D1.2 – Improved Freshkeeper Reference site (TRL7)

Improved Freshkeeper reference site in Noardburgum, the Netherlands (TRL7)

SUBSOL has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 642228

Title:	Improved Freshkeeper Reference site (TRL7)

Grant agreement no:	642228
Work Package:	WP1.1
Deliverable number:	D1.2
Partner responsible:	Vitens
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Planned delivery date:	28 February 2017
Actual delivery date:	26 June 2018
Dissemination level:	PU *PU = Public* *PP = Restricted to other programme participants (including the Commission Services)* *RE = Restricted to a group specified by the consortium (including the Commission Services)* *CO = Confidential, only for members of the consortium (including the Commission Services)*

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1. Introduction

Salinization of freshwater abstraction wells and freshwater well fields can be mitigated or even prevented by the interception (abstraction) of the intruding or upconing saline water. This is called the Freshkeeper concept (Figure 1). In 2009, drinking water company Vitens started a first field pilot to test this concept in an abandoned well field in Noardburgum, the Netherlands (Oosterhof et al., 2013). Fresh and brackish groundwater were abstracted simultanouesly (one well, two seperate filter screens) at similar abstraction rates (50 m^3/h). The freshwater was distributed directly to the nearby drinking water production plant; the abstracted brackish water was desalinated (brackish water reverse osmosis; BWRO), after which the fresh permeate was distributed to the production plant, while the BRWO concentrate was disposed of by deep well injection (seperate injection well) into the underlying (brackish) aquifer. This pilot ran until 2013, with unforeseen success regarding prevention of salinization: simultaneous abstraction of fresh and brackish groundwater had even provoked a downconing of the fresh-brackish water interface, i.e. a freshening of the production aquifer.

In 2014, a follow-up Freshkeeper pilot was initiated at Noardburgum, with the goal to optimize freshkeeper design and operation: maximizing the freshwater recovery, while minimizing saltwater interception (Raat et al., 2015). This pilot site has been adopted by the SUBSOL project as one the Subsurface Water Solutions reference sites. This new Freshkeeper is a dedicated well with three different well screens in a single borehole. The shallowest screen (60 – 80 mBLS; meters below the land surface) is used for freshwater production by drinking water company Vitens. Freshwater is pumped at a fixed rate of 70 m^3/h. Brackish groundwater is abstracted from the second well screen (143 – 154 mBSL), at an adjustable rate of 5 to 23 m^3/h. The intercepted brackish water is disposed into the underlying, more saline aquifer through the deepest filter at a depth of 190 mBLS.

Within the SUBSOL project, the following activities have been carried out at the Freshkeeper reference site, all aiding to full-scale implementation of the Freshkeeper concept at Noardburgum:

- A regional hydrological study, including additional monitoring of the regional salinity distributions and regional hydrological modeling (D1.1). This study will render a better understanding of the effects of full scale Freshkeeper application on the salinity distributions in nearby well fields and on the positioning of the salinity front up north of the Noardburgum well field.
- Continuation of the well-monitored pilot after 2015, including additional testing of the system under different pump regimes and data collection and monitoring under varying hydrological conditions (D1.2; this report). Prolonged testing and data collection allows for validation of the long-term applicability of the Freshkeeper and provides necessary data for up-scaling of Freshkeeper to the well field level.

- A full-scale design of the Freshkeeper for the Noardburgum well field, rendering important insights into Freshkeeper functioning at the well field level. Additionally, the design will provide the necessary information to explicate the economic viability of the concept, also in comparison with alternative water supply options in Northern Netherlands (D1.3).
- Support to the (already existing) local Noardburgum stakeholder group. This stakeholder group is an important network to be consulted in the commercialization, capacity building and knowledge sharing activities undertaken in WP4.

Aims (this report)

This report provides (1) an overview of the technical setup of the Noardburgum Freshkeeper, and (2) the results of Freshkeeper testing between June 2015 and November 2016.

Conclusions and practical lessons from this report (D1.2) and SUBSOL report D1.1 (Rijpkema and Van Doorn, 2017. *Validated regional scale groundwater model Noardburgum*) have been valuable input to full-scale Freshkeeper implementation at Noardburgum in April 2018.

