LIFE-Freshman project

(LIFE19 CCA/NL/001222)

Monitoring progress report 2

Covering the project activities from 01/07/2023 to 30/06/2024

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1. Introduction

1.1 The Freshman project

Europe faces tremendous pressure on its coastal freshwater resources and coastal ecosystems, as described in EEA report 7/2018: European waters - Assessment of status and pressures. Overexploitation already is a major cause of freshwater loss and salinization of coastal freshwater resources (river deltas, lakes, aquifers), and climate change 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 of coastal zones, both in Europe and globally.

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 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.

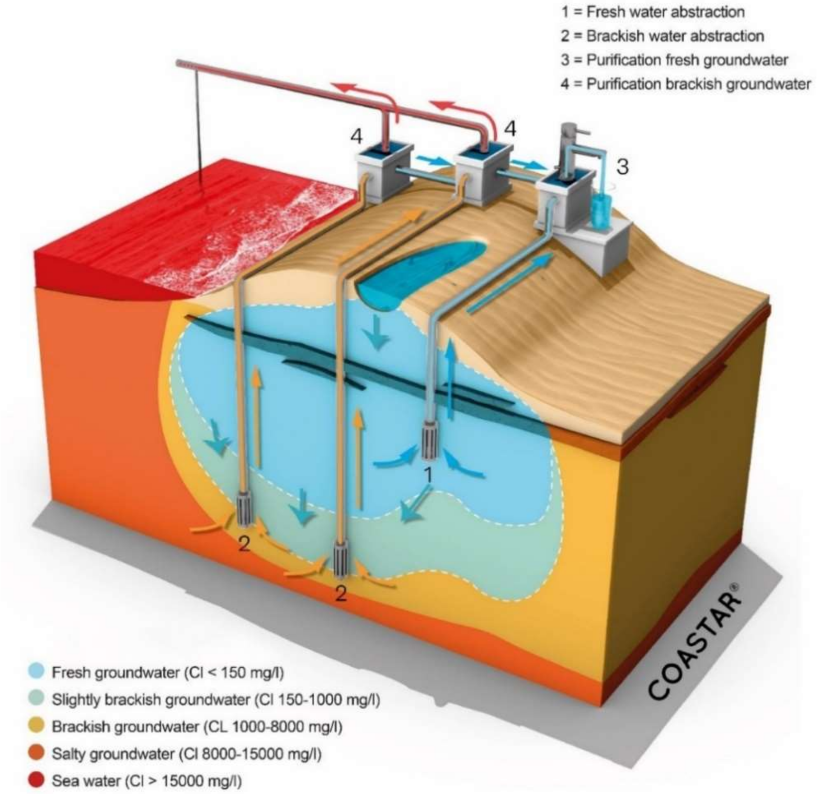


Figure 1.1: The Freshman concept: Withdrawal of deep fresh groundwater in the coastal dunes (1) leads to upconing of brackish groundwater and to salinization of the well. Withdrawal of brackish groundwater (2) leads to downconing of the interface between fresh and brackish water, increasing the volume 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 LIFE-FRESHMAN project consists of a demonstration project in The Netherlands and a replication project in Flanders. The demonstration project is located in the coastal dunes of Meijendel (The Hague), which have been used for drinking water production over a century. This coastal dune area features characteristics typical for (sandy) EU coastal zones, i.e. high urbanisation and industrialisation, high pressure on freshwater resources, vulnerable to water scarcity and droughts. The replication project is performed at Koksijde, Belgium. Koksijde is a typical coastal inland polder with saline groundwater aquifers topped by small freshwater lenses.

The main objective of the demonstration and replication projects is to monitor and control the vertical shift of the freshwater-brackish water interface in the respective aquifers, in order to protect the freshwater extraction filters from salinization (see Figure 1.1). The second objective is to increase the volume of the freshwater lens by pumping brackish groundwater at greater depth. The third objective, only applicable to the demonstration pilot, is to prove that brackish groundwater is a stable source of drinking water which can be desalinated without significant operational problems, such as well clogging or membrane fouling.

1.2 Purpose of this report

This is the second progress report of action D1: Monitoring the effects on the climate problem targeted. The first progress report covers the period from the start of the project (July 2020) until July 2023, including 17 months of practical operation of the demonstration pilot. The current report covers the period July 2023 until July 2024, i.e. a full year of additional experiments with the demonstration pilot. The replication pilot in Flanders was seriously delayed but is now ready to start. All the necessary infrastructure for the replication has been installed in Q2 2024, and the experiments will run from September 2024 until mid-2025.

According to the Freshman research proposal, the purpose of the monitoring programme is to demonstrate that the FRESHMAN technique is an effective climate adaptation measure in coastal areas. The monitoring programme intends to show that the FRESHMAN approach:

- enlarges and safeguards the availability of fresh groundwater;
- is able to create a strategic storage of fresh groundwater which can be successfully recovered in times of (extra) demand;
- has a limited hydrological impact on the environment, such that no significant negative impact on nature or infrastructure will occur;
- is easy to operate and automate.

1.3 Contents of the report

The monitoring programme of the demonstration pilot was developed to address the project objectives described in the previous section. According to the Freshman research proposal, the following items will be addressed by the monitoring programme:

1. the development of the fresh groundwater body, as indicated by the shift of the fresh-brackish water interface during groundwater extraction;
2. the quality of the various water types in the pilot. This concerns both brackish and fresh groundwater, and the water streams entering and leaving the purification hall: RO permeate (freshwater) and RO concentrate (waste stream);
3. the performance (e.g. freshwater recovery) and operational stability of the RO-membranes;

4. the hydrological effects in the vicinity of the extraction wells;
5. mapping of vegetation (species) and habitat types in the vicinity of the pilot location before, during and after the project, to assess the impact of brackish water extraction on the surrounding coastal dune ecosystems.

In this report, we will focus on items 1-3 of the demonstration pilot. Items 4-5 were found to be insignificant, i.e. we did not observe any changes on phreatic groundwater levels and associated vegetation changes in the vicinity of the extraction wells, after 2,5 years of operation.

For a general understanding of the project monitoring, it is necessary to have a clear view of the technical lay-out of the pilots. Therefore, this progress report will start with a description of the physical infrastructure of the pilots, pertaining to action C1 (demonstration) and C2 (replication).

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

2.1 The well field

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 fresh groundwater 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 B). 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 sampling. 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 the brackish extraction well 2, a schematic cross-sectional overview is also given in Figure 2.2.

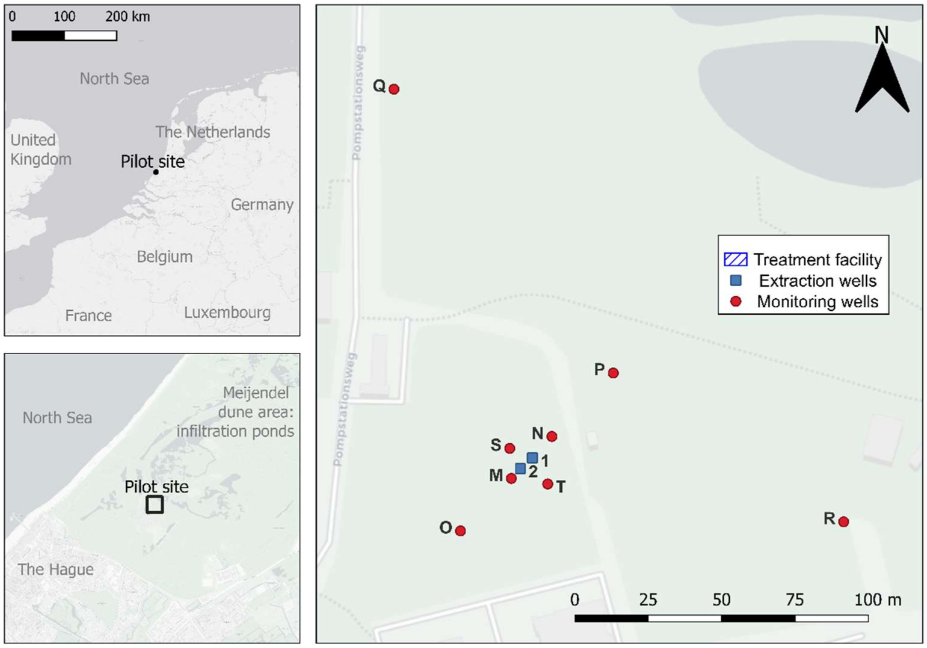


Figure 2.1: Overview of the well-field for the FRESHMAN demonstration pilot in Scheveningen. The numbers and letters given as labels correspond with the names of the wells given in Table 2.1.

Table 2.1: Overview of the metadata of the wells and of the monitoring equipment installed in each well.

