Each adjustment to increase the flow-averaged extraction depth initially caused a sudden increase in the combined salinity of extracted groundwater (Fig. 9a, b). This was followed by gradual freshening to a fairly constant salinity of ~1500 mS/m (~5 g/L chloride), regardless of the flow-averaged extraction depth. This indicates that the extraction with any of the screens produced a similar flow field and induced mixing towards the well screens because of the relatively high hydraulic conductance of the aquifer. The combined salinity stabilized at about 10% higher (~1700 mS/m, ~5.5 g/L chloride) when the total extraction rate was reduced to 30 m^3/h using only the deepest two screens (Figs. 3 and 9b, c), reducing the extent of downconing.

Mitigation of upconing by brackish groundwater extraction

During the second experiment, the 4-month extraction of only fresh groundwater induced rapid local upconing, with brackish groundwater eventually reaching the extraction well (Figs. 8d and 9a) and increasing the salinity of the extracted

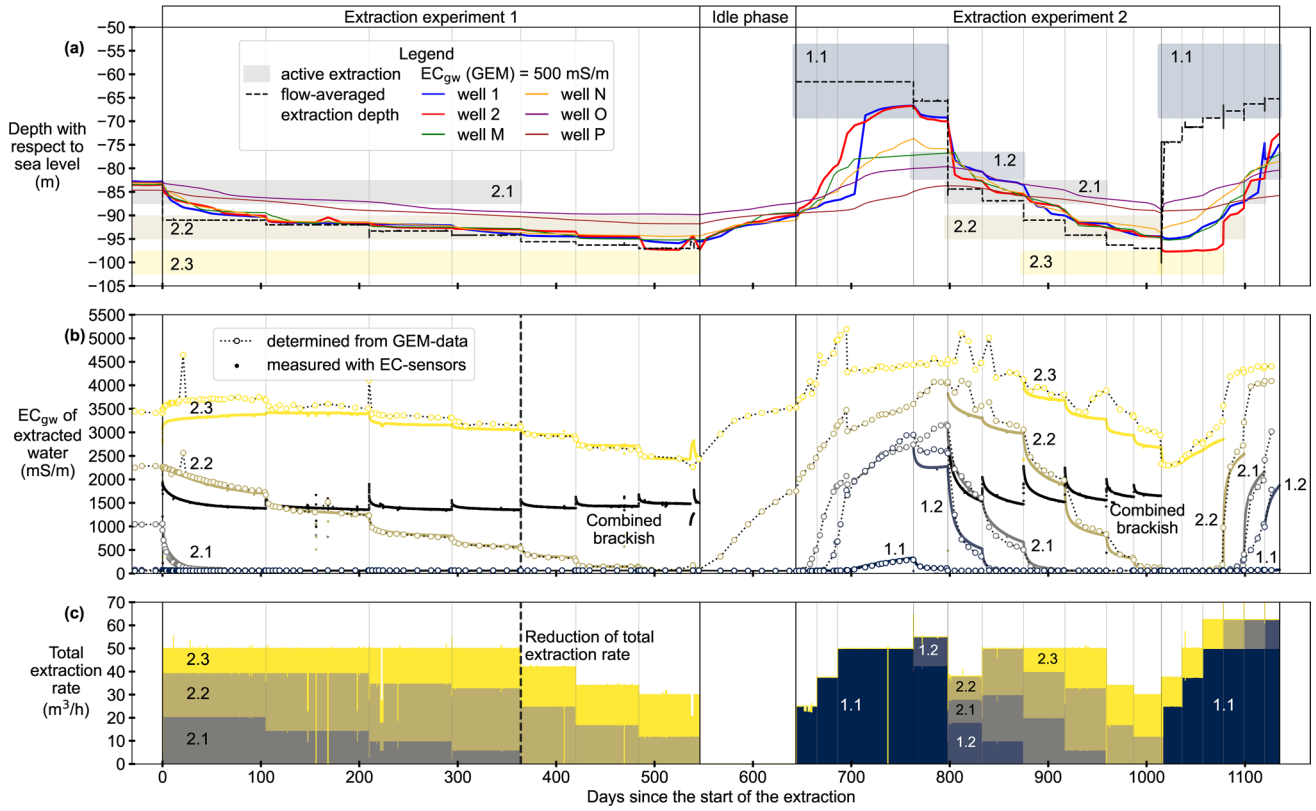


Fig. 9 Time series of flow-averaged extraction depth and depths at which the electrical conductivity of groundwater (EC_{gw}) determined from geoelectrical resistivity measurements (GEM) equaled 500 mS/m (EC_{gw} (GEM) = 500 mS/m) in wells 1, 2, M, N, O, and P (**a**), electrical conductivity of groundwater (EC_{gw}) extracted from each individual well screen, measured using EC-sensors and inferred from GEM data (**b**), and extraction rates applied with each well screen (**c**). The data for each extraction well screen (labeled 1.1, 1.2, 2.1, 2.2, and 2.3) are shown in distinct colors

groundwater to ~ 380 mS/m (~ 1 g/L chloride; Fig. 9b). These effects were reversed by the subsequent extraction of brackish groundwater (Figs. 8e and 9a). In the following 4-month simultaneous extraction of both fresh and brackish groundwater, upconing at wells O and P was similar to that observed during extraction of only fresh groundwater, but the extent and rate of upconing were mitigated at the central wells 1, 2, M, and N (Figs. 8f and 9a).

Extraction with the deepest brackish well screen (2.3) at 50% of the fresh extraction rate initially caused deepening of the 500 mS/m EC_{gw}-contour at well 2 (Fig. 9a) and freshening of the extracted brackish groundwater (Fig. 9b), indicating overextraction of brackish groundwater. The relative extraction rate of the brackish screen (2.3) decreased to 25% when the extraction rate of the freshwater well screen (1.1) was doubled to 50 m^3/h, leading to salinization of the brackish groundwater extracted with screen 2.3 and a minor salinity increase in fresh groundwater extracted with screen 1.1. The 500 mS/m EC_{gw}-contour determined from geoelectrical resistivity measurements (GEM) stabilized at the top of well screen 2.3 (98 m bsl), while having a shallower position in adjacent wells (Figs. 3 and 9a), suggesting that the minor salinity increase of the freshwater well screen (1.1) resulted from saline water bypassing the active screen for brackish groundwater extraction (2.3) laterally. The GEM-determined 500 mS/m EC_{gw}-contour in well 2 rose when shifting to shallower screens for brackish groundwater extraction and eventually reached shallower depths compared to the adjacent wells (Fig. 9a), indicating that bypassing was likely prevented. However, the GEM-determined 500 mS/m EC_{gw}-contour had not stabilized by the end of the extraction experiment, suggesting ongoing upconing and potential future salinization of the freshwater well screen (1.1).

