LIFE-Freshman project

(LIFE19 CCA/NL/001222)

Monitoring progress report 1

Covering the project activities from 01/07/2020 to 30/06/2023

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Summary

Europe faces tremendous pressure on its coastal freshwater resources and coastal ecosystems. Overexploitation already is a major cause of freshwater loss and salinization of coastal freshwater resources, and climate change only enhances this problem through increasing periods of extreme drought and sea level rise. Creating freshwater buffers and exploiting non-conventional sources of freshwater, such as brackish groundwater, is key to increasing resilience.

LIFE FRESHMAN demonstrates an innovative technique to enlarge fresh groundwater lenses in coastal aquifers by a push and pull principle: combined infiltration of surface water into a suitable aquifer (push) and extraction of brackish groundwater at greater depth (pull). The enlarged lens can be used as a strategic freshwater storage and also provides s a barrier against saltwater intrusion. The extracted brackish water is treated with reverse osmosis, creating an additional drinking water source. **The central objective** of LIFE_FRESHMAN is to prove this theoretical concept in practice.

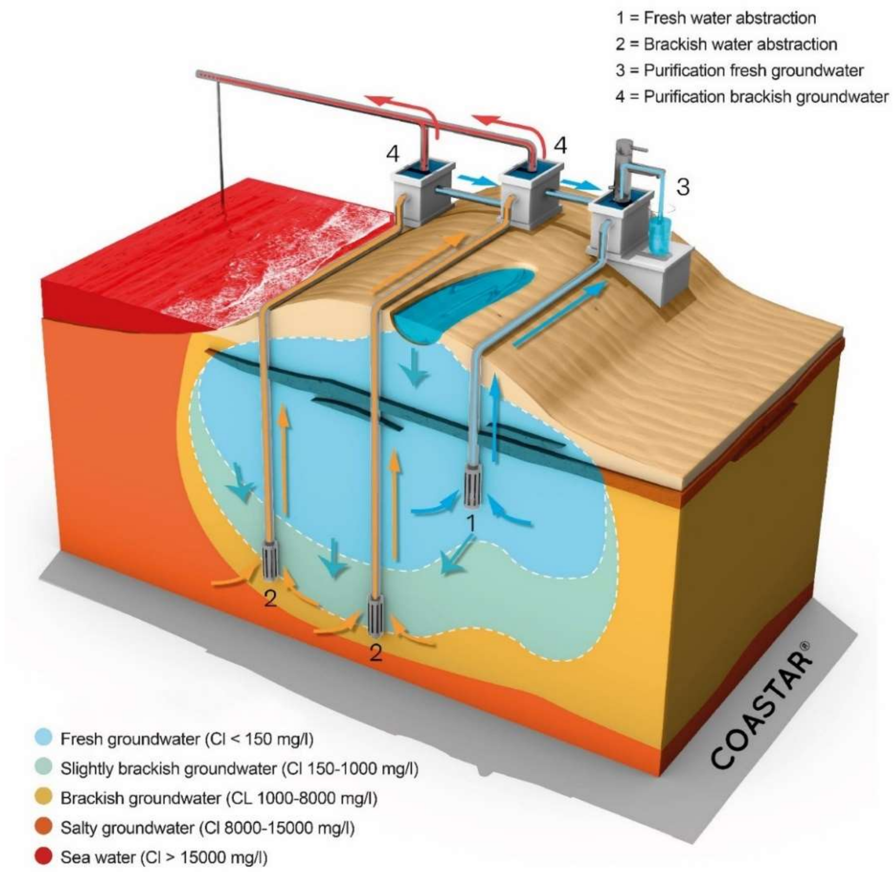


Figure 1: The Freshman concept: Withdrawal of deep fresh groundwater in the coastal dunes (1) leads to upconing of brackish groundwater and to salinization of the well. Withdrawal of brackish groundwater (2) leads to downconing of the interface between fresh and brackish water, increasing the volume of the freshwater lens and protecting the deep freshwater well from salinization. In the Freshkeeper mode, both wells are operated at the same time, with a stable fresh-brackish water interface. The freshwater is purified to drinking water with conventional techniques (3) and the brackish water is converted to fresh water by reversed osmosis (4). The freshwater produced by the RO is mixed with the drinking water from step 3 (blue arrows). The concentrate produced by the RO is discharged to the sewer (pilot phase) or the North Sea ((full scale well field; red arrows).

The expected results/outputs of LIFE_FRESHMAN are a successful demonstration of the Freshman technique as an effective climate change adaptation strategy that will safeguard and enlarge the availability of freshwater in coastal areas. The FRESHMAN technique is demonstrated in the coastal dunes near The Hague (NL), which is representative of sandy EU coasts. The replication in Flanders (BE) aims to demonstrate that FRESHMAN can be applied in various hydrogeological conditions.

The key deliverables are the physical installation of the demonstration and replication pilots, the monitoring reports on the impact of the operations (describing the growth of the freshwater lens), a report on socio-economical aspects of the technology, and a wide portfolio of dissemination actions, such as a visitor's programme, an educational programme, notice boards near the pilot sites, items on radio and television, articles in newspapers, magazines and websites, presentations on national and international conferences, and articles in professional and scientific journals.

Overview of project progress

Demonstration project

The complete technical installation of the demonstration pilot (well field, pipelines and water treatment) was realised in Q3 2021. Based on geohydrological calculations, we installed two more monitoring wells at greater distance from the extraction wells, as we expected impacts of the pilot on these more remote locations. We also installed innovative groundwater monitoring equipment (cross-hole ERT and AH-DTS) in a quadrant around the pumping wells. This innovative monitoring was not foreseen in the proposal phase but has great added value for the demonstration pilot, because of its high spatial and temporal resolution for groundwater dynamics. After installation and prior to operation, a SAT-test was carried out to determine whether the system is complete and functioning as desired. It was concluded that the system is fully operational and functioning as desired. On January 31, 2022, the pumps were switched on, ahead of schedule.

In the first year of operation (2022), 50 m3/h of brackish groundwater was pumped. A side stream of 20 m3/h was used to feed the RO membranes. Overall, the operation runs smoothly. The brackish groundwater is pumped up without operational problems (such as well clogging) and the water treatment through reverse osmosis runs with almost no interruption. After one year of piloting, the freshwater lens in the central area of the pilot area (40x40 meters) has grown by five to ten meters. So the theoretical concept of FRESHMAN, enlarging freshwater storage in coastal aquifers, has been proven in the field already.

In the RO experiments, the impact of changing fluxes and changing recoveries on membrane pressures, energy consumption and permeate water quality was investigated. Depending on the experimental conditions, a recovery (freshwater yield) of 50-65% of the feed water inflow was attained. The water quality of the freshwater produced was in good compliance with drinking water standards, with a few exceptions (e.g. hardness). Some 80.000 m^3 of fresh water was produced during the first year of operation.

The communication and dissemination actions are progressing very well. A comprehensive communication and dissemination plan is available, the website and social media accounts are live, notice boards have been placed near the pilot, networking with other relevant initiatives has started and two visitor's programmes are active. Thirteen visits of local stakeholders and water professionals have already taken place. Moreover, nineteen articles about the project have appeared in public and professional media, and the project featured in five items on radio or television. FRESHMAN also featured in the Deltafilm, that was presented during the National Delta Conference in November 2022 (attended by 1700 water professionals). As a highlight, the pilot was even mentioned in The New York Times.

Replication project

The design of the replication test in Flanders was based on a comprehensive hydrogeological study. The design of the surface water extraction, underground piping, infiltration ditch and groundwater extraction wells is finalized. Tender documents are in preparation. For the infiltration part of the test, a derogation from the general environmental quality standards for infiltration water was requested. The derogation was granted in December 2022. Unfortunately, the replication project is seriously delayed due to the time-consuming efforts to obtain an environmental permit. A class 1 permit was required which means that an extensive submission file had to be prepared. The procedure is still ongoing, and the permit is currently expected in July 2023. The actual planning foresees the start of the test in autumn 2023, however the effective start date depends on the date of issuing the permit and the civil works. If the civil works are not finalized on time, the start of the replication tests needs to be further postponed to October 2024. The test would then run till March 2025, which means that all results can still be obtained and reported before the end date of the project.