	Extraction wells		Monitoring wells							
	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						

2.2 Overview of experiments

After installation, a test phase followed to determine the expected effects of brackish groundwater extraction 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 continued until the 31st of July 2023, when a rest phase was initiated. In November 2023, an operational calamity was simulated for the first time by extracting deep fresh groundwater for four months without extracting brackish groundwater. In March 2024, the brackish groundwater extraction was activated again and fresh and brackish groundwater were extracted simultaneously for approximately one month. In April 2024, the fresh groundwater extraction was stopped but the brackish groundwater extraction continued and will be active for a total of about six months. In October 2024 a second calamity will be simulated by extracting deep fresh groundwater for five months, but the extraction of brackish groundwater will continue, in order to stabilize the interface between deep fresh and brackish groundwater. The Freshman demonstration pilot will end in March 2025, but the extraction of brackish groundwater can continue to gain more experience with the treatment of brackish groundwater.

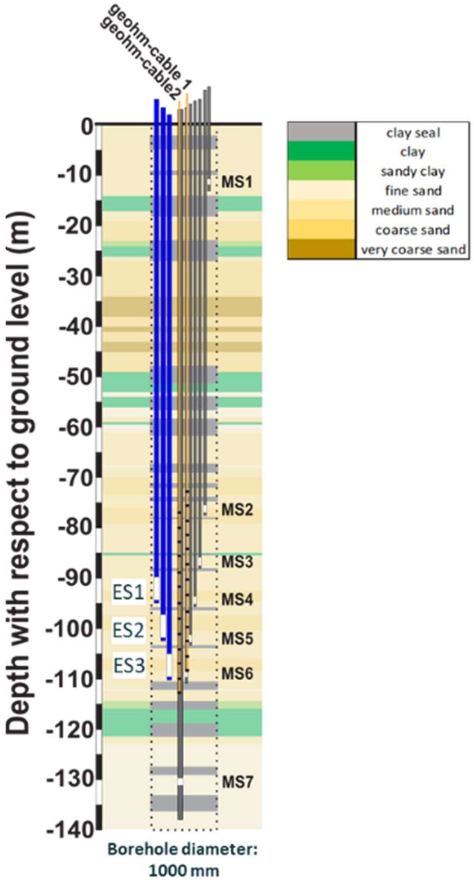


Figure 2.2: Schematic cross-sectional impression of the brackish water extraction well, with the three extraction screens indicated with 'ES', seven monitoring screens (piezometers) indicated with 'MS' and two geohm cables. The installed AH-DTS cables and LT(C)-dataloggers are omitted from this figure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

3. Action C2: Implementation of the FRESHMAN technique in Koksijde

3.1 Change in replication site: from Avekapelle to Koksijde

A conditional permit for the initial replication project in Avekapelle was granted on May 17th, 2023 to De Watergroep and Aquaduin. Despite consultancy of several partners and extensive discussions prior to filing the permit, two critical conditions remained under discussion:

- If the monitoring and measurements show that the project has a negative impact on the water quality of the water downstream in the Kromme Gracht, causing inconvenience to users (including farmers), appropriate measures must be taken so that sufficient water with suitable quality is still available.
- No (additional) pollution should be introduced into the groundwater or polder system. If it is suspected that this criterion is not met, the test shall be suspended until it can be completely ruled out.

The results of hydrogeological modelling indicated that during the test and certainly at the beginning of the extraction, water with a high salinity (up to 5700 µS/cm) would be discharged downstream in the Kromme Gracht. The formulation in the permit introduced the pertinent and serious risk that local stakeholders could request a suspension of the test based on measurement results at any time during the testing period, even at start-up. Therefore, the operational time of the pilot became uncertain due to juridical/administrative discussions. This was considered to be an unacceptable risk for pilot investment and operation. The argument was raised repeatedly to the concerned stakeholders and the permit authority, but unfortunately proved to be in vain.

An additional condition in the permit was that after the pilot test the landscape needed to be restored. Practically, this implied that the infiltration ditch (10-meter wide, 4-meter depth) needed to be filled up after the pilot to the actual situation. The original idea of the replication, i.e. investments in preparation of the replication test could be implemented as part of the full-scale scheme, thus was no longer valid. The condition to restore the landscape leads to direct additional costs for restoration and potential re-excavation works for a full scale project.

Based on these unexpected developments De Watergroep and Aquaduin considered the risk of failure of the replication project to be unacceptable. Meanwhile De Watergroep and Aquaduin developed additional projects in this region based on water reuse, treatment of surface water and seawater. One of these projects is based om groundwater extraction at a former ammunition depot near Koksijde, situated in a polder close to the coast. An economical evaluation showed that groundwater extraction at the ammunition depot with subsequent treatment at WWTP Torreele is feasible as both investment and operational costs are low.

3.2 Description of the new replication site

In 2020 Aquaduin performed a pumping test at the old ammunition site at Koksijde to determine the hydraulic parameters of the phreatic aquifer (GEOLOAB, 2020 and Lebbe, 2020). At this site, the phreatic aquifer consists of sand on top of a Tertiary clay layer. Along the site, a drainage canal (Langeleed) that drains the dunes north of it, flows from west to east over a length of 600 m (fig. 1). The site is situated close to WWTP Torreele, where water reuse is performed (Van Houtte et al., 2021), and where the extracted water from the aquifer can be treated and distributed (see Figure 3.1).

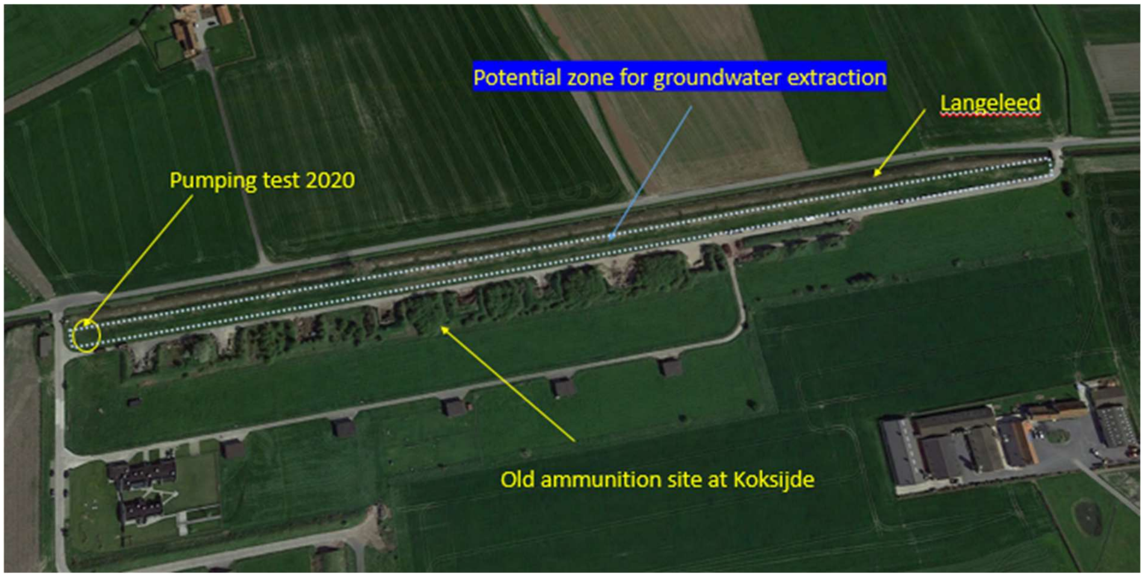


Figure 3.1: Overview of the new replication site (Koksijde): Potential zone for groundwater extraction, drainage canal of fresh dune water (Langeleed Canal) and location of the pumping test performed in 2020.

Implementing groundwater extraction in the land south of the Langeleed Canal (Figure 3.1) can be considered as river bank filtration. In this way part of the fresh water that is drained from the dunes could be 'harvested' instead of being lost to the sea.

Borehole logging (EM39-measurement) performed at the site shows that brackish to salt water is present at the bottom of the phreatic aquifer (Figure 3.2).

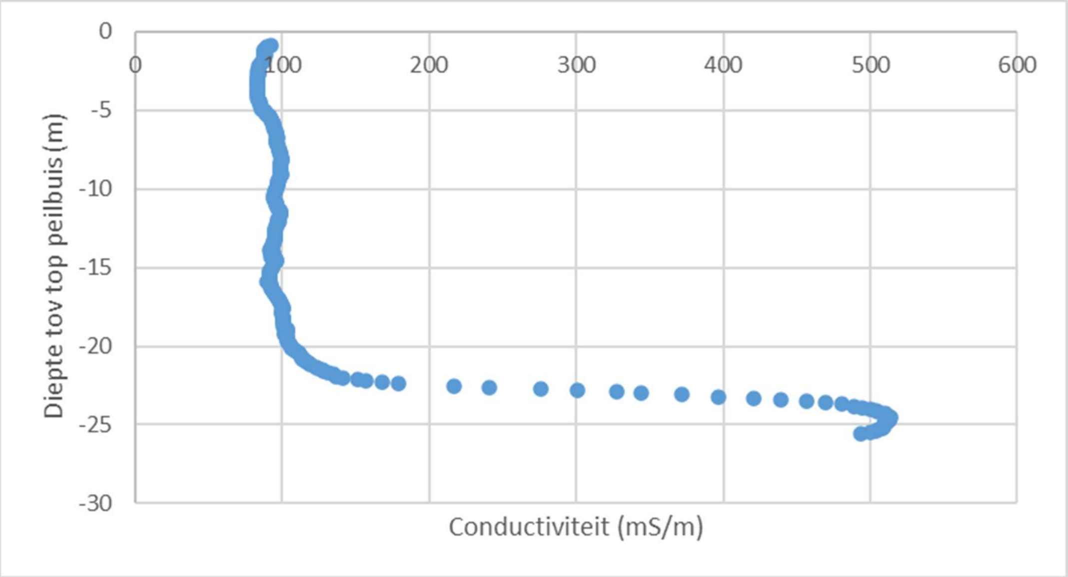


Figure 3.2: Result of borehole logging in the phreatic aquifer at the old ammunition site in Koksijde.