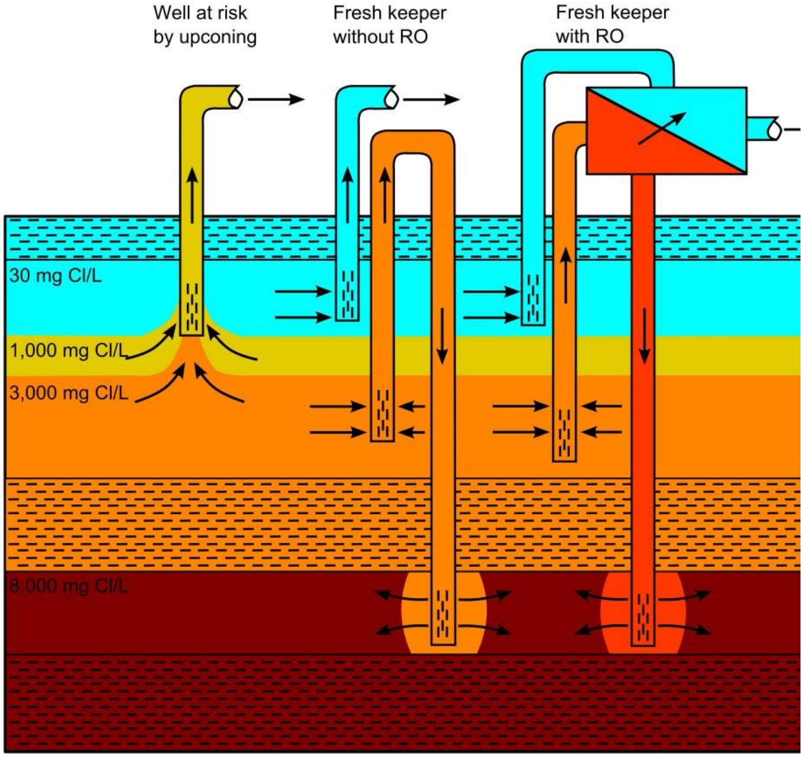

Figure 1: The Freshkeeper concept. From left to right: well at risk of upconing; Freshkeeper well, injecttion of intercepted brackish groundwater (Noardburgum pilot 2014 – ongoing); Freshkeeper well + BRWO, injection of BWRO concentrate (Noardburgum pilot 2019 – 2013).

2. Site description

2.1. Study area

The Freshkeeper pilot is situated at the former well field of Noardburgum, in the coastal province of Friesland, the Netherlands (Figure 2). Two other drinking water well fields are in the vicinity of the study area: well fields Ritskebos and Garyp. The well fields of Noardburgum and Ritskebos have been in production since 1935 and were both extracting approximately 12 Mm^3/year, resulting in a combined rate of 25 Mm^3/year. As the interface between freshwater and brackish groundwater is situated within the aquifer of freshwater production, the threat of salinization became more seriously over time and more and more brackish groundwater was being recovered. As a result of both well fields being active, the average chloride concentration of the recovered water from the Noardburgum well-field increased from 40 mg/L to 180 mg/L (Figure 3). Due to this salinization, the well field at Noardburgum was closed in 1994. The well field of Ritskebos was forced to reduce its capacity to 7.5 Mm^3/year in 2005 for similar reasons.

The area around Ritskebos and Noardburgum is an infiltration area and upconing of brackish groundwater that occurred from 1935 to 1994 is reduced by the natural recharge (precipitation surplus; infiltration from surface water).

Figure 2: Study area: well fields Noardburgum (abandoned in 1994), Ritskebos and Garyp, in the northen part of the Netherlands.