Effect of regional groundwater flow on mixing

During freshwater extraction, the 1, 4 and 8 g/L isochlors shifted to well screen 1.1, whereas higher isochlors (12 and 16 g/L) remained stable far below the extraction (Fig. 8d). A similar pattern was observed at well N, while the transition zone at well M showed more uniform mixing across the isochlors. Consequently, the 1 and 4 g/L isochlors at well M reached shallower depths during

freshwater extraction than at well N (Fig. 8d), but were also stabilized more effectively with simultaneous brackish groundwater extraction (Fig. 8f). Regional groundwater flow likely caused this radial asymmetry of the transition zone surrounding the extraction (e.g. Jakovovic et al. 2016), as flow is directed from wells P and N (northeast) to wells M and O (southwest), i.e., from the infiltration ponds to the city of The Hague (Fig. 2). Consequently, extraction-induced changes propagated further downstream, and extracting brackish groundwater upstream of freshwater extraction wells offers more effective protection than downstream.

Freshwater extractability and mixing losses

The freshwater volume increased by approximately 36,000 m^3 within a 100-m radius and by 11,000 m^3 within the radial domain between wells O and P when only brackish groundwater was extracted in the first experiment owing to the downconing of fresh groundwater (Fig. 8b). The simultaneous rapid narrowing of the transition zone suggests that the salinity of extracted groundwater mainly reflected mixing between fresh and more saline groundwater. Under this assumption, up to 58% of the 586,000 m^3 of extracted brackish groundwater was admixed fresh groundwater. This volume of freshwater (338,000 m^3) approximates 9 times the estimated local growth of the freshwater lens within a 100-m radius from the extraction well and 30 times the growth within the radial domain between wells O and P. This indicates that the loss of fresh groundwater through brackish groundwater extraction far exceeded the gain in locally present freshwater, and would further increase if extraction continued for the purpose of sustaining the enlarged freshwater lens.

In the second experiment, the 4-month extraction from well screen 1.1 alone yielded 48,000 m^3 of fresh groundwater ($\leq$ 100 mS/m) up to well salinization. Simultaneous extraction of brackish groundwater under identical freshwater extraction settings allowed at least 142,000 m^3 to be extracted without salinization, i.e., 94,000 m^3 more than when only well screen 1.1 was active. With the same mixing assumption for extracted brackish groundwater, a maximum of 19,000 m^3 of fresh groundwater was intercepted by the brackish well, i.e., only ~ 20% of the gain in freshwater extracted without salinization. The freshwater volume within the radial domain between wells O and P shrank by about 8000 m^3 relative to the initial volume when extracting only fresh groundwater (Fig. 8d), while it shrank by about 5000 m^3 when extracting both fresh and brackish groundwater (Fig. 8f).

The electrical conductivity of extracted brackish groundwater (EC_{gw}) stabilized at higher values when freshwater was simultaneously extracted (Fig. 9b), indicating lower associated freshwater losses in the brackish well. Shifting to shallower brackish well screens without changing the extraction rate resulted in an overall decrease in the salinity of extracted brackish groundwater (Fig. 9b), reflecting greater mixing losses in the brackish well. Nevertheless, the rate of freshwater lost right before stopping brackish groundwater extraction with screens 2.3, 2.2, 2.1 and 1.2 accounted for no more than 7.5, 9.7, 12.0, and 12.5%, respectively, relative to the rate of freshwater simultaneously extracted with well screen 1.1. The electrical conductivity of extracted brackish groundwater (EC_{gw}) was still increasing at these moments (Fig. 9b), suggesting a further decrease in freshwater losses upon eventual stabilization.

Induced mixing and ion-exchange processes

Concentrations of most water quality parameters generally followed those of chloride during the field pilot, as expected from the relative compositions of the fresh and saline groundwater endmembers (Appendix Table 1). Concentrations decreased with freshening and increased with salinization, except for alkalinity, pH, and silicon (Figs. 10 and 11). Some parameters, such as sulphate (Fig. 11), predominantly followed conservative mixing across the transition zone. However, concentrations of ammonium, barium, calcium, iron, and manganese were elevated in the intermediate brackish range (50–450 mmol/L chloride) with respect to what is expected from conservative mixing (Fig. 10). This is in accordance with the occurrence of cation exchange with magnesium, potassium and sodium, indicative of salinization (e.g., Valocchi et al. 1981; Appelo and Postma 2004). Boron concentrations are far lower than expected from conservative mixing (Fig. 11), probably because of adsorption of anionic borate. This adsorption is likely facilitated by the exchange with bicarbonate (Ravenscroft and McArthur 2004; Russak et al. 2015), desorbing to maintain calcite saturation in response to calcium mobilization.

In contrast to this more saline groundwater, a freshening signature is evident at concentrations below 50 mmol/L chloride, with ammonium, barium, calcium, iron and manganese adsorbing at the expense of primarily sodium, followed by the less easily desorbing magnesium and potassium (Stuyfzand 1992) in completely fresh groundwater (Fig. 10). The adsorption of calcium at low salinities likely