The presence of brackish to salt water at the bottom of the phreatic aquifer poses a threat to potential fresh groundwater extraction. Further investigation is needed how to control the upconing of brackish water and this research is proposed as the new replication project for the LIFE FRESHMAN project in which both Aquaduin and De Watergroep will participate. It fits within the concept of LIFE FRESHMAN as the phreatic fresh groundwater lens at the site can presumably be maintained and exploited by a combination of river bank filtration (push) and brackish groundwater extraction (pull).

The research proposed in the new replication project involves pumping tests both at the upper and lower part of the phreatic aquifer and a modelling of the future groundwater extraction. In this way the effect of the brackish groundwater present at the lower part of the aquifer on the freshwater extraction in the upper part of the aquifer can be investigated, and potentially mitigated.

The objective of the new replication test is to make the best choice for the configuration of the abstraction wells to avoid extraction of brackish water on the long term. In other words, to maintain a stable source of drinking water, in spite of the potential threat of salinization.

3.3 Permits and realization of the well field

For the replication pilot, an extra pumping well in the lower (brackish) part of the aquifer (PPd) and three additional monitoring wells (PB5, PB6o/d and PB7) were deemed to be necessary, see Figure 3.3. De Watergroep would perform the drillings and the mathematical modelling. Aquaduin is responsible for the permits, performing the pumping tests and the monitoring.

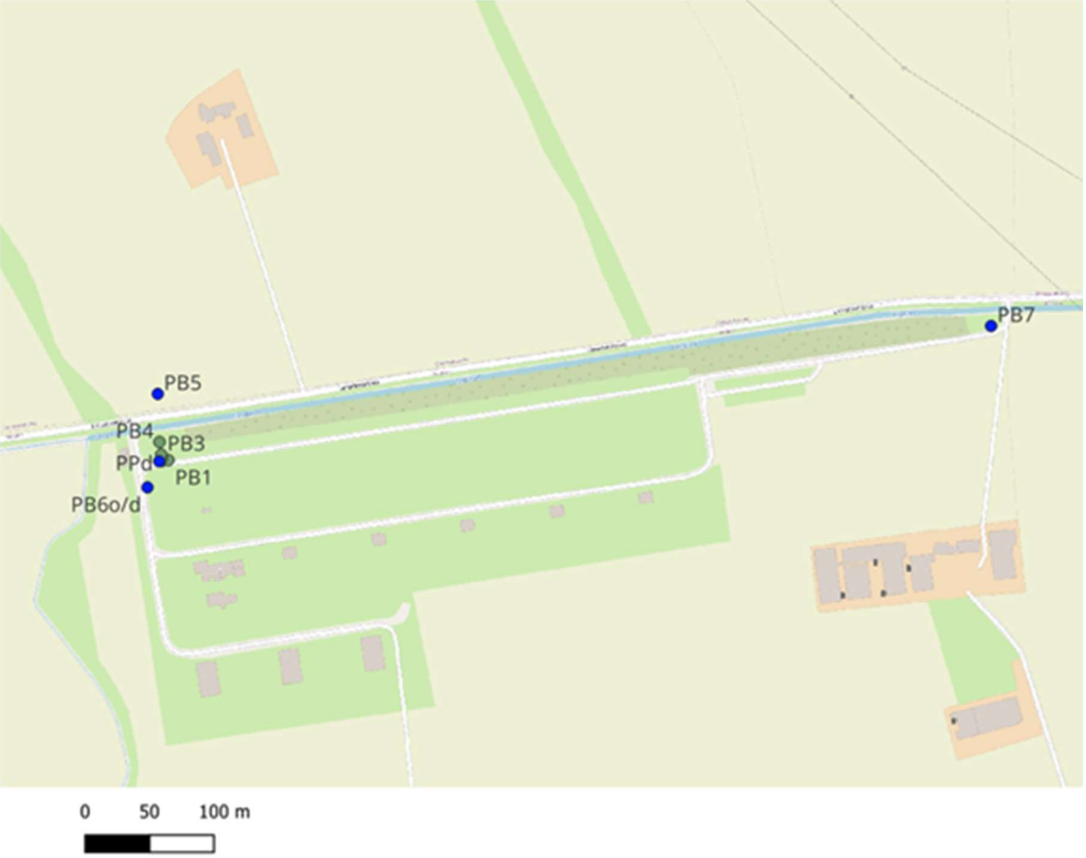


Figure 3.3: Existing (green dots) and new (blue dots) wells at the replication site.

The permit for the first pumping test was granted by the Municipality of Koksijde in April 2024. Based on price comparison (multiple quotations), the pumping test was awarded to GEOLAB and the EM39-measurements to the Geology Department of the University of Ghent (decision of the Board of Directors of Aquaduin, May 29th, 2024).

In June 2024, De Watergroep installed the pumping well and monitoring wells as agreed in the program (Figure 3.4 and Figure 3.5).

Figure 3.4: Four new wells installed by De Watergroep in June 2024.

Figure 3.5: Drilling of monitoring well PPo/d.

The well scheme of the deep pumping well PPd is added inFigure 3.6. As this well is very important for the replication test, a short test pumping was carried out for approximately one hour. Pumping was carried out at an average of 16,74 m³/h and this resulted in a reduction of the level in the well of 4,7 m. The specific well capacity is then 3,6 m²/h.