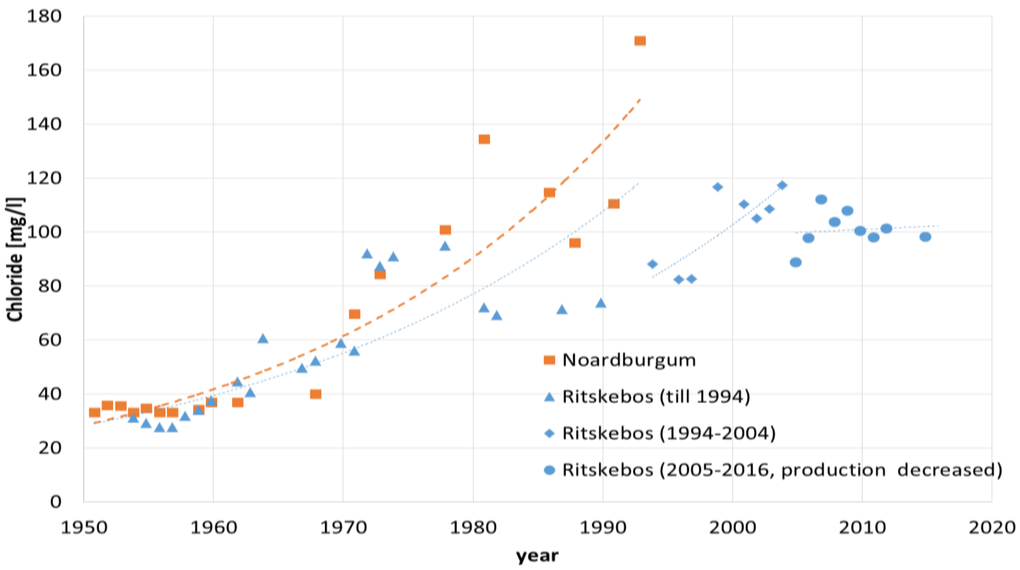

Figure 3: Average chloride concentration of the recovered water at the well fields of Noardburgum and Ritskebos from 1950 till 2014.

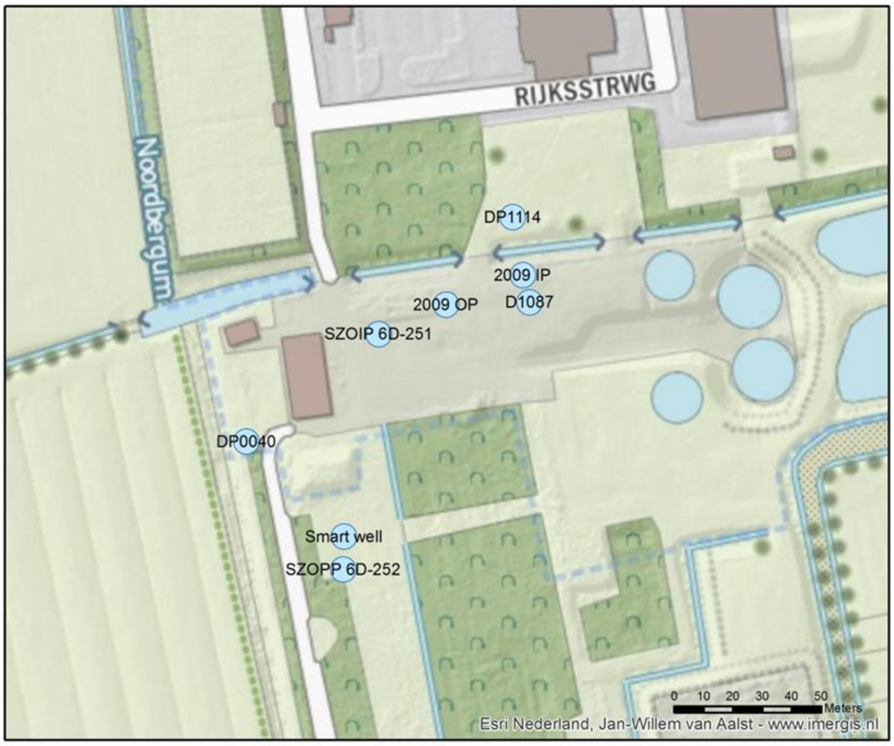

Figure 4: Well field in Noardburgum, including the disposal- (2009 IP) and recovery- (2009 OP) wells of the first Freshkeeper pilot (2009 – 2013), the dedicated ('smart') well of the second Freshkeeper pilot (2014 – ongoing), and the monitoring wells.

2.2. Aquifer characterization

A detailed characterization of the target aquifer was obtained by 8 borehole descriptions taken from all wells in Figure 4. The regional geohydrology and the dominant water types are presented in Figure 5 and Table 1. Combining both sources of information results in a uniform interpretation of the subsurface at the well field (Figure 6).