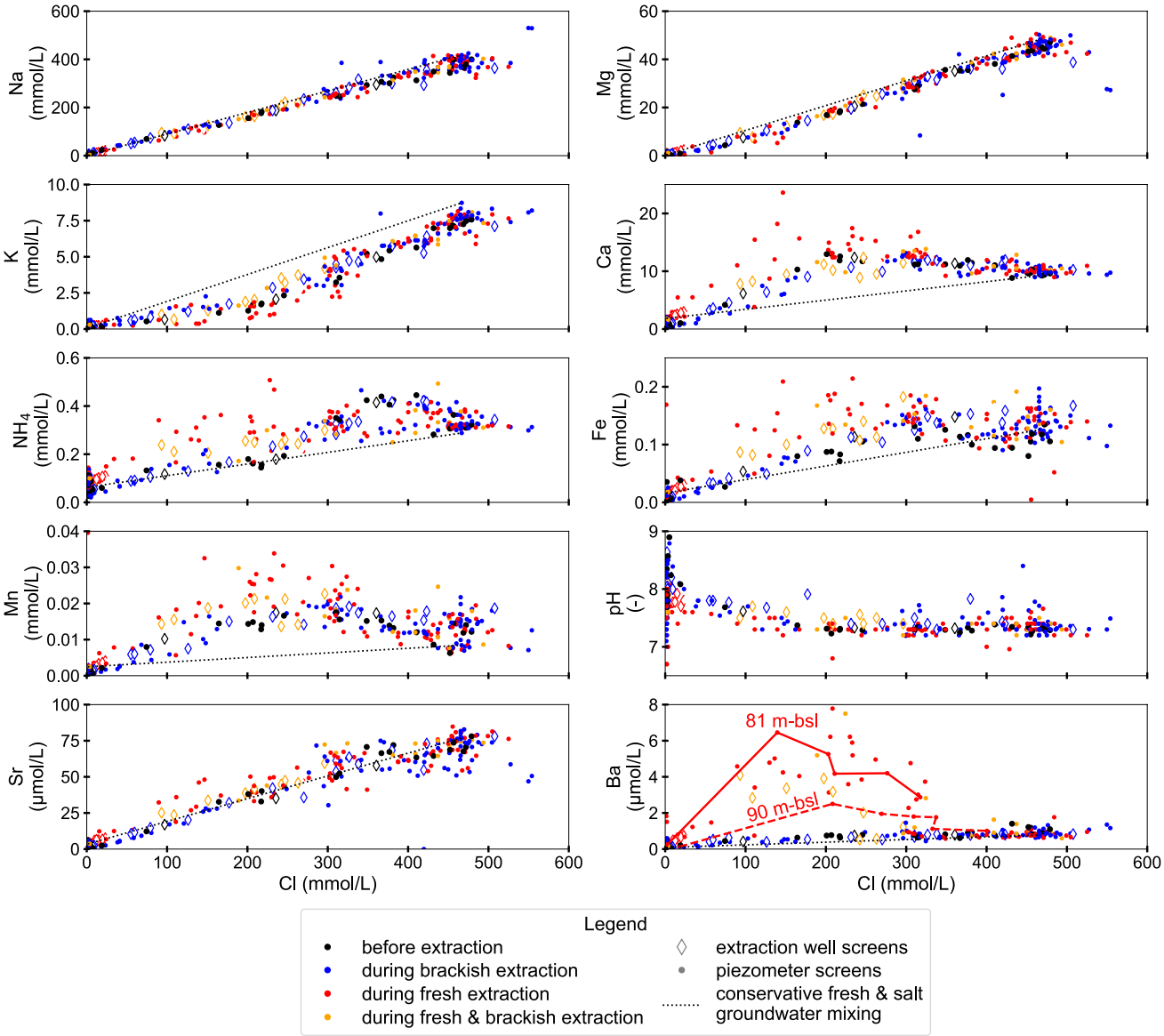


Fig. 10 Cross plots of cation concentrations and pH versus chloride concentrations (Cl) measured in groundwater from all pilot wells before extraction (black), during brackish extraction (blue), fresh extraction (red), and concurrent fresh and brackish extraction (orange). Panels are arranged row-wise from top left to bottom right: sodium (Na), magnesium (Mg), potassium (K), calcium (Ca), ammonium (NH_4), iron (Fe), manganese (Mn), pH, strontium (Sr), and barium (Ba). Concentrations are given in mmol/L, except for pH (-) and strontium and barium (µmol/L). The concentrations of barium observed at 81 and 90 m bsl in well 2 are highlighted with red solid and dashed lines, respectively

triggered calcite dissolution to maintain saturation, leading to elevated alkalinity levels (Fig. 11; e.g., Andersen et al. 2005; Seibert et al. 2018). Similar trends observed for dissolved organic carbon (DOC) and phosphate (Fig. 11) suggest deprotonation of anion adsorption sites at elevated pH values (Fig. 10; Appelo and Postma 2004).

Exchange between cations that are relatively more abundant in the fresh groundwater endmember with those that are relatively more abundant in the saline endmember (Fig. 12) was already evident in the native groundwater prior to extraction (Fig. 10), and can be linked to the site's hydrogeological history. The freshening signature in the relatively fresh groundwater is likely due to the decades-long large-scale infiltration of fresh river water in the coastal dunes. The salinization signature in the underlying brackish groundwater may reflect both the historical salinization from