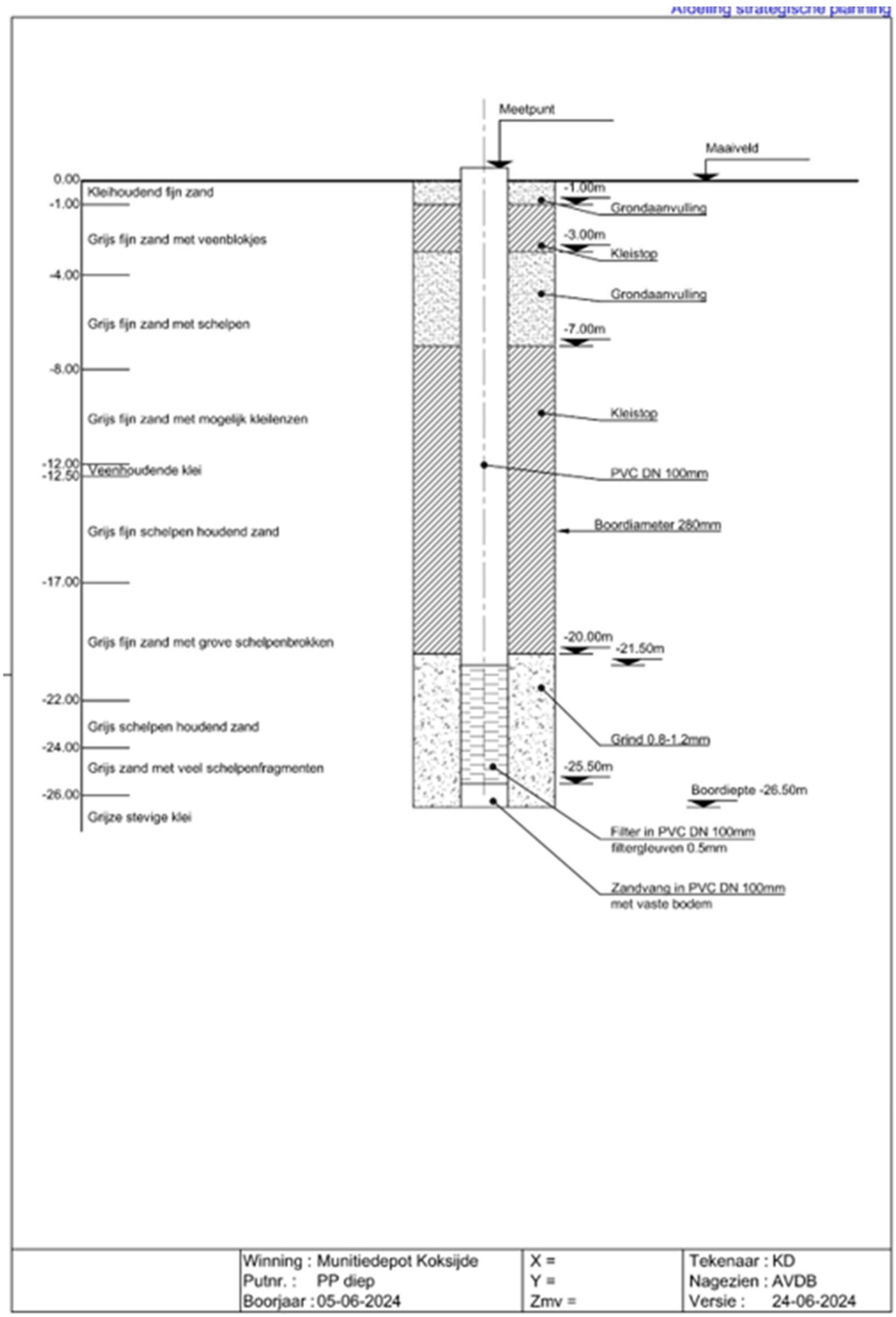


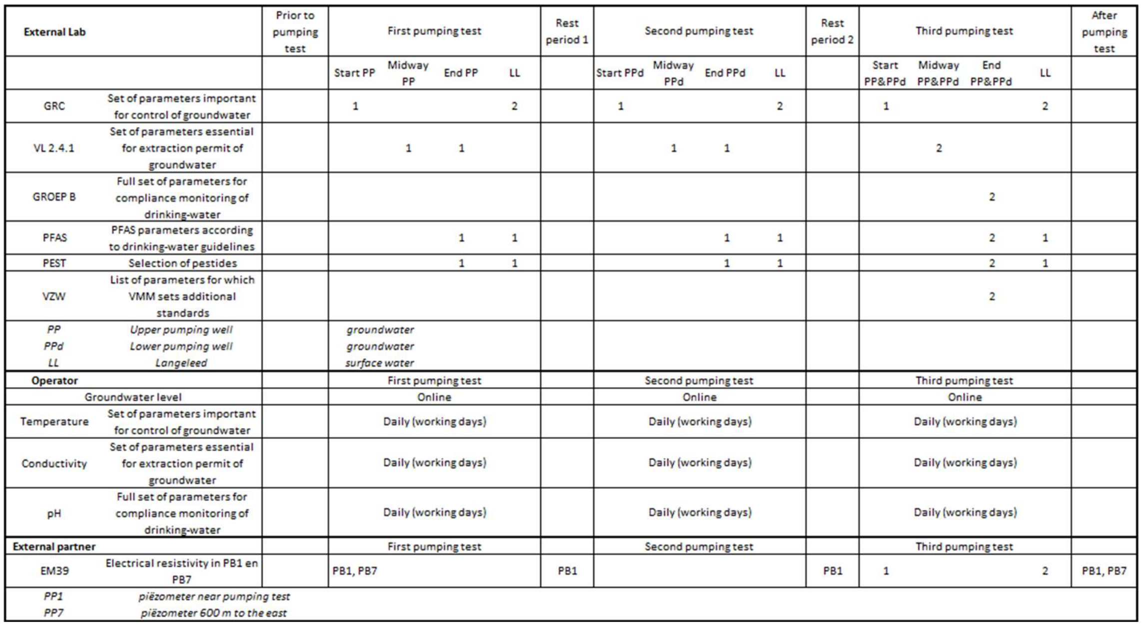
Figure 3.6: Well scheme of deep pumping well PPd.

A report was produced on the installation of the well field and its operational functioning, based on short pumping tests (Vandenbohede, 2024). This is the formal SAT report for the technical infrastructure of the replication site.

3.4 Project planning and monitoring plan

The scheme for the pumping tests and monitoring plan was proposed to the Steering Group of LIFE FRESHMAN and endorsed. Prior to the start of the pumping test electrical resistivity tests will be performed in PB1 and PB7. The first pumping test is due to start half September 2024. The experimental tests will run for four months and will be terminated in Q1 2025 (see Table 3.1).

Table 3.1: Planning of the experiments of the replication project.



External Lab		Prior to pumping test	First pumping test				Rest period 1	Second pumping test				Rest period 2	Third pumping test				After pumping test
			Start PP	Midway PP	End PP	LL		Start PPd	Midway PPd	End PPd	LL		Start PP&PPd	Midway PP&PPd	End PP&PPd	LL	
GRC	Set of parameters important for control of groundwater		1			2		1			2		1			2	
VL 2.4.1	Set of parameters essential for extraction permit of groundwater			1	1				1	1				2			
GROEP B	Full set of parameters for compliance monitoring of drinking-water														2		
PFAS	PFAS parameters according to drinking-water guidelines				1	1				1	1				2	1	
PEST	Selection of pestides				1	1				1	1				2	1	
VZW	List of parameters for which VMM sets additional standards														2		
PP *PPd* *LL*	*Upper pumping well* *Lower pumping well* *Langeleed*		*groundwater* *groundwater* *surface water*														
Operator			First pumping test					Second pumping test					Third pumping test				
Groundwater level			Online					Online					Online				
Temperature	Set of parameters important for control of groundwater		Daily (working days)					Daily (working days)					Daily (working days)				
Conductivity	Set of parameters essential for extraction permit of groundwater		Daily (working days)					Daily (working days)					Daily (working days)				
pH	Full set of parameters for compliance monitoring of drinking-water		Daily (working days)					Daily (working days)					Daily (working days)				
External partner			First pumping test					Second pumping test					Third pumping test				
EM39	Electrical resistivity in PB1 en PB7		PB1, PB7				PB1					PB1	1			2	PB1, PB7
PP1 *PP7*	*piëzometer near pumping test* *piëzometer 600 m to the east*																

For water quality analyses, existing packages will be used based on an official tender performed in 2023.

3.5 References

- GEOLAB, 2020. Grondboringen en Pompproef Koksijde. Verslag 20.06.104 – 30/06/2020, 10 p.
- Lebbe, L., 2020. Interpretatie van pompproef uitgevoerd nabij de Langeleed te Koksijde. Hydrogeo Consult, 20 p.
- Vandenbohede, A., 2024. LIFE FRESHMAN – Replicatiesite munitiedepot Koksijde. boorbeschrijving en putschema’s bijkomende putten, 11 p.
- Van Houtte, E. and Verbauwhede, J., 2021. Case Study 25: Water recycling with Managed Aquifer Recharge in sand dunes of St-André (Koksijde) as one of the multiple safety barriers for drinking water to Veurne area, Belgium, p 313-322 in: Zheng, Y., Ross, A., Villholth, K.G. and Dillon, P. (eds.), 2021. Managing Aquifer Recharge: A Showcase for Resilience and Sustainability. Paris, UNESCO.

4 Action D1: Monitoring the effects on the climate problem targeted (Demo project)

4.1 Dynamics of the freshwater lens

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 of the extracted groundwater (EC_w) are registered every five minutes and are given in Figure 4.2. The latter provides a good proxy for the salinity of the groundwater, as shown by its correlation with the chloride concentration (Figure 4.1). The results of the first phase of brackish groundwater extraction (January 2022 – July 2023) are already reported in the monitoring progress report of 2023 and are not further elaborated upon in this report.

The extraction of brackish groundwater was terminated on July 31, 2023, and succeeded by a rest phase of approximately three months. Subsequently, fresh groundwater was extracted with well screen 1.1 for about four months with a rate that was increased stepwise from 25 to 50 m^3/h. The EC_w of the extracted groundwater gradually increased during this period from 0.06 S/m (fresh) to approximately 0.38 S/m (slightly brackish), revealing the consciously induced salinization of well screen 1.1.

When the salinization slightly stabilized, well screen 1.2 was activated. Consequently, the EC_w of groundwater extracted by well screen 1.1 decreased to 0.12 S/m. This indicates that the deeper extraction is successful in reverting the salinization of freshwater well 1.1. After this phase of simultaneous extraction of fresh and brackish groundwater, the fresh groundwater extraction was deactivated and only brackish groundwater was extracted with the deeper well screens. Just like in the first phase of brackish groundwater extraction, the average depth of the extraction was gradually increased by stepwise decreasing the flow rate of the upper screens and increasing the flow rate of the lower screens. Consequently, the EC_w of the groundwater extracted with each well screen gradually decreased, indicating that the extracted groundwater freshened. After each change of flow rates, the EC_w of the combined extracted groundwater gradually stabilized, just like in the first phase of brackish groundwater extraction.