1. Introduction

Coastal areas are the most densely populated, productive and economically vibrant regions of the world. Almost half of the EU's population lives within 50 kilometres from the sea, and while this produces many economic benefits, the associated high freshwater demand puts tremendous pressure on coastal freshwater resources and coastal ecosystems. Overexploitation of groundwater resources already is a major cause of freshwater loss and salinization of coastal aquifers, which will only increase due to growing urbanization and climate change.

Due to climate change, the frequency as well as the intensity of droughts in Europe has increased, with the record-breaking droughts of 2018 and 2022 serving as the most recent examples. Prolonged droughts result in reduced groundwater recharge (i.e., less rainwater percolating to the deeper groundwater), subsequent lowering of groundwater levels, and increased risks of saltwater intrusion in coastal aquifers. Freshwater lenses are particularly vulnerable, because of the reduced recharge and because (thin) lenses are easily overexploited when the need for (Irrigation) freshwater is high.

When sea water levels are higher than groundwater levels (sea level rise, droughts), seawater may intrude into coastal aquifers, making the groundwater unfit for drinking water production or use by industry or agriculture. Sea level rise also has a negative impact on freshwater lenses that reside on top of brackish and saline aquifers. Through the buoyancy effect (density differences) these naturally occurring freshwater lenses will shrink when hydraulic pressures in the underlying brackish and saline aquifers increase. This is especially the case for freshwater lenses in coastal dunes or low-lying polders in the hinterland. To enlarge and safeguard freshwater availability in EU coastal areas, freshwater resources must become resilient to droughts and to the effects of saltwater intrusion aggravated by sea level rise.

LIFE FRESHMAN demonstrates an innovative technique, called FRESHMAN, to enlarge fresh groundwater lenses in coastal dunes (demonstration pilot) and low-lying polders (replication pilot) by a push and pull principle: combined infiltration of freshwater (push) and extraction of lower brackish groundwater (pull). The enlarged lens acts as a strategic freshwater storage and a barrier against saltwater intrusion. The brackish water can be treated with reverse osmosis creating a new, climate independent drinking water source (see figure 1; summary).

The demonstration is located at Meijendel, The Hague, The Netherlands. This is a representative coastal dune area, with characteristics typical for (sandy) EU coastal areas (high urbanisation and industrialisation, high pressure on freshwater sources, vulnerable to water scarcity and droughts). A replication of the project is performed at Avekapelle, Belgium. Avekapelle is a typical coastal inland polder with saline groundwater aquifers topped by small freshwater lenses (a so-called creek ridge).

The central objective is to demonstrate that FRESHMAN is an effective and cost-efficient climate adaptation technology in coastal areas:

- enlarging and safeguarding the availability of freshwater;
- creating a buffer for extreme drought;
- acting as a barrier against saltwater intrusion.

The expected project results are:

- A successful demonstration of the Freshman technique as:
    a. a (cost-)effective climate change adaptation strategy to enlarge and safeguard the availability of freshwater in coastal areas, and
    b. establishing a freshwater buffer for extreme periods of drought, that can also act as a barrier against saltwater intrusion:
        - The freshwater lens at the demonstration site (Meijendel, NL) is expected to grow by 350.000 m3 by the end of the project. A model study will provide a more accurate estimation.
- A new source of drinking water (brackish groundwater), providing a continuous freshwater production through reverse osmosis of 219.000 m3/year (25 m3/h) at the demonstration site (Meijendel, NL).
- Combined infiltration of freshwater and extraction of brackish water, both at 50 m3/h during the test period at the replication site (Avekapelle, BE). Replication will show build-up of the freshwater lens in a formerly brackish aquifer which can act as a potential source for drinking water production.
- Providing a guideline for implementation of FRESHMAN in other EU coastal areas facing increasing freshwater demand and saltwater intrusion.

2. Action C1: Implementation and operation of the FRESHMAN technique in Meijendel (NL)

2.1. Extraction of brackish groundwater

The well field that has been installed for the FRESHMAN demonstration pilot in Scheveningen is given in Figure 2.1, and a summary of the information on each well is given in Table 2-1. A more detailed overview of the wells is given in APPENDIX A. The installation of the wells took place between May and August of 2021. In total, two extraction wells have been installed (BR-001 and BR-002, abbreviated as 1 and 2 in Figure 2.1 and Table 2-1). Well 1 is used for the extraction of freshwater during (simulated) calamities and well 2 is used for the extraction of brackish groundwater. Both wells are equipped with multiple extraction screens, which enable a better manipulation of the salinity distribution, and a more flexible selection of the extracted groundwater quality. The individual extraction screens are connected to the treatment facility through pipelines. The two extraction wells are surrounded by eight monitoring wells (WP FM – WP FT, abbreviated as M – T in Figure 2.1 and Table 2-1). Both the extraction wells and the monitoring wells are equipped with several monitoring techniques to monitor qualitative and quantitative changes in the groundwater (Table 2-1 and APPENDIX A). Wells 1, 2, and M – R are equipped with piezometers. In several piezometers, data-loggers are installed such that the hydraulic heads are monitored in all aquifers at all wells. The piezometers can also be used for water quality analyses. Additionally, geohm cables are installed in these wells to monitor changes in the distribution of fresh, brackish and saline groundwater. Monitoring wells S and T only include two piezometers and the innovative monitoring technique 'Crosshole – ERT (electrical resistivity tomography)', which is also installed in wells M and N. Wells 1, 2, M and N include a second innovative monitoring technique called 'AH-DTS (activated heating – distributed temperature sensing)'. The lithology that has been observed at each well during the drilling process is given in APPENDIX A. For extraction well 2, a schematic cross-sectional overview is also given in Figure 2.2.

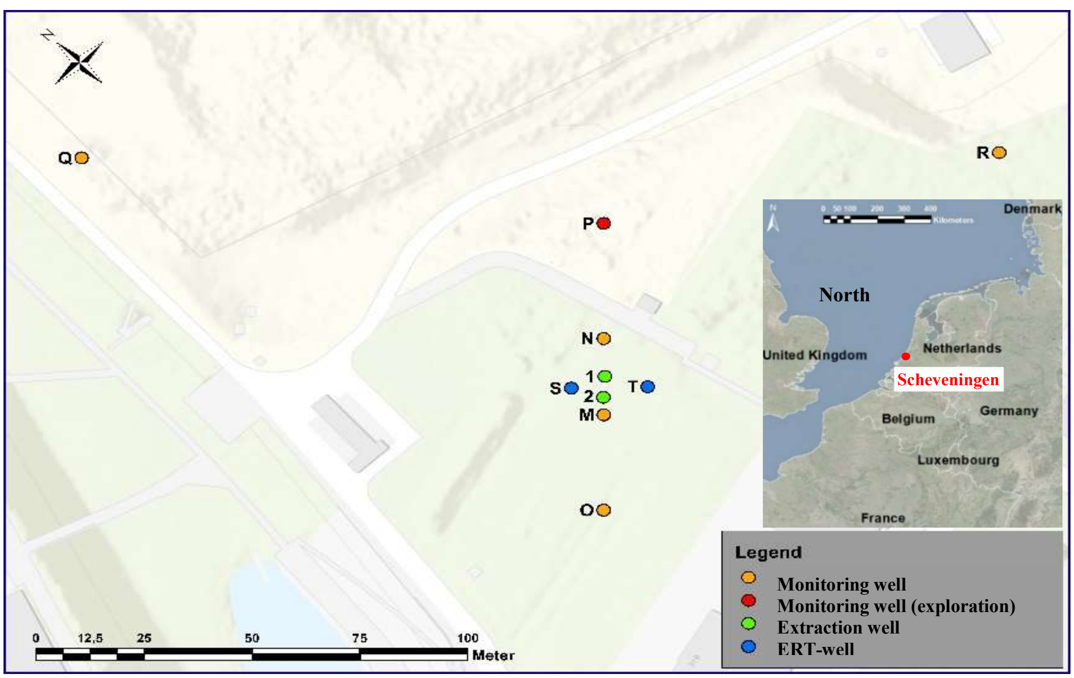


Figure 2.1: Overview of the well-field for the FRESHMAN demonstration pilot in Scheveningen. The numbers and letters given as labels correspond with the names of the wells given in Table 2-1.