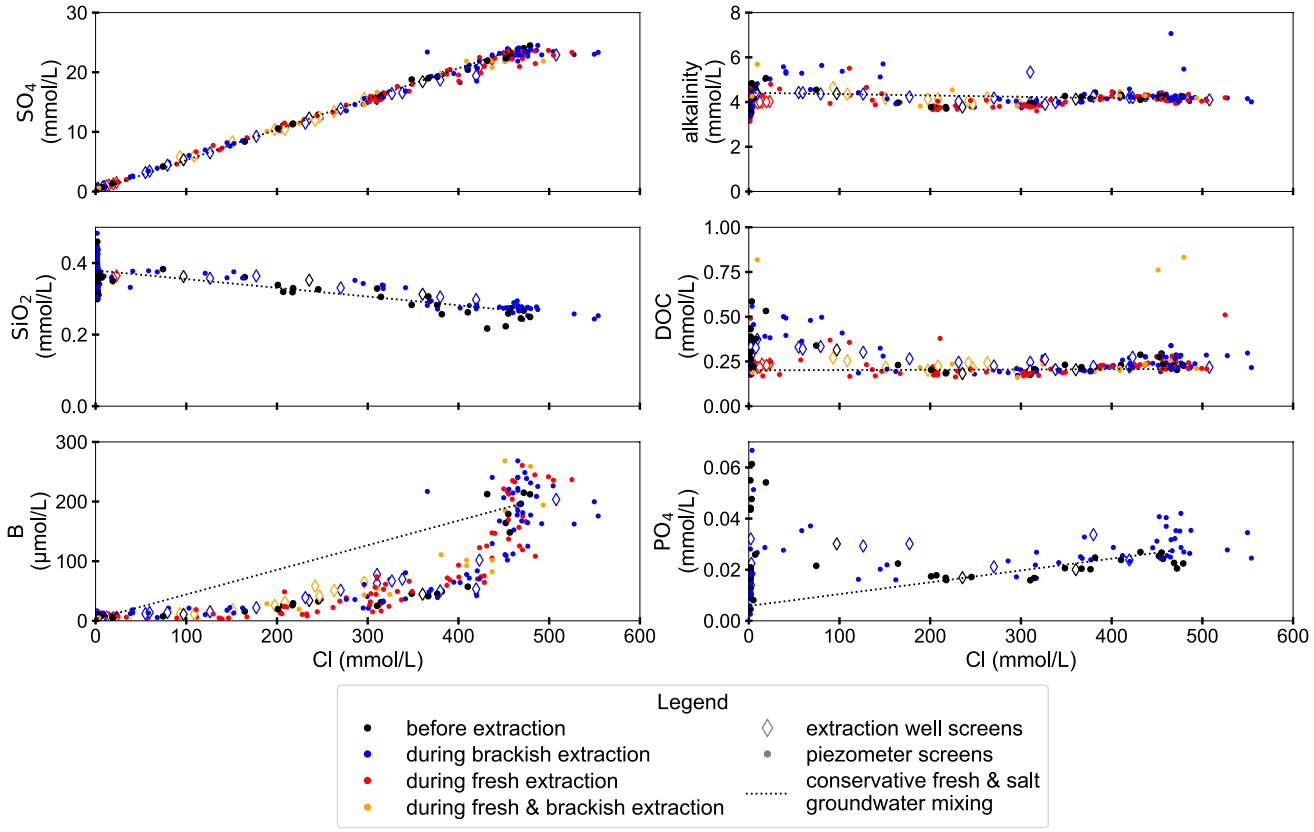


Fig. 11 Cross plots of anion concentrations versus chloride concentrations (Cl) measured in groundwater from all pilot wells before extraction (black), during brackish extraction (blue), fresh extraction (red), and concurrent fresh and brackish extraction (orange). Panels are arranged row-wise from top left to bottom right: sulphate (SO_4), alkalinity (as bicarbonate), silicate (SiO_2), dissolved organic carbon (DOC), boron (B), and phosphate (PO_4). Concentrations are given in mmol/L, except for boron (µmol/L)

before the 1950s (Stuyfzand 1993), as well as intermittent salinization from temporal pumping variations at the drinking water production site. The salinization signature remains relatively more pronounced because the impact of salinization lasts longer compared to freshening (Prusty and Farooq 2021) and mixing in the transition zone of freshwater lenses is dominated by slow transverse dispersion and diffusion (Eeman et al. 2011).

Groundwater compositions sampled from piezometers upon freshening during brackish groundwater extraction remained within the range of native groundwater compositions (Figs. 10 and 11), reflecting conservative mixing of the native groundwater as the dominant process. In contrast, concentrations of cations that are relatively more abundant in fresh groundwater increased above native concentrations upon salinization during fresh groundwater extraction, while those of cations that are relatively more abundant in saline groundwater decreased (Figs. 10 and 12). This distinction between freshening and salinization aligns with the findings of Russak and Sivan (2010), though in this case the endmember is native brackish groundwater rather than the underlying most saline groundwater. This hysteresis is most probably explained by the contrast in the ionic strength of the inflowing water, with a higher ionic strength of inflowing groundwater stimulating mixing-induced ion exchange. Reinitiating freshening by extracting brackish groundwater after salinization led to groundwater compositions in piezometers resembling those observed during initial freshening, illustrating the reversibility of hysteretic ion exchange.

The effect of hysteretic ion exchange on anion concentrations was less pronounced. Yet, the slightly lower DOC concentrations and alkalinity observed during salinization in groundwater at < 100 mmol/L chloride (Fig. 11) may have been facilitated by enhanced mobilization of calcium, triggering more calcite precipitation and pH-driven protonation of anion adsorption sites. Concurrent adsorption of anionic borate caused only a minor decrease of the already low boron concentrations (Fig. 11).

In the present study, hysteresis in the extraction wells was more pronounced in the priorly completely freshened

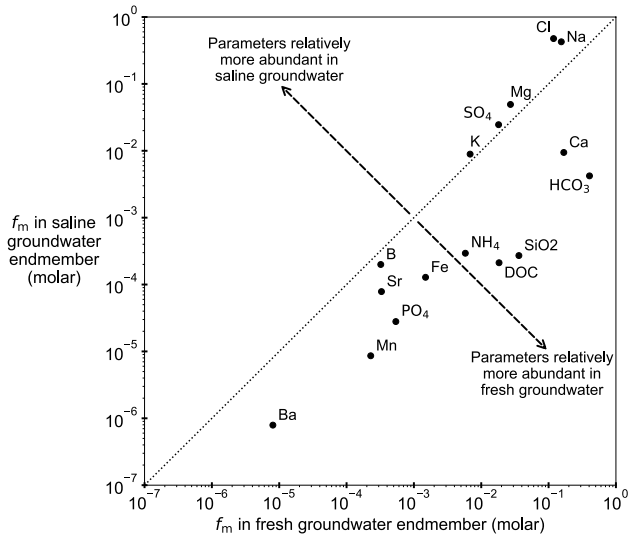


Fig. 12 Cross plot of relative parameter concentrations (f_m) in the saline groundwater endmember versus those in the fresh groundwater endmember. Shown are alkalinity (as bicarbonate, HCO_3), ammonium (NH_4), barium (Ba), boron (B), calcium (Ca), chloride (Cl), dissolved organic carbon (DOC), iron (Fe), magnesium (Mg), manganese (Mn), phosphate (PO_4), potassium (K), silicate (SiO_2), sodium (Na), strontium (Sr), and sulphate (SO_4). The absolute concentration values are reported in Appendix Table 1. For DOC, the molar mass of carbon (12 g/mol) is assumed in this plot

groundwater at 81 m bsl compared to the groundwater at 90 m bsl that incompletely freshened during earlier brackish groundwater extraction (see barium in Fig. 10). This suggests that the extent of hysteresis also depends on the extent of freshwater flushing that has previously occurred, loading adsorption sites with freshwater cations that are later released during salinization. Simultaneous extraction of both brackish and fresh groundwater attenuated mobilization of freshwater cations relative to when extracting fresh groundwater alone (Fig. 10), likely because the slower salinization pace allowed more complete equilibration of mobilizing cations with inflowing native groundwater.

Concentrations of trace metals, such as arsenic, cobalt, and nickel, did not seem to be affected by ion-exchange upon freshening or salinization. Their initial concentrations in groundwater sampled from piezometers were, however, elevated right after well installation and reduced gradually over time (not shown) owing to oxidative dissolution from sulfides triggered by the local intrusion of oxic drilling fluid (e.g., Antoniou et al. 2012; Zuurbier et al. 2016).

Signature of extracted groundwater

During the first phase of the second experiment, freshwater extraction caused progressive salinization of well screen 1.1 after approximately 7 weeks, causing the chloride concentration in extracted groundwater to exceed the (Dutch) drinking water standard of 0.15 g/L (Fig. 13d). This salinization also induced mobilization of barium, calcium, iron, and manganese in the extracted groundwater, with barium increasing to up to 5 times the concentration expected without ion exchange (Fig. 13a). Simultaneously, concentrations of ions that are relatively more abundant in saline groundwater (Fig. 12) decreased, with boron and potassium reaching half of the concentrations expected without ion exchange (Fig. 13a). These pronounced ion-exchange effects were not observed when salinization was mitigated by simultaneously extracting brackish groundwater (Fig. 13b, e), indicating that the scavenger well also stabilized the overall quality of fresh groundwater extracted from well screen 1.1.