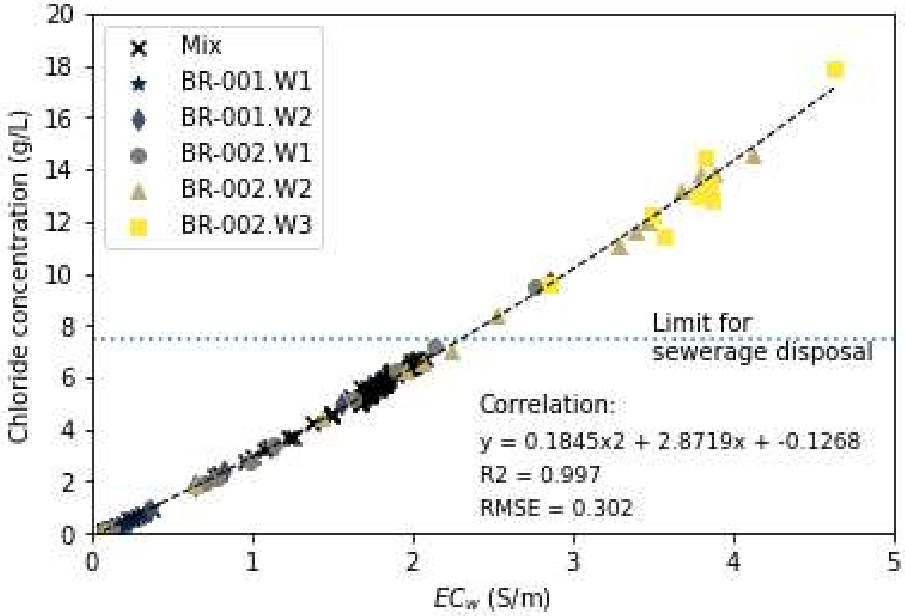


Figure 4.1: Correlation between EC_w and the concentration of chloride measured in the extracted groundwater.

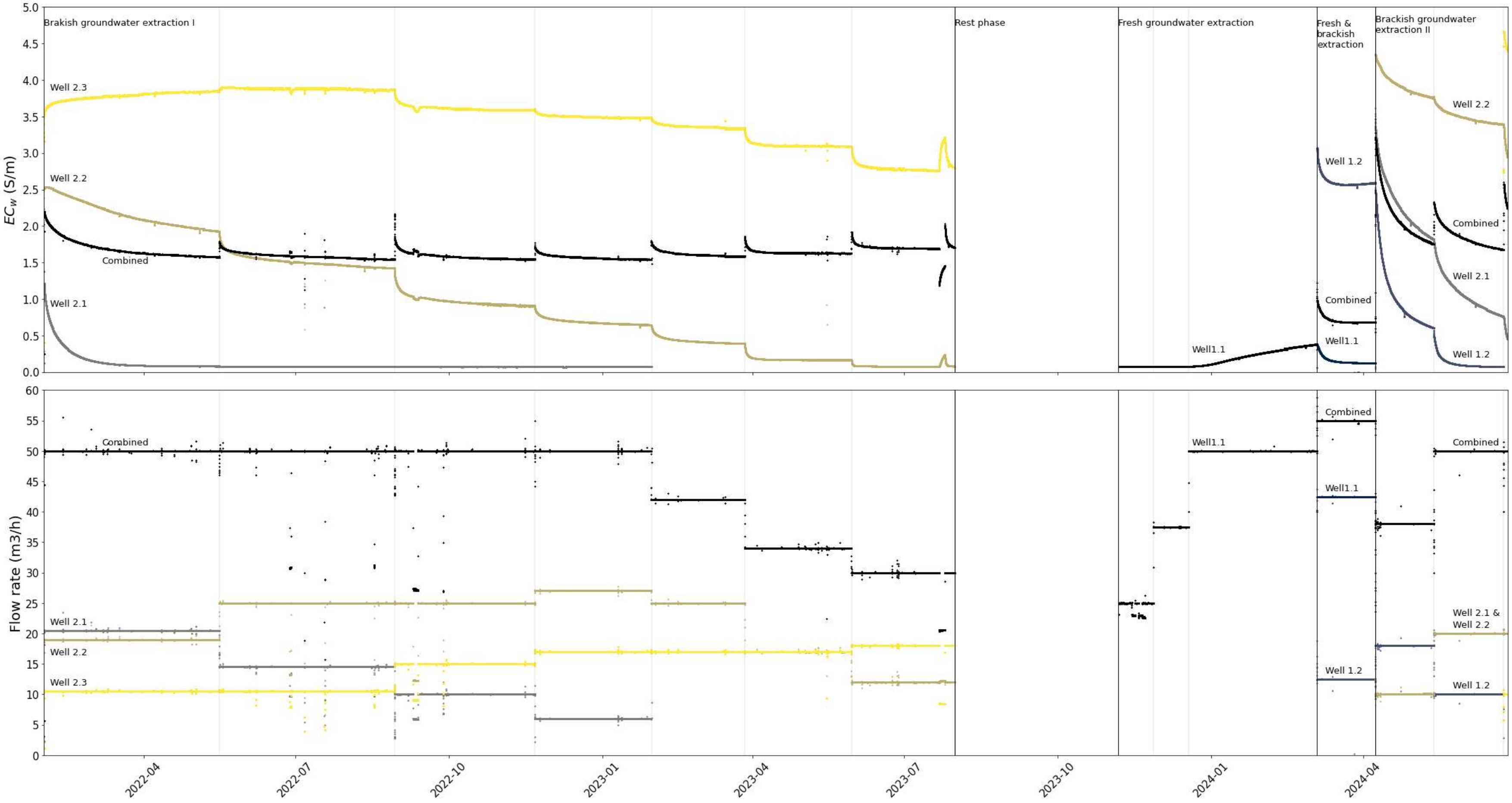


Figure 4.2: Electrical conductivity measured in the extracted groundwater (EC_w; top) and flow rate of the groundwater extraction (bottom).

The chloride concentration of the in situ groundwater was analysed at different stages during the pilot. The results of these measurements are given in Figure 4.3. The individual panels of Figure 4.3 will be discussed here in chronological order.

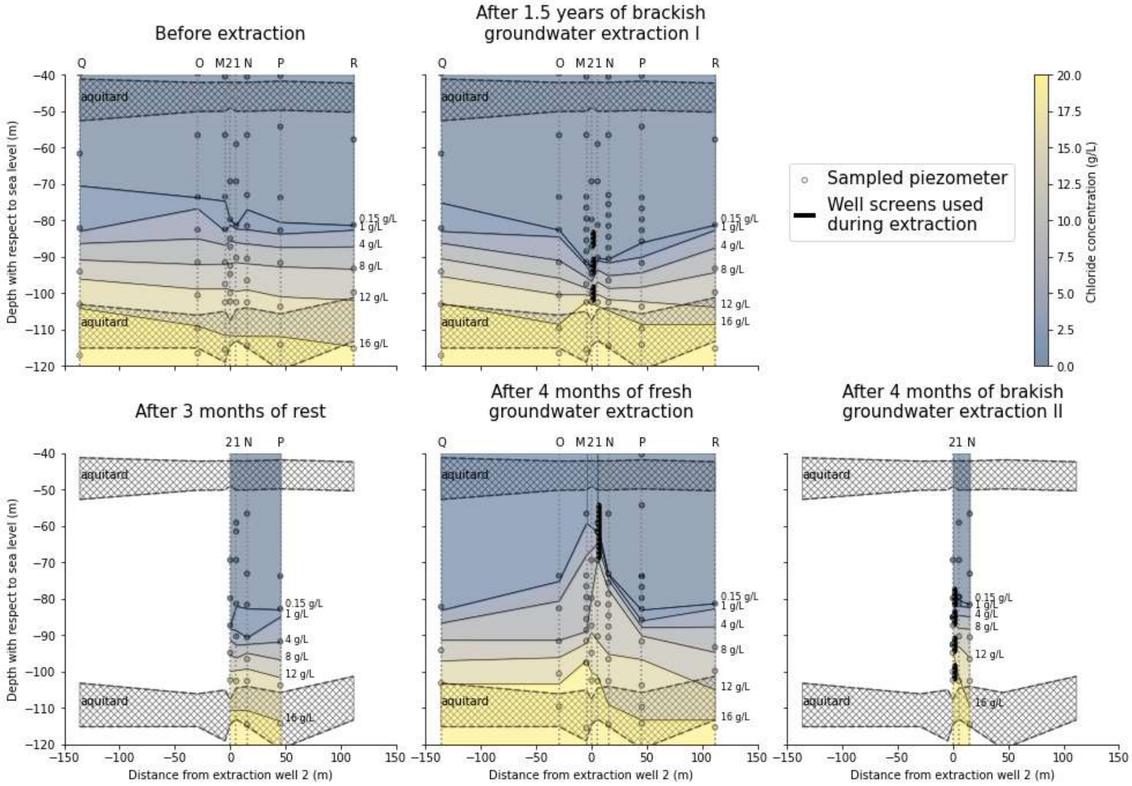


Figure 4.3: Indicative profiles of the chloride concentration during the pilot. The isochlors are linearly interpolated from the actual measurements. The reporting period for this progress report covers the three figures on the bottom: a) After three months of rest; b) After four months of deep freshwater extraction; c) After resuming brackish groundwater extraction during four months.