Table 2-1: Overview of the metadata of the wells and of the monitoring equipment installed in each well.

	Extraction wells		Monitoring wells							
Well	**1**	**2**	**M**	**N**	**O**	**P**	**Q**	**R**	**S**	**T**
X-coordinate (RD)	81183	81179	81176	81190	81158	81211	81138	81289	81176	81188
Y-coordinate (RD)	459452	459448	459445	459459	459427	459480	459578	549428	459455	459443
Distance to centre of well field (m)	5.5	0	4.6	15.3	29.4	45.4	136.0	111.7	7.8	10.6
Elevation of land surface (m+sl)	6.95	6.95	6.96	6.93	6.88	6.25	5.84	7.71	6.91	7.07
End depth of well (m)	120	140	135	135	135	213	140	140	140	135
Extraction screens	2	3								
Piezometer screens	6	7	11	11	10	12	7	7	2	2
Mini-piezometer screens			4	4		7				
LT-dataloggers	5	7	8	8	7	9	7	7		
LTC-dataloggers	3	2								
Geohm cable	2	2	1	1	1	1	1	1		
Crosshole-ERT cables			1	1					1	1
AH DTS – glass fibre cables	1	1	1	1						

After installation, a test phase followed to determine the expected effects that had to be reported to the permitting authority. Once the system was tested and the permit was granted, the pilot commenced on the 31st of January 2022 with the continuous extraction of brackish groundwater. This will continue until the 31st of July 2023, when a rest phase will be initiated. In November 2023, a calamity will be simulated for the first time by extracting fresh groundwater for four months without extracting brackish groundwater. In February 2024, the fresh groundwater extraction will stop and the brackish groundwater extraction will again become active for six months. In September 2024 the second calamity will be simulated by extracting fresh groundwater for five months, but the extraction of brackish groundwater will continue. The Freshman demonstration-pilot will end in February 2025, but the extraction of brackish groundwater can continue to gain more experience with the treatment of brackish groundwater.

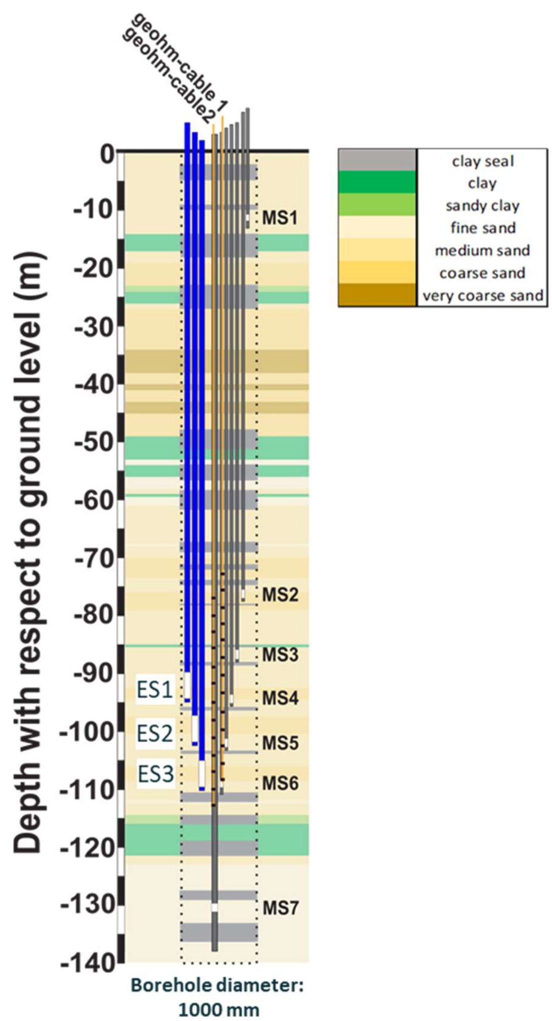


Figure 2.2: Schematic cross-sectional impression of the extraction well, with the three extraction screens indicated with 'ES', seven monitoring screens (piezometers) indicated with 'MS' and two geohm cables. The installed AH-DTS cables and LT(C)-dataloggers are omitted from this figure for clarity. The clay seals within the borehole are indicated in grey, and the observed lithology is indicated on the background (see legend).

2.2. Treatment of brackish groundwater

On the 31 January 2022, the research programme of the brackish water pilot started. Deep brackish groundwater has since been collected from three extraction wells and transported to a reverse osmosis (RO) treatment system (Figure 2.3). This deep groundwater is of good water quality; therefore, no pre-treatment is required, except for a cartridge filter (Figure 2.4). Deep groundwater contains no oxygen (anaerobic), and during treatment the water is kept in this anaerobic state.

Figure 2.3: Impression of the treatment facility.

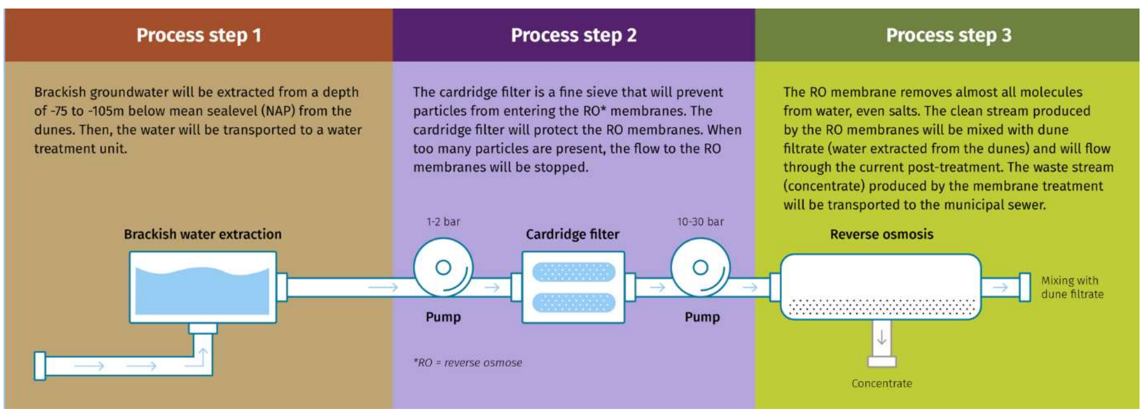


Figure 2.4: Treatment scheme of the brackish groundwater RO pilot.

Operation

The RO produces a constant stream of demineralised water, the permeate, and a waste stream, the concentrate. The system is flux driven, which means that the flux – production flow per membrane surface area – remains constant during operation while the transmembrane pressure (TMP) varies.

In the first year, three extraction wells collected 42 to 50 m^3/h with varying flows per well (Figure 2.5). These three streams can be mixed (or not) to feed the RO. Different combinations of extraction wells have been selected throughout the year to feed the RO with the desired water quality for research (Table 2-2). A conductivity between 15 and 20 mS/cm is preferred because it corresponds to the estimations for full-scale treatment of brackish groundwater. The conductivity of the feedwater of the RO is constantly changing (Figure 2.6) due to the changing flows and the changing combination of wells (Table 2-2).

The turbidity of the feedwater is constantly monitored before and after the cartridge filter. Throughout the year, the turbidity of the feedwater was below 1.0 FTU, the requirement of suppliers for RO feedwater. Furthermore, the turbidity after the cartridge filter was always lower than before.