The extracted brackish groundwater itself, however, did exhibit salinization-induced mobilization of cations that are relatively more abundant in fresh groundwater (Fig. 12), particularly barium, beyond native concentrations (Fig. 13c). This mobilization was not observed during freshening when only brackish groundwater was extracted. The extent of ion mobilization in extracted brackish groundwater thus depends on whether the system is freshening or salinizing. Notably, shifting to progressively shallower brackish screens reduced the salinity of extracted brackish groundwater (Fig. 13f), but led to relatively more mobilization of mainly barium (Fig. 13c). The relative deviations of freshwater cations subsequently decreased as salinization of the individual brackish screens progressed (Fig. 13c, f), indicating that the composition of the extracted brackish groundwater approached that of the saline groundwater endmember. Conservatively mixing brackish groundwater of different salinities extracted from multiple well screens also reduced the relative enrichment of cations that are relatively more abundant in fresh groundwater with respect to the concentrations observed for a single well screen at the same average salinity (not shown). This indicates that mixing across well screens can buffer the mobilization seen in individual screens.

Mobilization of fines

After well development, groundwater turbidity was generally low at the onset of the first extraction experiment (< 1 NTU). However, turbidity levels were relatively high (> 5 NTU) at piezometer screens near the transition from fresh to brackish groundwater (Fig. 14a). These turbidity peaks coincided with zones of relative sodium enrichment and calcium depletion, and relatively high pH values (Fig. 14b–d). These zones migrated downward with the freshening front during the first extraction experiment with only brackish groundwater extraction. This elevated turbidity at the freshening front observed in the piezometers is likely caused by the swelling, repulsion,

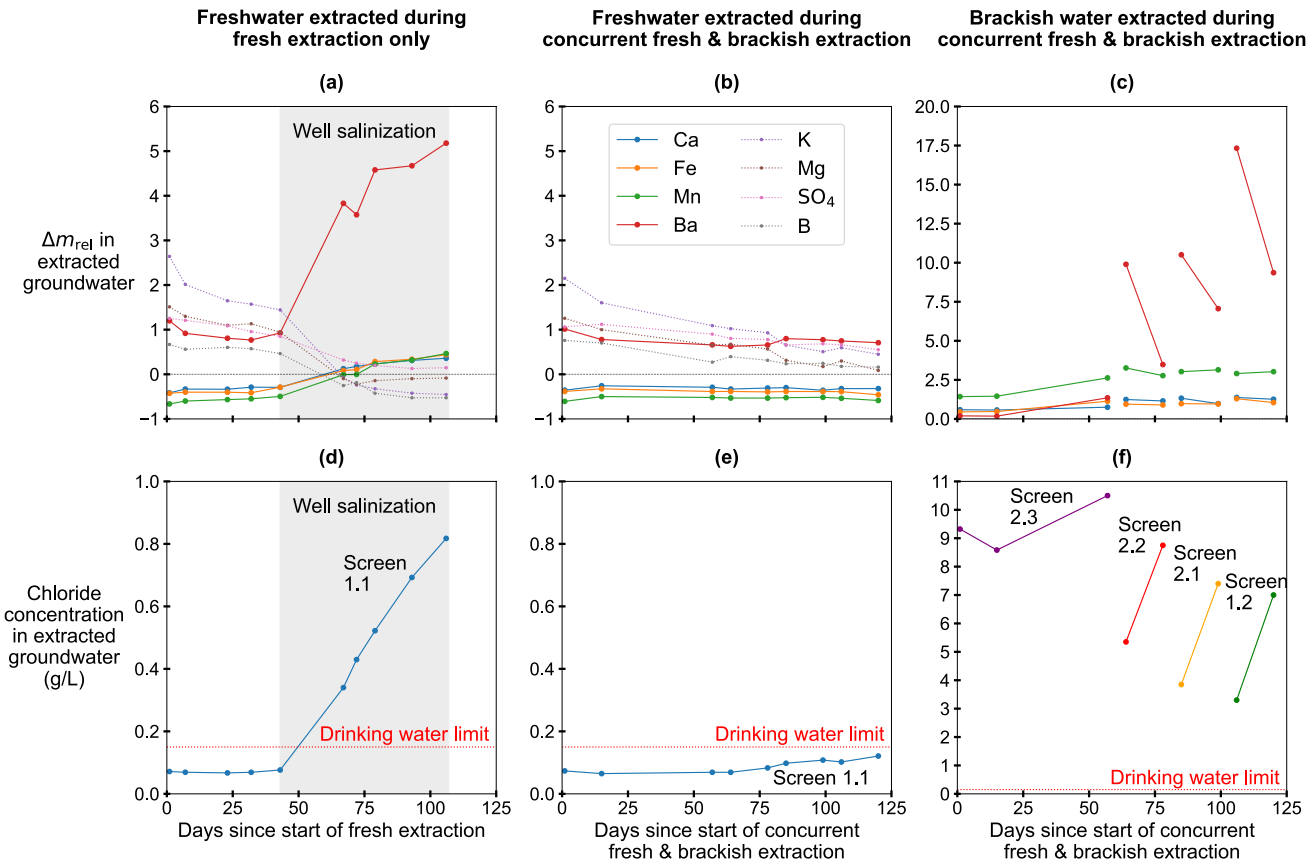


Fig. 13 Time series of major relative deviations of parameters (Δm_{rel}; **a**–**c**) and chloride concentrations (**d**–**f**) in extracted groundwater during the second extraction experiment. Panels show well screen 1.1 during freshwater extraction only (**a**,**d**); well screen 1.1 during concurrent fresh and brackish groundwater extraction (**b**,**e**); and brackish well screens 1.2–2.3 during concurrent fresh and brackish groundwater extraction (**c**,**f**). The colors in **a–c** correspond to parameters with major relative deviations, including barium (Ba), boron (B), calcium (Ca), iron (Fe), magnesium (Mg), manganese (Mn), potassium (K), and sulphate (SO_4). The distinct colors in **d–f** correspond to the extraction screens (1.1, 1.2, 2.1, 2.2, and 2.3). The Dutch drinking water limit for chloride (0.15 g/L) is indicated by a horizontal dashed line in **d–f** for reference