Figure 4.3, top two panels (February 2022 - July 2023): After the first phase of brackish groundwater extraction (18 months in operation), the transition from fresh to brackish groundwater shifted down by about 10 - 15 meters in the centre of the well field. This freshening was, to a lesser degree (five meters downward shift), also observed at observation wells O and P. At observation wells Q and R, located 136 and 112 meters from the extraction wells, almost no change was observed in the salinity distribution. 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. In contrast, slight salinization occurred at greater depths due to upconing, but this process was mainly prevented by the underlying aquitard.

Figure 4.3, panel bottom left (August - October 2023): After three months of resting, the original salinity distribution was partially restored. However, for a full restoration to the original salinity distribution prior to the extraction, a longer rest phase would have been required.

Figure 4.3, panel bottom middle (November 2023 - February 2024): When fresh groundwater was extracted, the effects were again most dominant at the centre of the well field and diminished away from the extraction. However, now the boundary between fresh and brackish groundwater moved upwards by 20 meters with respect to its original position. Hence, salinization occurred as a response to the extraction of deep fresh groundwater. The deeper saline groundwater also moved upwards, reflecting more significant upconing.

Figure 4.3, panel bottom right (March - June 2024): When brackish groundwater was subsequently extracted, the transition from fresh to brackish groundwater moved down again, resulting in freshening of the aquifer. The two deep freshwater wells (1.1 and 1.2) turned from brackish into fresh again, as can be seen on the right side of Figure 4.2. This clearly indicates that salinization of the deep freshwater wells can be reversed by extraction of brackish groundwater. The freshening that is evident after 4 months of brackish groundwater extraction does not have the same magnitude as the freshening observed after the first 1.5-year period of brackish groundwater extraction. However, the extraction will continue for approximately three more months and will probably further increase the extent of freshening within the aquifer.

4.2 Hydraulic heads

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. The hydraulic heads measured in the phreatic aquifer and in aquifers 2, 3 and 4, are given in Figure 4.4. Aquifer 3 hosts the extraction screens of the pilot wells 1 and 2. Hydraulic heads measured within that aquifer responded to changes in flow rates of the pilot. However, the hydraulic heads in this aquifer responded more significantly to (de)activation of series E, a series of conventional fresh groundwater wells with its extractions screens positioned in aquifer 2 at approximately 300 meters to the north of the pilot site with a total flow rate of 250 m^3/h. The response to this extraction is even more evident from the hydraulic heads of aquifer 2, whereas no response to the pilot extraction is observed in that aquifer. The phreatic groundwater levels did not respond clearly to either of the extractions. As such, the pilot results reveal that the extraction of fresh and brackish groundwater from aquifer 3 does not have a significant impact on hydraulic heads and groundwater levels in the overlying phreatic aquifer and aquifer 2, due to the presence of aquitards. As phreatic groundwater levels are not influenced by the pilot, it follows that impacts of the pilot on nature values will be insignificant. However, increasing the flow rate may cause lowering of heads in aquifer 2, as suggested by the response of heads to the (de)activation of series E.

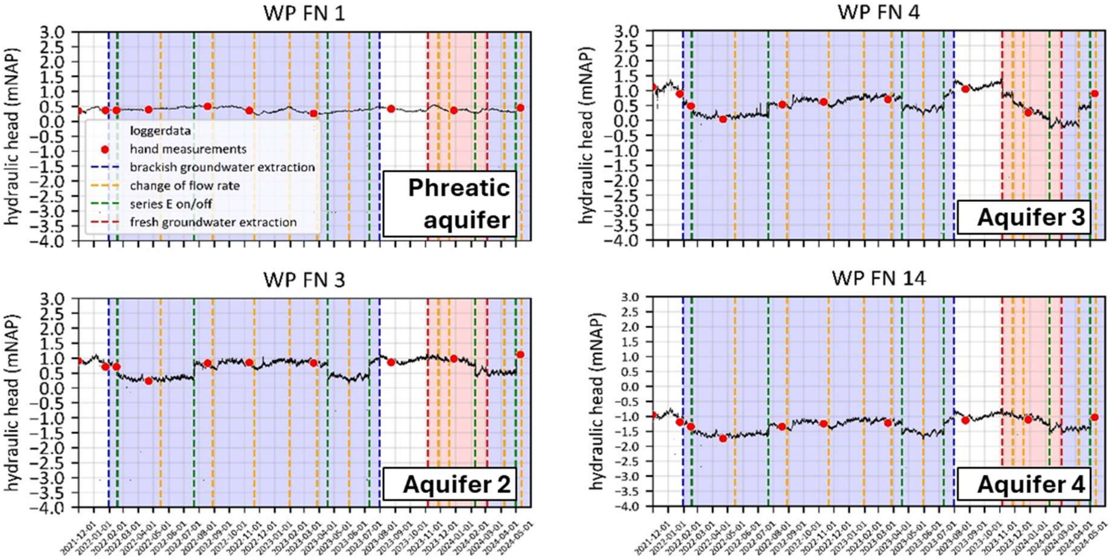


Figure 4.4: Hydraulic heads measured in WP FN 1 (top left), 3 (bottom left), 4 (top right) and 14 (bottom right), which are positioned in the four different aquifers.

4.3 Other groundwater monitoring efforts

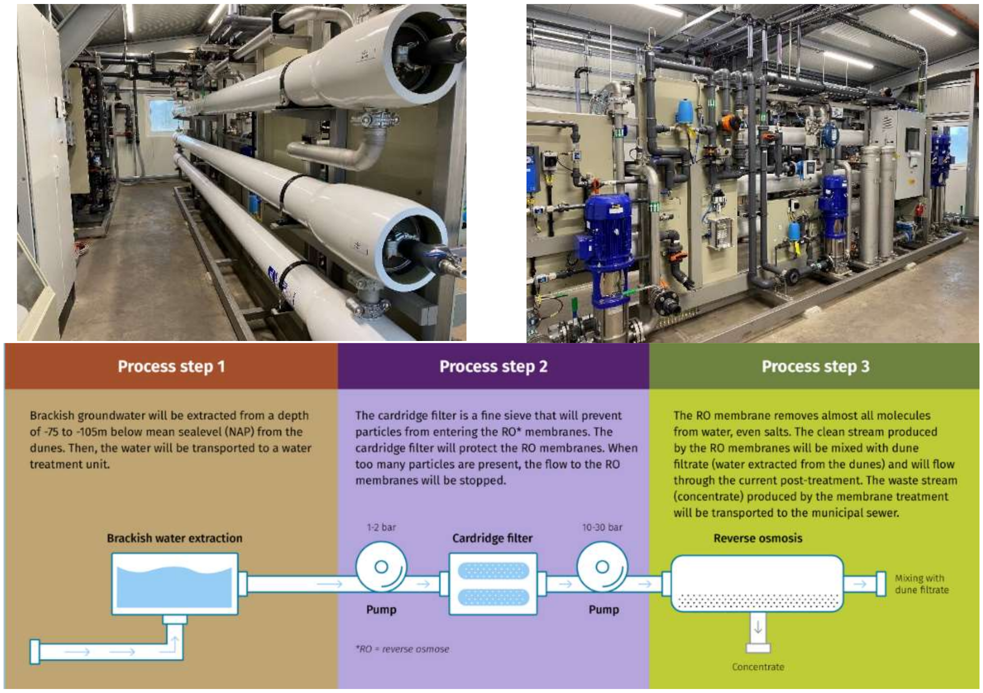
Multiple geophysical measurements (geophysical borehole measurements and GEM data from geohm cables) have been carried out to complement the salinity data obtained from water quality analyses (APPENDIX B). The Crosshole-ERT and AH-DTS are continuously active. The results of these measurement techniques will be presented in other deliverables.

The chemical water quality of the groundwater has been analysed five times up to now. For brevity, only the most important water quality results of the reference measurement prior to the pilot (31-1-2022) in extraction well BR-002 are included in this report (APPENDIX C).

4.4 Treatment of brackish groundwater

4.4.1 Introduction

Since January 2022, we have collected brackish groundwater and later also deep fresh groundwater, using five abstraction wells (see Figure 4.2). This water is transported to a reverse osmosis (RO) treatment system, which is illustrated in Figure 4.5. The groundwater is of good water quality; therefore, no pretreatment is required, except for a cartridge filter to as a protective measure. Deep groundwater contains no oxygen, and during treatment the water is kept in this anaerobic state. This means that some gases (hydrogen sulphide and methane) will be present in the freshwater produced by the membranes.



Brackish groundwater will be extracted from a depth of -75 to -105m below mean sealevel (NAP) from the dunes. Then, the water will be transported to a water treatment unit.

The cardridge filter is a fine sieve that will prevent particles from entering the RO* membranes. The cardridge filter will protect the RO membranes. When too many particles are present, the flow to the RO membranes will be stopped.