The permeability of the membrane can be calculated by the flux per TMP. Scaling and fouling block the membrane surface, making it more difficult for water molecules to pass through the membrane. This increases the TMP and thus lowers the permeability. A higher conductivity also leads to a higher TMP and thus a lower permeability. The permeability varied between 0.5 and 2.0 L/m^2/h/bar (Figure 2.7). Since the conductivity increased over the past year (Figure 2.6), it is difficult to determine whether or not the permeability has decreased due to scaling and fouling.

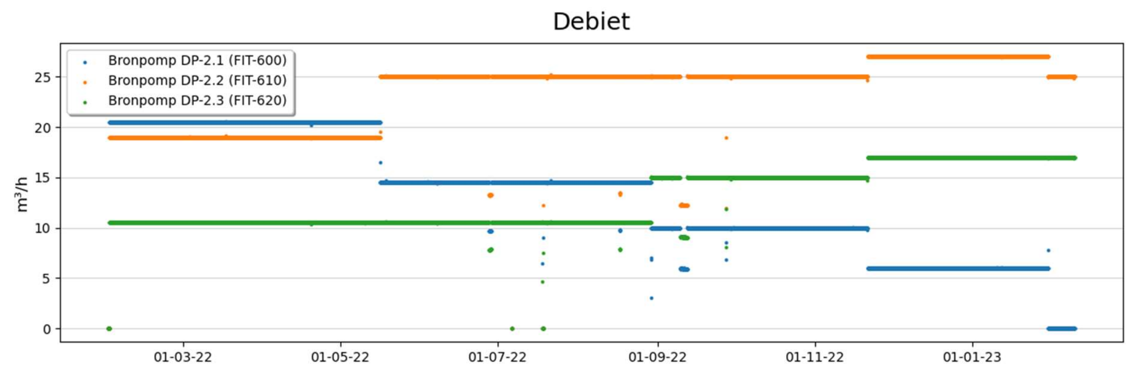


Figure 2.5: Flow of extraction well 2.1 (blue), 2.2 (orange), and 2.3 (green). Every three months, the flows of the extraction wells have been changed: on May 18th, August 29th, November 21th, and January 30th.

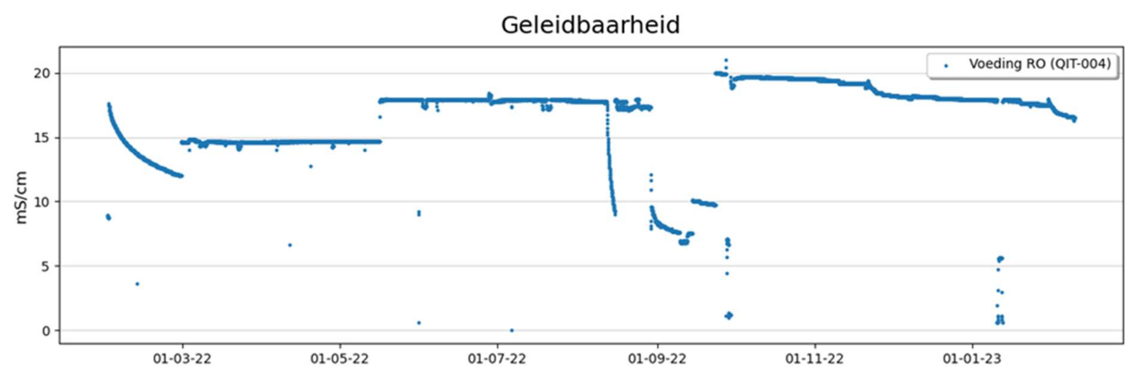


Figure 2.6: Conductivity of RO feedwater after the cartridge filter. Conductivity changed due to different flow of the extraction wells and by mixing the flows of different extraction wells.

Table 2-2: Overview of flows of extraction well 2.1, 2.2, and 2.3, the total extraction, and extraction wells that feed the RO.

Date	Well 2.1	Well 2.2	Well 2.3	Total extraction	Unit	Wells towards RO
31-01-2022	20.5	19	10.5	50	m^3/h	2.1 & 2.2
28-02-2023	20.5	19	10.5	50	m^3/h	2.1 & 2.3
16-05-2022	14.5	25	10.5	50	m^3/h	2.1 & 2.3
28-08-2022	10	25	15	50	m^3/h	2.1 & 2.3
21-11-2022	6	27	17	44	m^3/h	2.1 & 2.3
30-01-2023	0	25	17	42	m^3/h	2.1 & 2.3

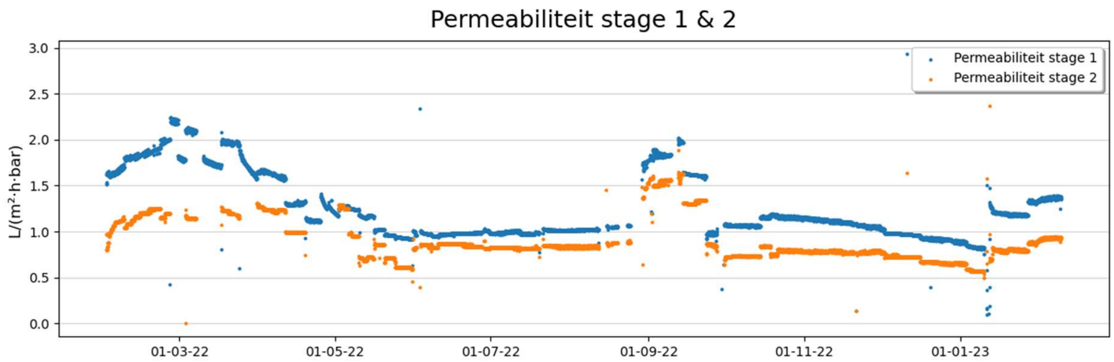


Figure 2.7: Permeability – flux per TMP – of stage 1 (blue) and stage 2 (orange) in L/m2/h/bar.

Recovery experiments

During recovery experiments, the RO operated at a constant flux of 14.9 L/m^2/h with two stages, resulting in a permeate flow of 10 m^3/h. The recovery was increased from 50% to 65% in a 6-week period. These experiments have been executed two times with different feed water quality. With increasing recovery the TMP increased because more pressure is required to produce more permeate from the feed water. The conductivity of the permeate increased with increasing recovery. Although the quantity of the concentrate decreased, it became more concentrated and showed a higher conductivity. The concentrate will probably have to be discharged (after additional treatment). Emission norms are strict in the Netherlands, this should be considered when designing a full-scale plant.

Flux experiments

In this research, a flux of 14.9 L/m^2/h has been used as a baseline setting. From there different fluxes have been tested with one and two stage(s). The highest flux tested with one stage was 26.9 L/m^2/h and 21.7 with two stages, producing 12 and 14.5 m^3/h, respectively. A higher flux resulted in a better water quality – in terms of conductivity – of the permeate water, as expected. Due to a higher flux, the crossflow in the membranes is higher and therefore the salt concentration near the membrane surface layer is lower than with lower fluxes. This causes more water particles to pass through the membrane layer and improving the water quality of the permeate water: the dilution effect.

Cleaning in place (CIP)

Two CIP events took place in the research period, in September 2022 and January 2023. During these events the RO membranes were cleaned by recirculation and soaking with a solution with a low concentration of chemicals (caustic followed by acid) to remove scaling and fouling from the membranes. Samples were taken from the chemical solution after CIP to analyse the nature of the scaling and fouling. Many metals with a low solubility were measured in this solution. Ions with the highest concentrations were sodium, iron, magnesium, manganese, silicon, aluminum, and potassium.

3. Action D1: Monitoring the effects on the climate problem targeted

3.1. Extraction of brackish groundwater

A detailed overview of monitoring activities during the pilot is given in APPENDIX B. The flow rates of the individual extraction well screens and the electrical conductivity (EC) of the groundwater extracted by each screen are registered every five minutes and are given in Figure 3.1. As shown, the extraction started on the 31st of January 2023 and the total rate was kept constant at 50 m^3/h during the first year. It was later reduced to 42, 34 and 30 m^3/h. In total, 0.56 Mm^3 has been extracted until the midst of June 2023.