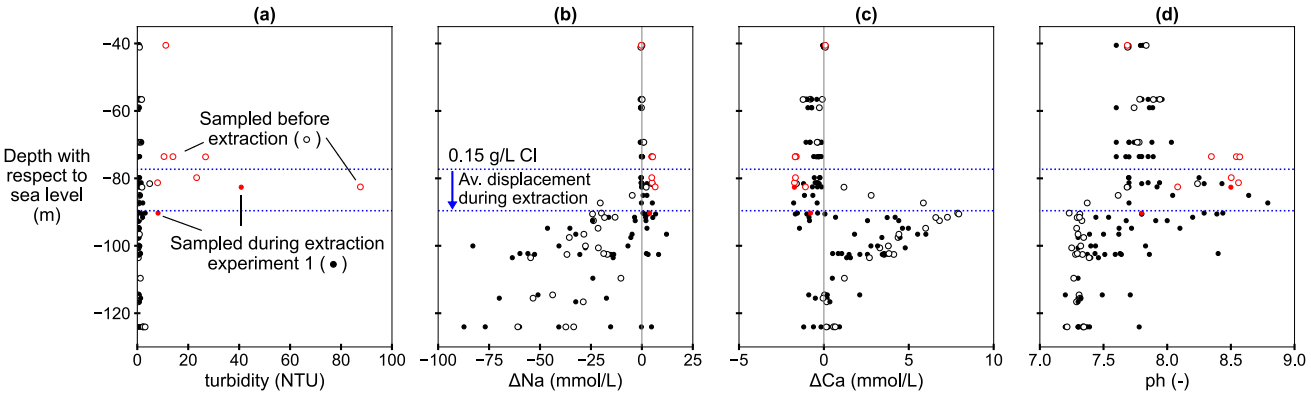


Fig. 14 Depth profiles of turbidity (**a**), the deviation of sodium concentrations (ΔNa; **b**) and calcium concentrations (ΔCa; **c**) relative to those expected from conservative mixing, and pH (**d**) of groundwater sampled from extraction wells 1 and 2, and monitoring wells M, N, and O before (open circles) and during (closed circles) the first extraction experiment. Samples with elevated turbidity levels (> 5 NTU) are highlighted in red. The blue dotted lines indicate the average displacement of the 0.15 g/L isochlor at wells 1, 2, M, N, and O during the first extraction experiment

and subsequent mobilization of clay particles from the aquifer matrix (Vinogradov et al. 2018). The turbidity of the extracted freshened brackish groundwater, however, remained low (< 1 NTU), with no signs of well clogging. Groundwater turbidity levels also remained low during the second extraction experiment, suggesting that the locally mobilized fine particles were either sufficiently diluted in the well during extraction or filtered out by the aquifer medium before reaching the extraction well.

Discussion

The results of this study provide an integrated perspective on the installation and operation of groundwater extraction wells in fresh–saline transition zones by linking drilling-induced disturbances, extraction-induced salinity dynamics, and hydrogeochemical processes influencing groundwater quality. The following discussion contextualizes the observed salinity disturbances, ion-exchange behavior, and freshwater losses through mixing, with a focus on minimizing drilling-induced disturbances and on optimizing well design and operation to enhance freshwater extractability.

EC logging while drilling through fresh-saline groundwater transitions

Monitoring the electrical conductivity of the drilling fluid (EC_{df}) at the outflow of the settling containers helped ensure that freshwater entered the borehole. Attempts to reconstruct the observed EC_{df} from the electrical conductivity profile of ambient groundwater (EC_{gw}; Fig. 6) identified groundwater transport through the drilling string and dilution with drilling fluid as the major causes of the significantly delayed and dampened EC_{df} increase with drilling depth. This discrepancy between the logged electrical conductivity of drilling fluid (EC_{df}) and the observed electrical conductivity of ambient groundwater (EC_{gw}) will increase with larger volumes of aboveground settling basins, greater borehole diameters, and deeper transition zones. Ideally, the logged electrical conductivity of drilling fluid (EC_{df}) may serve to infer the electrical conductivity profile of ambient groundwater (EC_{gw}), allowing optimal positioning of well screens relative to the transition zone without requiring exploratory wells or geophysical logs. This can be achieved by minimizing the impact of dilution, e.g., by also monitoring the flow and electrical conductivity of the drilling fluid immediately after transport through the drilling string. However, downward-intruding drilling fluid will inevitably cause some dilution and delay.

Minimizing disturbance of the salinity profile during drilling

Borehole logging revealed that drilling fluid can remain in zones not affected by well development for years, particularly in clay seals and hydraulically isolated permeable layers with high drilling fluid uptake (Fig. 7). This complicates geophysical interpretations and may prolong groundwater quality changes at screened intervals after well development through slow advective and diffusive processes. However, clay seals also prevent boreholes from acting as vertical conduits for upconing and in-borehole mixing of groundwater with varying salinities. Over the long term, properly placed clay seals thus allow the salinity measured with geophysical logs in unscreened sections to represent the salinity of the surrounding aquifer more accurately, provided that the aquifer's salinity distribution remains stable. However, it remains uncertain how accurately unscreened sections capture the actual dynamics of fresh–saline transition zones, given their limited radial connectivity with the aquifer owing to residual borehole skin.

A priori knowledge or real-time monitoring of native salinity may allow drilling operators to adjust drilling fluid salinity to ambient conditions while drilling, thereby reducing disturbances at depth. However, this approach exacerbates disturbances in shallower fresh groundwater through recirculation, as borehole plastering is never absolute. Using fresh drilling fluid minimizes disturbance of native fresh groundwater when drilling through a fresh–saline transition zone, as ion-exchange effects from salinization persist longer than those from freshening (Prusty and Farooq 2021). This strategy may seem counterintuitive, since using freshwater as drilling fluid inevitably entails losses by mixing with more saline groundwater while drilling. Yet only 470 and 690 m^3 of drinking water were required for the drilling fluid used to install extraction wells 1 and 2, respectively, compared with the gain of 94,000 m^3 of additional freshwater that was extracted by operating the scavenger well. Preventing the reuse of salinized drilling fluid within the drilling process can further limit the disturbance of native fresh groundwater, but may substantially increase the required volume of externally supplied freshwater. The use of fresh drilling fluid can be reduced by limiting the borehole depth or diameter, or by speeding up the drilling and backfilling process. Additives may also help to reduce drilling fluid losses, but can increase the volume of native fresh groundwater lost during subsequent, more elaborate well development.

Using GEM-cables for high resolution predictive salinity monitoring

Geophysical borehole measurements allowed capturing a high vertical resolution of salinity along a well, while geoelectrical resistivity measurements (GEM) with electrode cables provide much higher temporal resolution than borehole logging or water quality sampling for monitoring the fresh–saline transition zone. GEM data collected from extraction wells during idle periods also reliably predicted the salinity of groundwater that will be extracted when pumping is resumed (Fig. 9b), facilitating the operational settings. However, accurately determining the salinity distribution from GEM data requires reliable formation factors, which can only be derived through periodic sampling and sufficient variation of salinity at electrode pair depths. Establishing relationships between formation factors and aquifer or borehole properties can further improve salinity estimates from GEM data and potentially reduce the need for periodic sampling.