The RO membrane removes almost all molecules from water, even salts. The clean stream produced by the RO membranes will be mixed with dune filtrate (water extracted from the dunes) and will flow through the current post-treatment. The waste stream (concentrate) produced by the membrane treatment will be transported to the municipal sewer.

Figure 4.5: *Water treatment scheme of the brackish groundwater pilot. The RO tubes are shown on the top left panel and the cartridge filters on the top right panel (two vertical tubes).*

The RO membranes produce a constant stream of demineralized water, called permeate, and a waste stream, called concentrate. The system is flux driven, which means that the flux – production flow per membrane surface area in liter per m^2 per hour (LMH) – remains constant during operation while the transmembrane pressure (TMP) varies. Antiscalant chemicals are used to prevent scaling of the RO membranes. During the operation, the booster pump is not in use.

4.4.2 Pumping regime and types of water abstracted

In the reporting period, between 1-7-2023 and 30-06-2024, three phases of the research can be discriminated: 1) a resting period of three months without groundwater abstraction, 2) deep freshwater abstraction during five months and 3) resumption of brackish groundwater abstraction for three months (see Table 4.1). The conductivity of the abstracted groundwater is shown in Figure 4.6. Obviously, the conductivity varies with the abstraction of different types of water, as shown in Table 4.1.

Table 4.1: Overview of flows of each abstraction well, total abstraction and type of water abstracted in the reporting period.

Date	Well 1.1	Well 1.2	Well 2.1	Well 2.2	Well 2.3	Total abstr.	Unit	Type of water abstracted
30-7-2023	0	0	0	0	0	0	m3/h	No abstraction
6-11-2023	25					25	m3/h	Deep freshwater
27-11-2023	37					37	m3/h	Deep freshwater
18-12-2023	50					50	m3/h	Deep freshwater
7-3-2024	42,5	12,5				55	m3/h	Deep freshwater
8-4-2024	0	18	10	10		38	m3/h	Brackish water
13-5-2024	0	10	20	20		50	m3/h	Brackish water
24-6-2024	0	0	20	20	10	50	m3/h	Brackish water

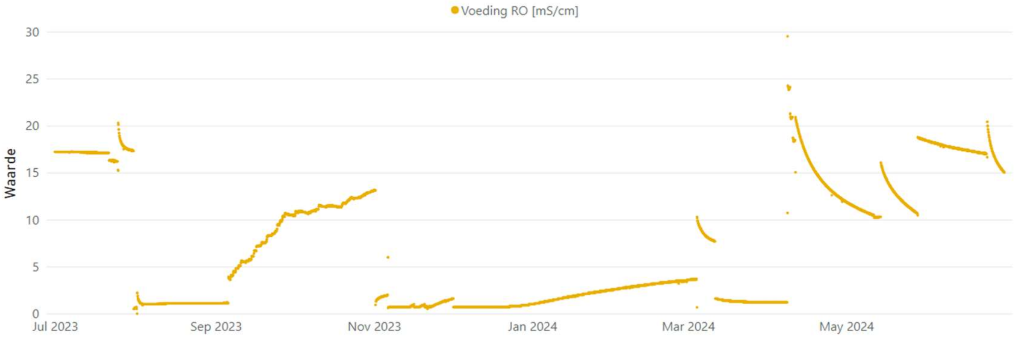


Figure 4.6: The conductivity in mS/cm of the influent water of the RO in the reporting period.

4.4.3 General operation and water quality aspects

During the resting period, the RO membranes were preserved, and the system was not in use for three months. Subsequently, the deep freshwater well 1.1 was switched on and the pumping continued for five months. In the beginning (November 2023), the groundwater pumped by this well was truly fresh, but after two months salinization occurred (upconing) and the well became brackish, as shown in Figure 4.6. The pumping rate of the deep freshwater well varied between 25 to 50 m3/h from 6-11-2023 to 7-4-2024 (see Table 4.1). During this period the recovery was set to 80% and the flux was 18 liter per m^2 per hour (LMH). During the deep freshwater abstraction period, no operational problems occurred. The water quality of the influent and the permeate are shown in Table 4.2. The maximum influent concentrations for ammonium, chloride, magnesium and hydrogen carbonate were higher than the requirements for drinking water, as shown in Table 4.2. The RO membranes were able to reduce the concentrations of these compounds to below the national drinking water standards. The maximum chloride concentration of the pumped groundwater was 2759 mg/L, but the average concentration was 433 mg/L. Total hardness, calculated as the amount of Ca^{2+} and Mg^{2+} in mmol/l, should be >1 mmol/l when 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. However, after mixing RO permeate with current drinking water the legal standard will be met. Methane poses a real challenge to drinking water production, as this gas is not removed during RO treatment. Therefore, a degassing step will be required during posttreatment, which is included in the regular drinking water process of Dunea (cascades). For buffering, the bicarbonate concentration in drinking water should be higher than 60 mg/l. After mixing with pumped dune water, the average of 6 mg/l in RO permeate is elevated sufficiently to comply with this standard.

Table 4.2: Overview of maximum influent concentrations and average and maximum permeate concentrations measured from November 2023 until April 2024 during the deep freshwater abstraction. Parameters in red do not meet the requirements, being either the internal Dunea standard or the National Drinking Water Standard (DWB).

Deep freshwater well 1.1						
Parameter	Unit	Influent (max)	Permeate (avg)	Permeate (max)	Requirement	Standard
Ammonium (N/l)	mg/l N	2,03	0,046	0,065	0.04	Dunea
Arsenic	µg/l As	0,210	<0,03	0,035	1	Dunea
Barium	µg/l Ba	253	<1	<1	20	Dunea
Boron	mg/l B	0,115	0,045	0,088	0.125	Dunea
Calcium	mg/l Ca	201	<0,05	0,161	Hardness > 1 mmol/l	DWB
Chloride	mg/l Cl	2759	6,5	49,9	150	DWB
Fluoride	mg/l F	0,378	<0,01	0,012	1	DWB
Iron	mg/l Fe	3,52	0,001	0,005	0.05	Dunea
Kalium	mg/l K	24,9	0,169	0,545		
Copper	µg/l Cu	1,28	0,192	1,2	2000	DWB
Mercury	µg/l Hg	<0,05	<0,05	<0,05	0.25	Dunea
Lead	µg/l Pb	3,63	<0,5	<0,5	10	DWB
Magnesium	mg/l Mg	167	<0,05	<0,05	Hardness > 1 mmol/l	DWB
Manganese (ug/l)	µg/l Mn	518		0,25		
Methane	µg/l	91,0	77,5	90,0		
Natrium	mg/l Na	1410	5,58	34,7	150	DWB
Nitrate	mg/l N	0,605	0,103	0,947	3	Dunea
Nitrite	mg/l N	0,001	0,000	0,001	0.0075	Dunea
Orthophosphate	mg/l P	0,486	0,007	0,019		
Sulfate	mg/l SO4	407	<2	<2	75	Dunea
Sulfide	mg/l S	<0,1	<0,1	<0,1		
Total phosphate	mg/l P	0,58	0,013	0,052	0.15	Dunea
Hydrogen carbonate	mg/l HCO3	250	5,99	7,81	> 60	DWB

In the next pumping phase, starting on April 8, 2024, the abstraction wells 1.2, 2.1, 2.2 and 2.3 collected 38 to 55 m3/h with varying flows per well (see Table 4.1). During this period the recovery was set to 60% and the flux was 15 liter per m^2 per hour (LMH). The recovery and flux were set to these values after evaluation of the recovery and flux experiments conducted in 2023. These settings were used to do a long-term test with brackish water abstraction. During the brackish water abstraction period, no operational problems occurred. After this long-term test it can be concluded that a flux of 15 LMH and a recovery of 60% are representative values for a full-scale operation. The water quality of the influent and the permeate are shown in Table

4.3. Some parameters were higher than the requirements for drinking water. But as explained before, after mixing RO permeate with current drinking water the legal standards will be met.

Table 4.3: Overview of maximum influent concentrations and average and maximum permeate concentrations measured from April 2024 until June 204 during the brackish water abstraction. Parameters in red do not meet the requirements, i.e. the internal Dunea standard or National Drinking Water Standard (DWB).