The EC of well screens 2.1 and 2.2 initially decreased, whereas that of well screen 2.3 initially increases. Given the correlation between the EC and the concentration of chloride (Figure 3.1; right), a proxy for the salinity of groundwater, this means that freshening is occurring at the upper two well screens, while salinization is occurring at well screen 2.3. Consequently, the transition zone from fresh to saline groundwater has sharpened by the extraction. Since well screen 2.1 was already completely fresh in April 2022, its flow rate was decreased and that of well screen 2.2 was increased to deepen the position of the average extraction. This resulted in a new stage of freshening at well screen 2.2, while the EC of well screen 2.3 increases further to a maximum of about 3.9 S/m, corresponding with saline groundwater. At the end of August 2022, the flow rate of well screen 2.3 was increased while decreasing the rate in screen 2.1, leading to a slight freshening of groundwater in well screen 2.3. In November 2022, the rates of both screens 2.2 and 2.3 were increased while decreasing the rate of screen 2.1. In January 2023, well screen 2.1 was turned off and the extraction rate of well screen 2.2 was decreased a bit. In March 2023, the rates of screens 2.2 and 2.3 both were equal at 17 m^3/h. From May 2023 onwards, the rate of well screen 2.3 was kept higher than that of 2.2. The applied extraction schemes lead to an eventual electrical conductivity of 2.8 S/m in well screen 2.3. Well screen 2.1 has remained completely fresh from April 2022 onwards, whereas well screen 2.2 turned fresh in May 2023 when the rate of well screen 2.3 was set higher than that of 2.2. The average EC of all groundwater that is extracted decreased initially and gradually stabilized at a value of about 1.5 s/m after the first extraction regime. Hence, net freshening has occurred to a chloride concentration of about 5 g/L. The EC of all extracted groundwater that is reached after stabilization in the subsequent extraction regimes appears to be fairly independent of the distribution of the extraction rates applied for the individual well screens, as long as the total flow rate remains the same (Figure 3.1). However, when the total extraction rate was reduced in the subsequent extraction regimes in 2023, the EC at stabilization increased to a higher value of about 1.6 S/m eventually.

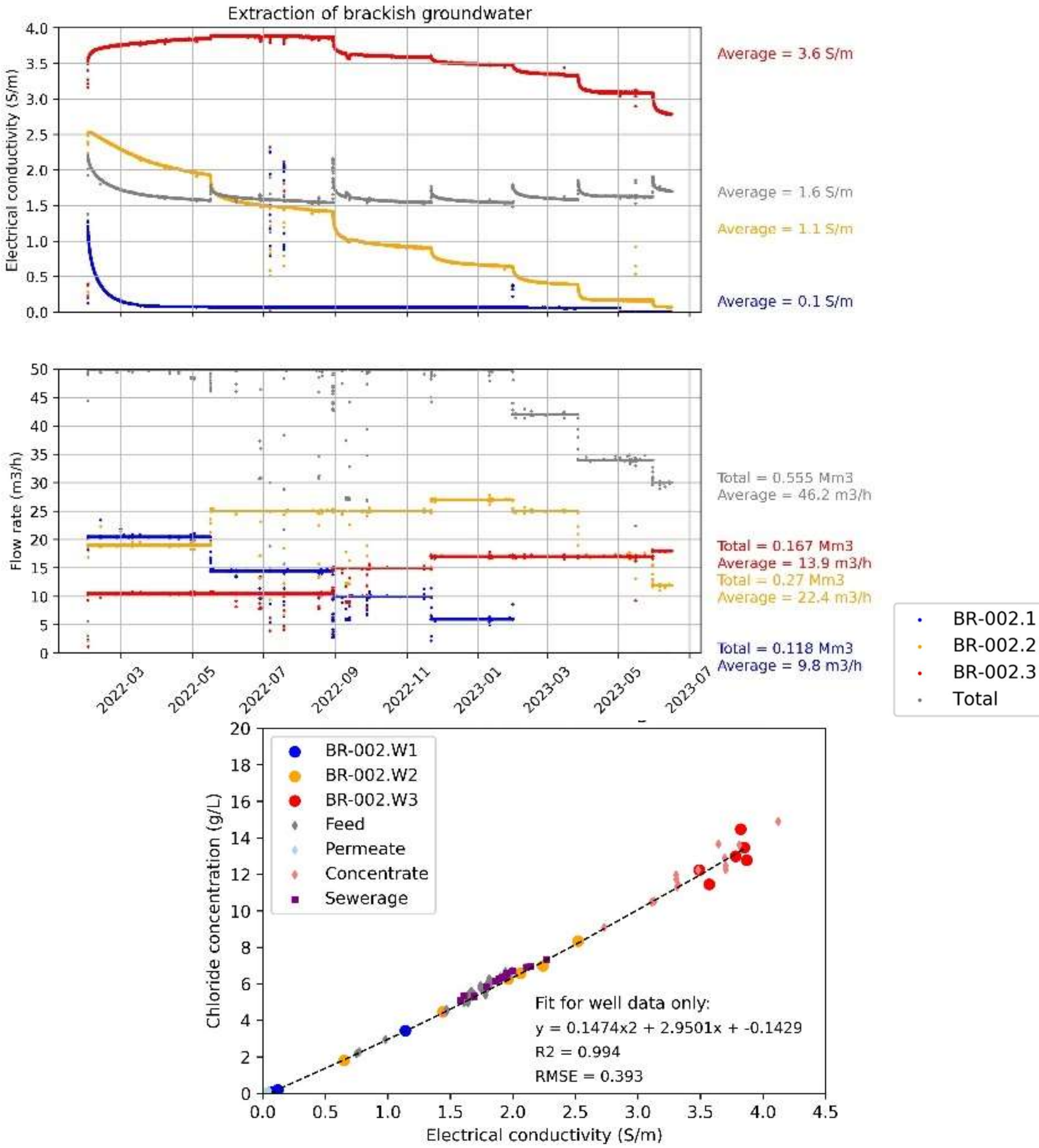


Figure 3.1: Electrical conductivity (EC) measured in the extracted groundwater and flow rate of the groundwater extraction (top) of each well screen, and the correlation between the EC and the concentration of chloride measured in the extracted groundwater (bottom).

Geohm cables are used to monitor the electrical resistivity of the subsurface. Data was obtained with them on a frequent basis (more than twice a week) after a change in the operation of the wells, and on a less frequent basis when no change in operation has occurred for a while (once every one or two weeks) (APPENDIX B). For clarity, only three measurements are included in this report in APPENDIX C.

- Measurement just prior to the pilot operation (31-1-2022)
- Measurement after one year of extracting brackish groundwater (30-1-2023)
- Measurement after about one and a half year of extracting brackish groundwater (12-6-2023)

The resistivity measured by a geohm cable is a function of the resistivity of the matrix of the subsurface (lithology) and the resistivity of the groundwater within the pores. As the lithology is assumed to remain constant through time, changes in resistivity can be interpreted as changes in groundwater salinity. A decrease of the resistivity can hence be interpreted as salinization, as saline water contains more ions and therefore provides less electrical resistance, whereas an increase of the resistivity can be interpreted as freshening. The general transition from high resistivities (fresh groundwater) to low resistivities (saline groundwater) has shifted down in the extraction wells by about 11 meters after about one year of extracting brackish groundwater, and by about 13 meters after one and a half year (APPENDIX C). The transition has also shifted down in monitoring wells WP FM – WP FP, but to a lesser degree depending on the distance from the extraction wells (Table 2-1). At WP FQ and WP FR, located about 136 and 112 meters from the extraction wells, almost no change is observed in the resistivity profiles. Consequently, freshening is more significant in the centre of the well field where extraction takes place and dissipates radially outward until no significant effect can be observed anymore at WP FQ and WP FR.