Anticipating impacts of ion exchange on extracted freshwater quality

As anticipated, extracting brackish groundwater primarily induced freshening of the brackish transition zone, whereas extracting fresh groundwater caused salinization in the aquifer. The relative chemical compositions of the fresh and saline endmembers (Fig. 12) provided a useful generic indication for the cation-exchange effects expected in the transition zone. Cation exchange was more pronounced when the inflowing water had a higher ionic strength. Moreover, salinization-induced mobilization of freshwater cations at a given salinity was stronger when the initial groundwater had lower salinity and when brackish groundwater extraction did not mitigate salinization (Fig. 10). Thus, both the contrast in ionic strength and the rate of salinization drive mobilization of freshwater cations.

Even slight salinization of the initially fresh extraction well substantially increased concentrations of cations that are relatively more abundant in fresh groundwater, with barium increasing to 5 times the concentration expected without ion exchange (Fig. 13). These increases occurred only once chloride concentrations exceeded the (Dutch) drinking water limit of 0.15 g/L. However, higher chloride limits may be acceptable in other contexts, possibly allowing other constituents to exceed their respective limits before the extracted water exceeds a certain salinity threshold. Consequently, higher scavenging rates may be required than anticipated when relying on salinity alone.

Strategic placement and operation of extraction wells to enhance freshwater extractability

In this field study, the transition zone narrowed rapidly when only brackish groundwater was extracted, and the extracted groundwater was more likely a blend of the fresh and saline endmembers than the native brackish groundwater present before extraction. The similarity in quality between extracted and native groundwater (Figs. 10 and 11) indicates that mixing occurred mainly within the aquifer rather than across the well screens. The quality resulting from mixing brackish groundwater from multiple well screens, however, reflected more conservative mixing between the fresh and saline endmembers, suggesting that more in-screen mixing is expected when well screens are relatively long compared to the thickness of the transition zone.

Freshwater losses due to mixing in the scavenger well should be considered when determining the net freshwater extractability from freshwater lenses or other settings with a limited freshwater source. Results of this field study suggest that a brackish groundwater extraction well is best operated as a scavenger well when the primary goal is to increase freshwater extractability while limiting freshwater losses. Placing the scavenger well closer to the freshwater well was the most effective strategy for preventing saline groundwater from bypassing the scavenger well in the relatively short-term extraction scenario, although freshwater losses due to mixing were higher with respect to those for a deeper scavenger well with the same extraction rate. The ongoing upconing (Fig. 9a) and salinity increases observed in extracted fresh and brackish groundwater (Figs. 9b and 13e, f) indicate that salinization will occur eventually. Sustaining the extraction long beyond the 4 months will require higher extraction rates and result in greater freshwater losses by mixing in the scavenger well. In addition, a deeper scavenger well requires higher extraction rates for sustainable operation compared to a scavenger well directly below the freshwater well for the relatively short-term extraction scenarios examined. Optimizing the extraction rate and the position of the scavenger well is thus critical for minimizing freshwater losses in a sustainable operation where the freshwater well does not salinize. Moreover, initial freshwater losses can be reduced by initiating brackish groundwater extraction only when the salinity of groundwater extracted from the freshwater well exceeds a defined threshold or when upconing brackish or saline groundwater is detected at a specific depth.

The transition from fresh to brackish groundwater followed the flow-averaged extraction depth (Fig. 9a), also

when extracting from multiple individual well screens positioned at different depths. This implies that the sustainable relative extraction rate of a scavenger well may be determined a priori by maintaining the flow-averaged extraction depth below the bottom of the freshwater extraction well.

Solely extracting brackish groundwater reduces lateral freshwater outflow at the boundaries of the freshwater lens by lowering freshwater heads (Gao et al. 2024). In this field study, groundwater extraction amounted to only 0.5% of the total recharge and extraction for drinking water production in the dune area. Even so, solely extracting brackish groundwater proved inefficient for increasing net freshwater availability, as mixing losses in the brackish well far exceeded the volumetric growth of the freshwater lens resulting from the increased transition zone depth. Extracting brackish groundwater from greater depths may still be preferable if the goal is to increase the volume of the freshwater lens on a regional scale. In the study area, a confining clay layer limited salinization in the deeper part of the brackish transition zone, which enhanced net freshening but also constrained further downward freshening. Progressively increasing the flow-averaged extraction depth may enhance the increase of the fresh–saline transition zone depth in settings without underlying clay layers.

The observed processes are relevant both for coastal dune systems and for freshwater lenses in island settings with unconsolidated sediments, where such lenses often represent the sole source of freshwater (e.g., Stoeckl et al. 2015; Seibert et al. 2018). In this field pilot, the regional flow dynamics and the overall freshwater lens geometry remained largely unaffected because the extraction rate was relatively low (~ 0.5% of total recharge). With higher extraction rates, regional flow patterns and lens geometry are more likely to be altered, potentially leading to different system responses in coastal dunes than in island settings.

Potential for desalination of extracted brackish groundwater

Freshwater lost by mixing in the scavenger well may be recovered by desalinating the extracted brackish groundwater, with lower feedwater salinity resulting in higher freshwater recovery (e.g., Stein et al. 2016, 2019; Ebeling et al. 2019). Determining the extent to which desalination can increase net freshwater availability is thus of specific interest. Brackish groundwater extracted from a freshening system resembled the quality of native brackish groundwater, whereas salinization resulted in mobilization of freshwater cations in the extracted brackish groundwater beyond native concentrations (Fig. 13c). The distinction between freshening and salinization is therefore crucial when considering desalination of the extracted brackish groundwater.

Using multiple vertically separated well screens within a single aquifer had limited impact on the combined salinity of extracted brackish groundwater (Fig. 9b). However, it offers greater flexibility to manipulate the aquifer's salinity distribution and to target a specific water quality for treatment. Conservatively mixing brackish groundwater of two different salinities led to lower concentrations of freshwater cations, like calcium, than a single well screen at the same average salinity. This likely reduces scaling risks, as the water is kept undersaturated with respect to calcite (Rezaei et al. 2005), and can thereby benefit the longevity of a desalination facility. Operators can therefore also tailor the extraction strategy to the intended reuse or treatment of the brackish groundwater.