Brackish water Component	Unit	Influent (max)	Permeate (avg)	Permeate (max)	Requirement	Standard
Ammonium (N/l)	mg/l N	2,68	0,085	0,114	0.04	Dunea
Arsenic	µg/l As	0,35	<0,03	0,05	1	Dunea
Barium	µg/l Ba	263	<1	<1	20	Dunea
Boron	mg/l B	0,363	0,188	0,275	0.125	Dunea
Calcium	mg/l Ca	326	0,077	0,131	Hardness > 1 mmol/l	DWB
Chloride	mg/l Cl	6206	115	158	150	DWB
Fluoride	mg/l F	0,402	<0,01	<0,01	1	DWB
Iron	mg/l Fe	5,22	0,002	0,005	0.05	Dunea
kalium	mg/l K	86,9	1,73	2,58		
Copper	µg/l Cu	2,32	0,383	0,48	2000	DWB
Mercury	µg/l Hg	<0,05	<0,05	<0,05	0.25	Dunea
Lead	µg/l Pb	1,71	<0,5	<0,5	10	DWB
Magnesium	mg/l Mg	379	0,060	0,102	Hardness > 1 mmol/l	DWB
Manganese	mg/l Mn	0,776	0,000	0,001		
Methane	µg/l	53,0	44,4	54,0		
Natrium	mg/l Na	3331	73,4	102	150	DWB
Nitrate	mg/l N	0,994	0,110	0,291	3	Dunea
Nitrite	mg/l N		0,000	0,001	0.0075	Dunea
Orthophosphate	mg/l P	0,244	0,007	0,009		
Sulfate	mg/l SO4	837	<2	<2	75	Dunea
Sulfide	mg/l S	<0,1	<0,1	<0,1		
Total phosphate	mg/l P	0,919	0,013	0,019	0.15	Dunea
Hydrogen carbonate	mg/l HCO3	265	6,33	7,42	> 60	DWB

4.4.4 Flux experiments

To test the robustness of the RO system, the flux across the RO membranes has been temporarily increased. We wanted to investigate whether a temporary flux increase is feasible if water production needs to be increased. This test is done to investigate if a temporary increase in flux does not cause a significant increase in TMP and pressure when the flux is reduced back to the original setting. The flux in the original setting is 15 LMH, which was temporarily increased to 18 LMH for two weeks. During this experiment, the chloride concentration of the influent was 5,6 grams per liter. In Figure 4.7 the flux increase is shown. In Figure 4.8 the change in TMP is shown before and after the increase of the flux.

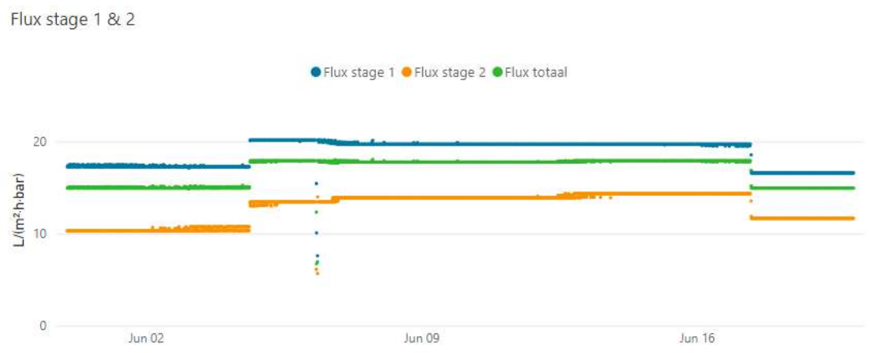


Figure 4.7: Flux of stage 1 (blue), stage 2 (orange) and the total flux (green) before and after the increase of the flux from 15 to 18 LMH.

When switching back to the flux of 15 LMH, there is an increase of 0.4 bar in the TMP and pressure compared to the TMP and pressure before the flux increase. During the period of the higher flux, the flux in stage 1 is decreasing while the flux in stage 2 is increasing. The reason for this difference needs to be further investigated. Maintenance took place on June 6, which meant the water treatment was off for a short time. This affected the TMP and the flux, which can also be seen in Figure 4.7 and Figure 4.8. The temporary shutdown of the pilot might be the reason why the TMP and pressure were increased after the increase of the flux. These experiments will be repeated in the coming months to gain a better understanding of the influences of a temporary flux increase on the TMP and pressure of the system.

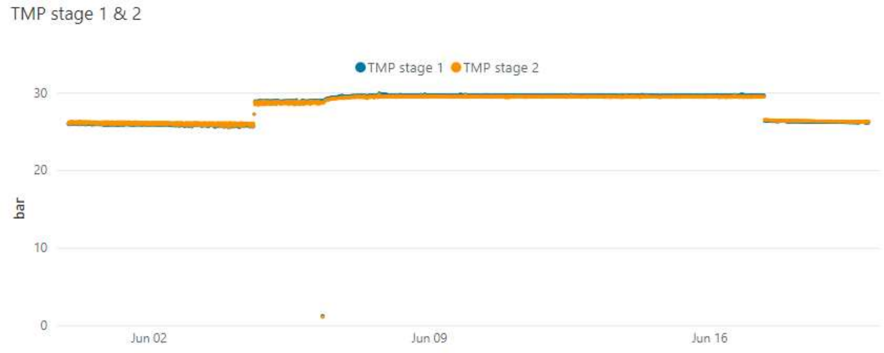


Figure 4.8: Transmembrane Pressure (TMP) of stage 1 (blue) and stage 2 (orange) before and after the increase of the flux from 15 to 18 LMH.

4.4.5 Cleaning in place

One Cleaning In Place (CIP) event took place in the research period, in April 2024. During this event 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 residues from the membranes. Samples were taken from the chemical solution after CIP to analyze the nature of the scaling and fouling. Many metals were measured in this solution. Ions with the highest concentrations were sodium, iron, magnesium, manganese, silicon, aluminum, and potassium.

5 Conclusions and recommendations

5.1 Conclusions (demo project)

- The combined infiltration of surface water on top (push) and extraction 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.

- Pumping up deep fresh groundwater resulted in salinization of the pumping well after six weeks. The salinization increased during prolonged pumping and rendered the well unfit for drinking water production (in the absence of RO treatment). However, the salinization was reduced and finally disappeared when the brackish groundwater wells were switched on again. This proves that salinization is a reversible process and that the robustness of the deep freshwater wells of Dunea in the dunes of Meijendel can be improved by brackish groundwater abstraction at greater depth.

- The pilot results reveal that the extraction of fresh and brackish groundwater from aquifer 3 does not have a significant impact on hydraulic heads and groundwater levels in the upper phreatic aquifer, due to the presence of aquitards. As phreatic groundwater levels are not influenced by the pilot, it follows that impacts of the pilot on nature values in the vicinity of the pilot area will be insignificant.

- The optimal conditions for water purification have been assessed by long-term testing of the RO membranes. It can be concluded that a flux of 15 LMH and a recovery of 60% are representative values for a full-scale operation. In order to be potable, the permeate needs post-treatment: degassing and hardness adjustment. This can easily be achieved by mixing the permeate with the dune water pumped up at the site for drinking water production, followed by post-treatment to drinking water at the production location.

- With regard to the replication project, no conclusions can be drawn yet, as the pilot will start in September 2024. The well field has been installed in June 2024 and has passed all the operational tests. The experiments will run from September 2024 until Q1 2025.

5.2 Recommendations (demo project)

- We recommend some additional RO membrane experiments which were not foreseen during the proposal stage. Firstly, we recommend to widen the salinity range of the brackish groundwater to be tested. Up to now, we focused on chloride concentrations of 5000-6000 mg/l, which is the expected average salinity of a full-scale brackish well field in Meijendel. However, we are also interested in testing RO performance on individual well series, both in the eastern part of Meijendel (3000 mg/l) and in the western part (12.000 mg/l). The tests with brackish groundwater of high chloride concentration (12.000 mg/l) require replacement of the membranes.

- We also intend to investigate options for purification of the saline waste stream from the RO (called brine or concentrate), as Dunea will probably be obliged to purify the waste stream before discharging it to the sea.

APPENDIX A: Overview of pilot lithology, wells, and monitoring equipment (demo project)

APPENDIX B: Planning of monitoring activities (demo project)

- **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:
  Data is retrieved from the geohm cables up to 2x/week for the central wells after a change in the operation. The frequency of the measurements is lower at the outer wells and when 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
  - 24-7-2023: Measurements prior the first rest phase.
  - 1-11-2023: Measurements at the end of the rest phase and prior to the first simulated calamity
  - 29-2-2024: Measurements at the end of the first simulated calamity.

  Planned for the remainder of the pilot:
  - 14-10-2024: Measurements prior to the second simulated calamity.
  - 24-2-2025: 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 rest 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
- October 2023: Reference measurements prior to fresh groundwater extraction
    - Selected piezometers (mainly in the transition zone from fresh to saline groundwater) in BR-001, BR-002, WP FM, WP FN and WP FP: analysis on all relevant chemical constituents
- November 2023 – July 2024: Frequent measurements during extraction
    - Selected piezometers (mainly in the transition zone from fresh to saline groundwater) in BR-001, BR-002, WP FM, WP FN were sampled regularly and analyzed on all relevant chemical constituents (1x every two – six weeks.
    - Active extraction screens were sampled and analyzed frequently (1x every one – three weeks) on all relevant chemical constituents.
    - In February 2024, 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 were analyzed on field parameters and salinity.
    - In February and July 2024, 5 piezometer screens in WP FP were analyzed on all relevant chemical constituents.
- For the remainder of the pilot, a similar procedure will be applied for water quality analyses.

APPENDIX C: Concentration profiles of relevant chemical constituents in groundwater of BR-002 prior to the extraction (31-1-2022).