This resistivity data can, after a correction for temperature, be correlated to the salinity of groundwater obtained from periodic water quality analyses (Figure 3.2). Hence, the resistivity profiles of the wells can be translated to chloride profiles and can be interpolated between the wells to get an indicative impression of the changes in groundwater salinity (Figure 3.3). Freshening is indeed most significant in the centre of the well field and dissipates radially outward. Consequently, the extraction of brackish groundwater has resulted in a sharpening of the transition zone that is also most evident in the centre of the well field (Figure 3.3). The local increase of the fresh groundwater volume that has occurred from 31-1-2022 till 12-6-2023 is approximated at 43,000 m^3 by radially integrating the depth increase of the 150 mg/L-isochlor. This amounts to about 8% of the total brackish groundwater extraction during that period (0.56 Mm^3). It should be noted that this is a strict approximation, as the calculation holds simplifying assumptions. Moreover, the freshening is interpreted as a local increase of fresh groundwater around the extraction well, but may have lead to a diffuse depletion of fresh groundwater elsewhere.

Hydraulic heads and electrical conductivity measured with the TD(C)-dataloggers are logged every one or two minutes and data is saved when head changes of >1cm occur (APPENDIX B). Hand measurements of hydraulic heads have been carried out several times to calibrate the logged data. This logged data is omitted from this report for the sake of its length and will be reported in other deliverables. Geophysical borehole measurements have been carried out prior to the pilot and after 4 months to complement the salinity data obtained from geohm cables and water quality analyses (APPENDIX B). The Crosshole-ERT and AH-DTS are continuously active. The results of these measurement techniques will be elaborated upon in other deliverables. The water quality has been analysed five times up to now (APPENDIX B). For brevity, only the most important water quality results of the reference measurement prior to the pilot (31-1-2022) in BR-002 are included in this report (APPENDIX D).

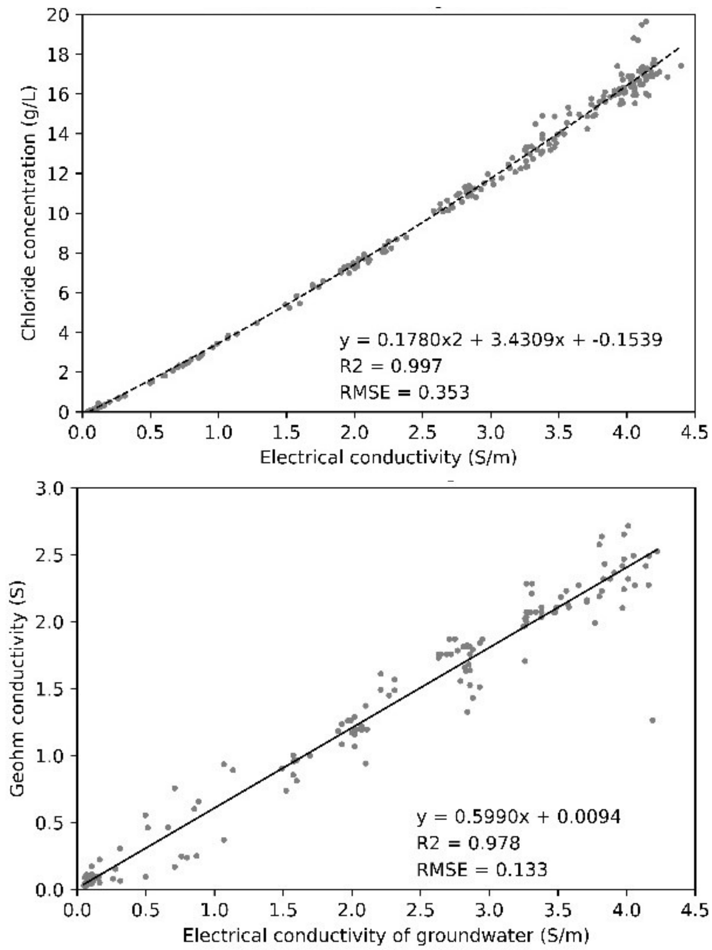


Figure 3.2: Correlation between the EC and the concentration of chloride in groundwater at monitoring well screens (top), and between the EC measured in groundwater and the EC calculated from the resistivity measured by the geohm cables (bottom).

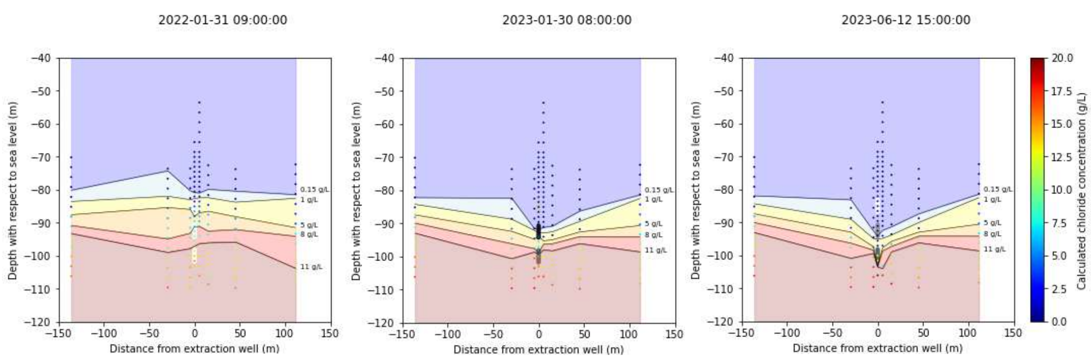


Figure 3.3: Indicative profiles of the chloride concentration prior to the pilot (31-1-2022; left), after approximately one year (30-1-2023; middle), and after approximately one and a half year of extracting brackish groundwater (12-6-2023; right). The profiles are calculated from the resistivity measurements (APPENDIX C) and the correlation trendlines (Figure 3.2). The colours of the dots represent the calculated concentrations of chloride for each electrode pair of the geohm cables as given by the legend, whereas the black lines and the background colours indicate isochlors (for 150, 1000, 5000, 8000, and 11000 mg/L) interpolated between the wells.

3.2. Treatment of brackish groundwater

In Table 3-1, the water quality of the influent water and the produced permeate is shown. Parameters that do not directly meet the drinking water requirement after RO treatment are marked in red. These compounds are elaborated below.

Table 3-1: Overview of maximum influent concentrations and average and maximum permeate concentrations measured from February 2022 until January 2023. Parameters that already meet the requirement in the influent water are not shown. DWB stands for National Drinking Water Standard.

Parameter	Unit	Influent	Permeate		Requirement	Standard
		max	average	max		
Ammonium	mg/l N	3.0	0.07	0.10	0.04	Dunea
Barium	µg/l Ba	75	<1.0	1.5	20	Dunea
Boron	mg/l B	0.4	0.2	0.2	0.125	Dunea
Calcium	mg/l Ca	297	<0.05	<0.05	hardness >1 mmol/l	DWB
Chloride	mg/l Cl	6695	55	111	150	DWB
Fluoride	mg/l F	1.3	<0.01	0.01	1	DWB
Iron	mg/l Fe	4.2	<0.01	0.07	0.05	Dunea
Potassium	mg/l K	231	1.0	1.8		
Magnesium	mg/l Mg	434	<0.05	0.5	hardness >1 mmol/l	DWB
Manganese	µg/l Mn	504	<5.0	<5.0	50	DWB
Methane	µg/l	66	55	65		
Sodium	mg/l Na	5848	35	71	150	DWB
Nitrate	mg/l N	<1.4	<0.2	<0.2	3	Dunea
Nitrite	mg/l N	<0.002	<0.002	<0.002	0.0075	Dunea
Silicate	mg/l Si	10.3	<0.3	<0.3		
Sulphate	mg/l SO4	930	<2.0	2.7	75	Dunea
Sulphide	mg/l S	0.18	<0.1	0.12		
Total phosphate	mg/l P	0.9	<0.02	<0.02	0.15	Dunea
Bicarbonate	mg/l HCO3	269	6	8	>60	DWB

The company standard for ammonium of 0.04 mg/l N is exceeded regularly. However, the concentration in the permeate always meets the legal standard of 0.16 mg/l N. With an average of 0.2 mg/l B, the concentration of boron in the permeate is always higher than the company standard of 0.125 mg/l B. However, the concentration is always far below the legal standard of 0.5 mg/l B. The total hardness, calculated as the amount of Ca^{2+} and Mg^{2+} in mmol/l, should be >1 mmol/l when softening or desalination is applied. As Ca and Mg are almost completely removed during RO treatment, the total hardness of the permeate is too low for drinking water standards. However, after mixing RO permeate with current drinking water the legal standard will be met. For buffering, the bicarbonate concentration in drinking water should at least be 60 mg/l. After mixing, the average of 6 mg/l in RO permeate is elevated sufficiently to comply with this standard. The pH of the permeate fluctuates between 5-7.5. Mixing with drinking water should lead to a pH value in the required range of 7.0-9.5.