Conclusions

This integrated field study examined extraction wells installed and operated within the fresh–saline transition zone of a thick freshwater lens in an unconsolidated coastal aquifer beneath the Dutch coastal dunes. In addition to a freshwater extraction well, a deeper scavenger well was installed to extract brackish groundwater with the aim of increasing freshwater extractability. Geophysical and hydrogeochemical analyses were conducted to address three key objectives: (1) to assess disturbances of the native salinity distribution introduced by well installation, (2) to evaluate salinity dynamics during extraction of both fresh and brackish groundwater, and (3) to characterize mixing and ion-exchange processes affecting groundwater quality. The results demonstrate that salinity dynamics, hydrogeochemical processes, and freshwater extractability and mixing losses must be jointly considered in the design, installation, and operation of wells for the combined extraction of fresh and brackish groundwater.

Well installation mainly freshened the deeper, brackish and saline groundwater by introducing and recirculating relatively fresh drilling fluid. Well development restored the native groundwater quality at screened intervals, but disturbances persisted in less permeable and unscreened intervals. This underscores the need to minimize drilling fluid intrusion by, e.g., speeding up the drilling and backfilling process. Clay seals initially prolong the persistence of drilling fluid in the borehole, but they allow for a more accurate determination of a stable salinity profile by limiting vertical mixing in the borehole. Fresh drilling fluid is preferred in uncased

drilling because of its limited impact on the native fresh groundwater quality, even though it is unavoidable that a small part is lost by mixing with the native more saline groundwater.

Two extraction strategies were evaluated. In the first experiment, 586,000 m^3 of brackish groundwater was extracted with multiple well screens. The transition from fresh to more saline groundwater followed the deliberately increased flow-averaged extraction depth, resulting in an estimated volumetric growth of ~ 36,000 m^3 of the freshwater lens within a 100-m radius from the extraction. During this process, freshwater losses by mixing in the brackish well were about 9 times greater (~ 338,000 m^3) during the 1.5-year extraction. In contrast, the concurrent extraction of fresh and brackish groundwater in the second experiment nearly tripled the amount of freshwater that was extracted within 4 months from 48,000 to 142,000 m^3. Meanwhile, freshwater losses by mixing in the brackish well were limited to 19,000 m^3, i.e., 20% of the gain in extractable freshwater. Brackish groundwater extraction thus increases freshwater availability most efficiently when operated as a scavenger well that locally protects freshwater wells from salinization, rather than as a means of expanding the freshwater lens. The best position of a scavenger well for the relatively short-term extraction scenarios examined is directly below a freshwater well, where it is most effective in preventing upconing saline groundwater from bypassing the scavenger well. The position and extraction rate of a scavenger well should be tailored to sustain freshwater extraction beyond 4 months with minimal losses of freshwater owing to mixing in the scavenger well.

The salinization induced by extracting fresh groundwater triggered mobilization of cations that are relatively more abundant in fresh groundwater (ammonium, barium, calcium, iron, and manganese) through the exchange with cations that are relatively more abundant in saline groundwater (magnesium, potassium, and sodium). This mobilization is driven by the higher ionic strength of upconing more saline groundwater. The calculated relative compositions of the fresh and saline endmembers explained these exchanges, while the extent of cation mobilization varied with the rate and magnitude of the salinity change. Even slight salinization already resulted in a 5 times higher concentration of barium in extracted fresh groundwater than expected without ion exchange. Cations may mobilize in extracted fresh groundwater before well salinization if a chloride threshold higher than, for example, 0.15 g/L is applied, potentially causing other ions to exceed their limits.

Concurrent extraction of fresh and brackish groundwater stabilized the extracted freshwater quality, but triggered salinization-induced cation mobilization in the extracted brackish groundwater. In contrast, solely extracting brackish groundwater induced freshening without deviating from conservative mixing between native brackish groundwater and inflowing freshwater. Hence, the quality of extracted brackish groundwater, and thus its suitability for reuse or treatment, depends on whether the groundwater is freshening or salinizing.

Overall, this study highlights that (1) applying fresh drilling fluid and clay seals during well installation disturbs the initial ambient salinity profile but improves the long-term representativeness of groundwater quality monitoring, (2) extracting brackish groundwater with a scavenger well directly below a freshwater well increases freshwater extractability effectively with limited mixing losses, and (3) accounting for salinization-induced cation exchange is essential to anticipate the quality of extracted fresh and brackish groundwater.

Appendix

Table 1 Composition of drinking water and of the fresh and saline endmembers considered in this study

Parameter	Unit	Drinking water (29 June 2021)	Fresh groundwater endmember (well P, screen 5; 31 July 2023)	Saline groundwater endmember (well P, screen 17; 31 July 2023)
EC_{gw}	mS/m	52.1	55.6	4150
pH	-	8.4	7.6	7.3
Turbidity	NTU	0.4	0.23	1.02
Cl	mg/L	53	45.8	16,500
Alkalinity	mg/L	175	269	252
SO_4	mg/L	45	18.9	2310
Na	mg/L	57	38.7	9600
Ca	mg/L	43	73.5	371
Mg	mg/L	8.1	7.20	1170
K	mg/L	5.4	2.91	342
Fe	mg/L	<0.005[a]	0.91	7.02
Mn	mg/L	<0.005[a]	0.14	0.46
NH_4	mg/L	<0.02[a]	1.14	5.20
PO_4	mg/L	0.15[a]	0.56	2.60
SiO_2	mg/L	-	22.8	16.0
DOC	mg/L	1.54[a]	2.41	2.50
Al	µg/L	2.0[a]	3.64	3.93
As	µg/L	1.8[a]	0.41	0.64
B	µg/L	45[a]	37.9	2110
Ba	µg/L	-	12.0	106
Co	µg/L	-	0.14	0.17
Cr	µg/L	-	0.16	4.42
Cu	µg/L	0.5[a]	0.75	4.65
Ni	µg/L	-	0.97	0.41
Sr	µg/L	-	315	6740
Zn	µg/L	-	0.87	22.5
Sum of anions and cations	meq/L	10.7	12.2	1060

[a]Not sampled, but average value reported in the water quality report of the second quarter of 2021 for the drinking water utility's main production site Scheveningen (Dunea 2024)

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Data availability The raw datasets used in this study are available in the 4TU Research Data repository at https://doi.org/10.4121/56438e46-0b04-415b-b7c7-9cfe047c3730. The overview map of the well field (Fig. 2) was produced using QGIS Desktop (version 3.32.2; https://qgis.org). The conceptual schematic of a scavenger well (Fig. 1) and the schematic representation of the drilling set-up (Fig. 4) were created using Microsoft PowerPoint for Microsoft 365 (version 2507, build 16.0.19029.20136). All other figures were generated using Matplotlib (version 3.7.1; Hunter 2007).

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors have no conflicts of interest to declare that are relevant to the content of this article.

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