On average the RO pilot has produced 10 m^3/h permeate. This production was continuous except for two CIP events of 4 days each and due to downtime. Since 29 July 2022, the permeate has been added to the drinking water production. In total about 65,000 m^3 permeate has been produced, of which 45,000 m^3 has been used for drinking water production.

The energy consumption of the RO is strongly dependent on the settings of the RO and the salt concentration of the water. At a higher salt concentration of the feed water, more pressure and thus more energy is required to produce the same amount of permeate. The same applies for a higher flux and/or a higher recovery. Last year, the RO consumed an estimated 1.1-1.7 kWh/m^3, dependent on the settings and conductivity of the feed water. This value cannot be directly translated to a full-scale installation since the pumps are over dimensioned in this pilot installation. Moreover, in a full-scale installation an energy recovery device (ERD) should be installed to recover a large part of the energy. This ERD was not installed in the pilot because they are not efficient enough for small installation.

4. Conclusions

- The combined infiltration of surface water on top (push) and abstraction of brackish water at greater depth (pull) has resulted in a significant growth (by several meters) of the freshwater lens at the demonstration site. Thus, the theoretical concept of the FRESHMAN technique, to enhance freshwater availability in coastal aquifers, has been validated in the field.

- After one year of operation, it can be concluded that the abstraction of brackish water and the treatment of this water by reversed osmosis runs smoothly. Operational setbacks such as well clogging did not occur, whereas membrane clogging or fouling could be limited by a small dosage of anti-scalants and one cleaning in place action after eight months of operation.

- Mathematical modelling suggests that the pilot can be upscaled to a complete well field with a capacity of 5 million m^3 drinking water per year, without relevant impacts on the nature values of the dunes. This is sufficient to sustain the needs of 110.000 people, which is half the anticipated population growth in the area up to 2040.

- The cost efficiency of brackish water as a source of drinking water has not yet been established. However, it is foreseen that drinking water produced from brackish water will be more expensive than the current source of Dunea (river water). On the other hand, diversification of the resources portfolio makes Dunea more robust against interruptions of water supply, due to calamities or extreme droughts. Increased robustness always comes with a price.

- The communication and dissemination actions are progressing very well. The website, social media accounts (80.000 views on LinkedIn) and notice boards are live, networking with other relevant initiatives has started, and the visitor's programmes are active, with thirteen site visits of local stakeholders and water professionals having already taken place. In fact, the project partners have gone above and beyond the project targets to promote LIFE FRESHMAN. For instance, nineteen articles about the project have appeared in public and professional media, including two national newspapers (with 200.000 and 340.000 subscribers). The project was featured in five items on radio or television and in the Deltafilm, the latter of which was presented to 1700 professionals in the Dutch delta community. An international article on the FRESHMAN project was published in IWA journal The Source, the leading journal for water professionals worldwide (8000 subscribers). As a highlight, the pilot was even mentioned in The New York Times (9 million subscribers).

* Freshman film: https://www.youtube.com/watch?v=TmCBlelWpMA
* Freshman animation: https://youtu.be/2qND2g724qM
* The Source, April 20222: https://lnkd.in/eTHYPpj9
* Deltafilm 2022 (featuring Freshman): https://www.deltaprogramma.nl/documenten/videos/2022/11/10/deltafilm-2023

APPENDIX A: Overview of the wells, including its lithology and the installed monitoring equipment

APPENDIX B: Planning of monitoring activities

- **Sensors for flow rate and EC** on the pipelines coming from each extraction well screen:
  - Data is registered every 5 minutes, also when extraction well screens are inactive.

- **LT(C)-loggers** in piezometers (L = groundwater level, T = temperature, C = conductivity):
  - Data is checked every X minutes and saved whenever the head change is > 1 cm.
  - X = 1 for all LT-loggers in piezometer screens, X = 2 for all LT-loggers in extraction well screens, X = 5 for all LTC-loggers in piezometer screens.

- **AH-DTS**: continuous measurements in BR-001, BR-002, WP FM and WP FN.

- **Crosshole-ERT**: continuous measurements in WP FM, WP FN, WP FS and WP FT

- Retrieving data from **Geohm-cables** in BR-001, BR-002, WP FM – WP FR:
  - 31-1-2022: Reference measurement in BR-001, BR-002, WP FM – WP FR
  - 31-1-2022 – 20-2-2022:
    - 5 measurements/week in BR-001, BR-002, WP FM – WP FN
    - 2 measurements/week in WP FO – WP FR
  - 21-1-2022 – 3-4-2022:
    - 2 measurements/week in BR-001, BR-002, WP FM – WP FN
    - 1 measurements/week in WP FO – WP FR
  - 4-4-2022 – 15-5-2022:
    - 1 measurements/week in BR-001, BR-002, WP FM – WP FN
    - 1 measurements/2 weeks in WP FO – WP FR
  - 16-5-2022 – 29-5-2022:
    - 2 measurements/week in BR-001, BR-002, WP FM – WP FN
    - 1 measurements/week in WP FO – WP FR
  - 30-5-2022 – 19-6-2022:
    - 1 measurements/week in BR-001, BR-002, WP FM – WP FN
    - 1 measurements/2 weeks in WP FO – WP FR
  - 20-6-2022 – 28-8-2022:
    - 1 measurements/2 weeks in BR-001, BR-002, WP FM – WP FR
  - 29-8-2022 – 4-9-2022:
    - 2 measurements/week in BR-001, BR-002, WP FM – WP FN
    - 1 measurements/2 weeks in WP FO – WP FR
  - 5-9-2022 – 18-9-2022:
    - 1 measurements/week in BR-001, BR-002, WP FM – WP FN
    - 1 measurements/2 weeks in WP FO – WP FR
  - 19-9-2022 – 20-11-2022:
    - 1 measurements/2 weeks in BR-001, BR-002, WP FM – WP FR
  - 21-11-2022 – 27-11-2022:
    - 2 measurements/week in BR-001, BR-002, WP FM – WP FN
    - 1 measurements/2 weeks in WP FO – WP FR
  - 28-11-2022 – 11-12-2022:
    - 1 measurements/week in BR-001, BR-002, WP FM – WP FN
    - 1 measurements/2 weeks in WP FO – WP FR
  - 12-12-2022 – 29-1-2023:
    - 1 measurements/2 weeks in BR-001, BR-002, WP FM – WP FR

- 30-1-2023 – 5-2-2023:
    - 2 measurements/week in BR-001, BR-002, WP FM – WP FN
    - 1 measurements/2 weeks in WP FO – WP FR
- 6-2-2023 – 19-2-2023:
    - 1 measurements/week in BR-001, BR-002, WP FM – WP FN
    - 1 measurements/2 weeks in WP FO – WP FR
- 20-2-2023 – 26-3-2023:
    - 1 measurements/2 weeks in BR-001, BR-002, WP FM – WP FR
- 27-3-2023 – 2-4-2023:
    - 2 measurements/week in BR-001, BR-002, WP FM – WP FN
    - 1 measurements/2 weeks in WP FO – WP FR
- 3-4-2023 – 16-4-2023:
    - 1 measurements/week in BR-001, BR-002, WP FM – WP FN
    - 1 measurements/2 weeks in WP FO – WP FR
- 17-4-2023 – 28-5-2023:
    - 1 measurements/2 weeks in BR-001, BR-002, WP FM – WP FR
- 29-5-2023 – 4-5-2023:
    - 2 measurements/week in BR-001, BR-002, WP FM – WP FN
    - 1 measurements/2 weeks in WP FO – WP FR
- 5-5-2023 – 18-5-2023:
    - 1 measurements/week in BR-001, BR-002, WP FM – WP FN
    - 1 measurements/2 weeks in WP FO – WP FR
- 19-5-2023 – 30-7-2023:
    - 1 measurements/2 weeks in BR-001, BR-002, WP FM – WP FR

For the remainder of the pilot, a similar procedure will be followed for retrieving data from the geohm cables by increasing the frequency of measurements after a change in the operation (up to 2x/week for the central wells) and reducing the frequency if no change in operation has occurred in a while (up to 1x/2 weeks).

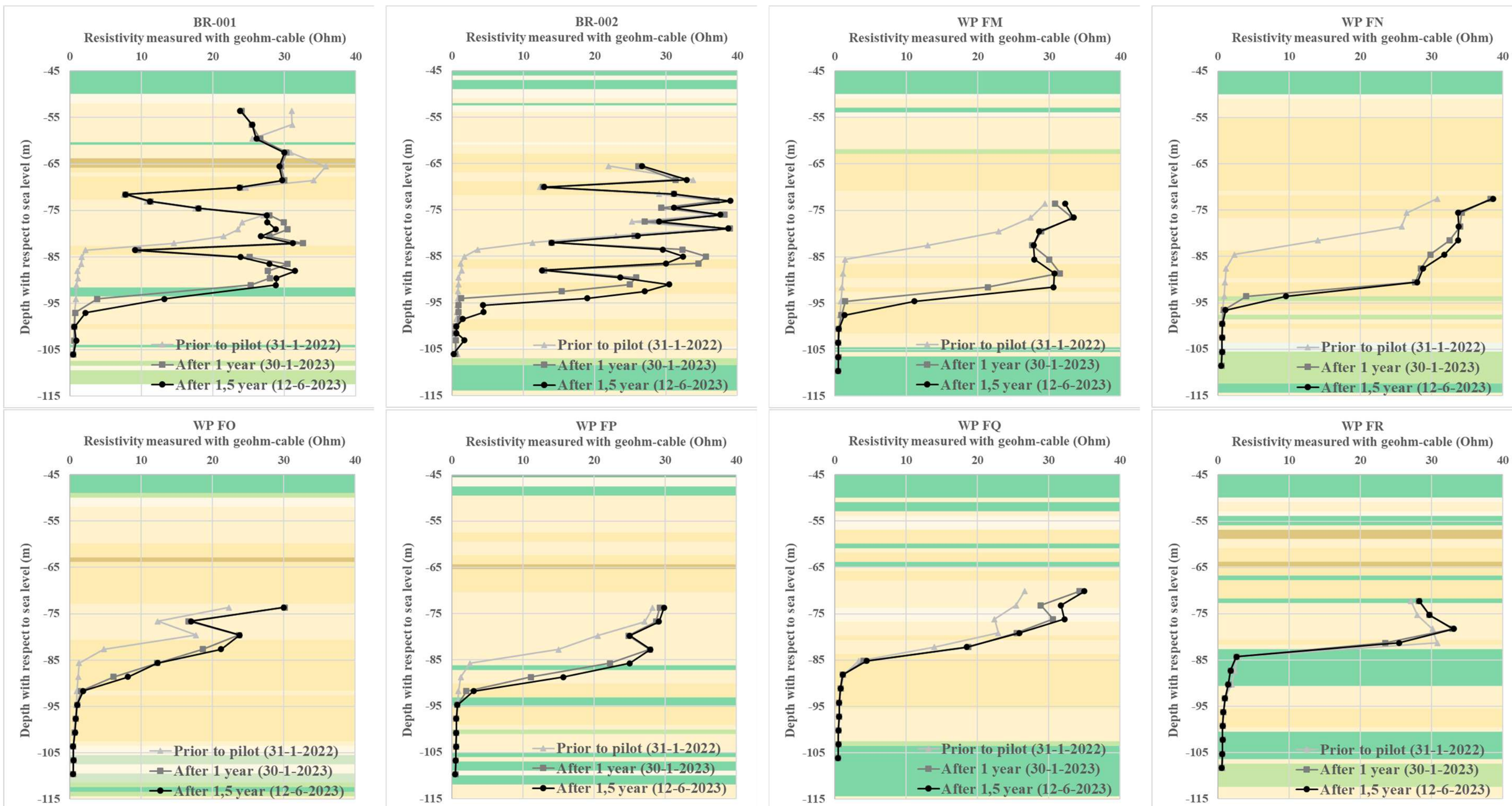
- **Geophysical borehole measurements** in BR-001, BR-002, WP FM – WP FT:
    - 10-1-2022: Reference measurements prior to the start of the pilot
    - 19-5-2022: Measurements prior to the first change of flow rates

  Planning for the remainder of the pilot:
    - 24-7-2023: Measurements prior the first rest phase.
    - 30-10-2023: Measurements at the end of the rest phase and prior to the first simulated calamity
    - 8-1-2024: Measurements when upconing has caused salinization in the first simulated calamity
    - 4-3-2024: Measurements at the end of the first simulated calamity.
    - 16-9-2024: Measurements prior to the second simulated calamity.
    - 10-2-2024: Measurements at the end of the second simulated calamity, which is also the end of the pilot.

- **Water quality measurements:**
    - January 2022: Reference measurements prior to the start of the pilot
        - All piezometers: analysis on field parameters and salinity
        - Selected piezometers and extraction screens (mainly in the transition zone from fresh to saline groundwater) in BR-001, BR-002, WP FM – WP FP: analysis on all relevant chemical constituents
    - February 2022: Calibration measurement for salinity

        - Selected piezometers and extraction screens (mainly in the transition zone from fresh to saline groundwater) in BR-001, BR-002, WP FM and WP FN: analysis on field parameters and salinity
    - March 2022: Calibration measurement for salinity
        - Selected piezometers and extraction screens (mainly in the transition zone from fresh to saline groundwater) in BR-001, BR-002, WP FM and WP FN: analysis on field parameters and salinity
    - April 2022: Measurement on chemical constituents
        - Selected piezometers and extraction screens (mainly in the transition zone from fresh to saline groundwater) in BR-001, BR-002, WP FM and WP FN: analysis on all relevant chemical constituents
    - August 2022: Measurement on chemical constituents
        - Selected piezometers and extraction screens (mainly in the transition zone from fresh to saline groundwater) in BR-001, BR-002, WP FM and WP FN: analysis on all relevant chemical constituents
    - January 2023: Calibration measurement for salinity
        - All piezometers and extraction screens that are placed at the same depth as the electrode pairs of geohm cables in BR-001, BR-002, WP FM – WP FR: analysis on field parameters and salinity
    - July 2023: Reference measurements prior to the next pilot phase
        - All piezometers: analysis on field parameters and salinity
        - All piezometers and extraction screens in BR-001, BR-002, WP FM – WP FP: analysis on all relevant chemical constituents
    - Measurements during the simulations of calamities are now being determined.

APPENDIX C: Resistivity measurements of the geohm cables in pilot wells BR-001, BR-002 and WP FM – WP FR prior to the operation of the pilot (31-1-2022), after 1 year of extracting brackish groundwater (30-1-2023) and after approximately 1,5 year of extracting brackish groundwater (12-6-2023). The background colours represent the lithology, corresponding with the legend given in Figure 2.2.



APPENDIX D: Concentration profiles of the most important chemical constituents in groundwater sampled from the extraction screens and piezometer screens of BR-002 prior to the pilot (31-1-2022).