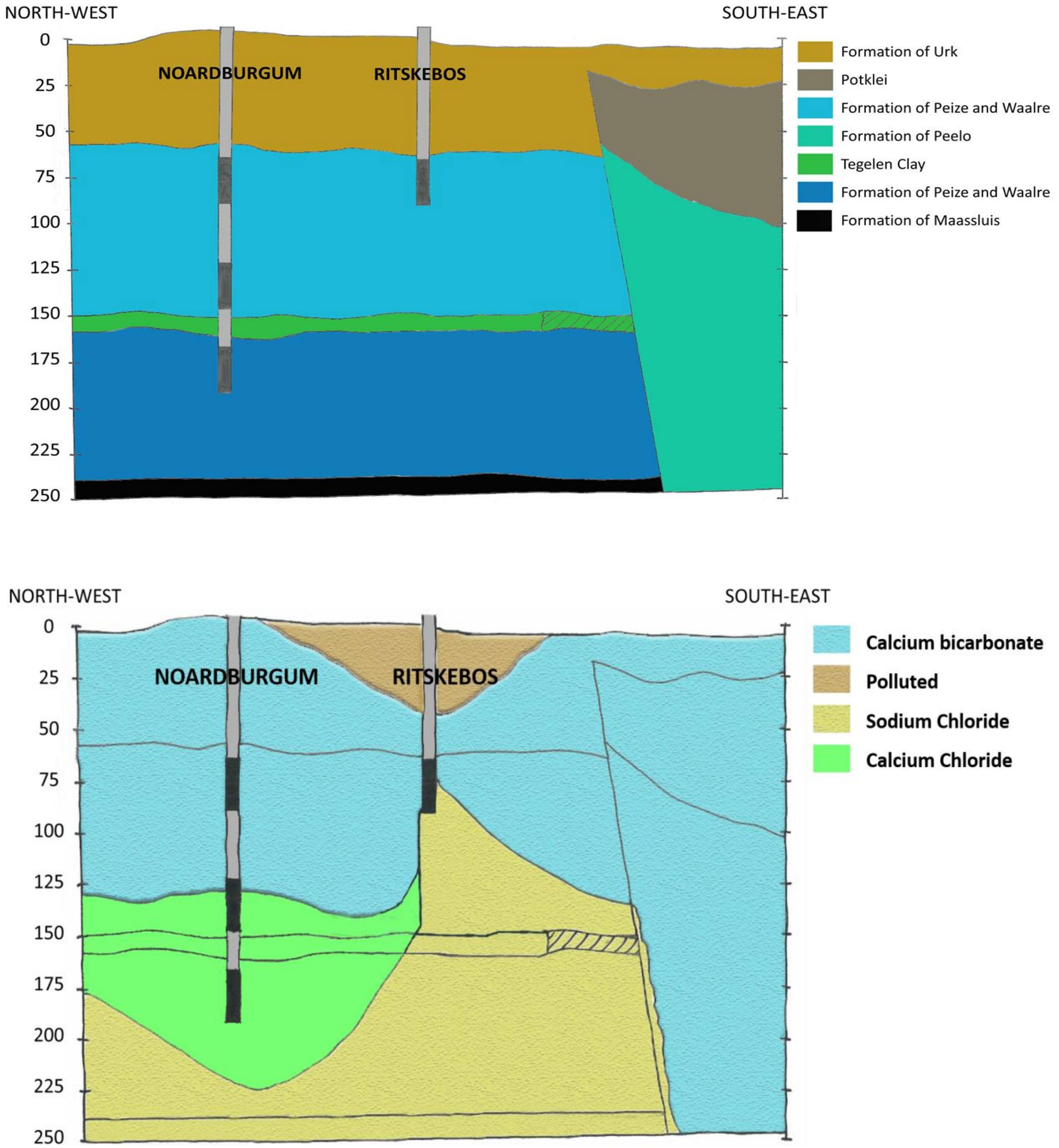

Figure 5: Cross-section along the well fields of Noardburgum and Ritskebos for the geohydrology and the dominant watertypes (Geul, 2016).

Table 1: Lithology and characteristics of the subsurface at the Noardburgum well field.

	Top [m BSL]	Bottom [m BSL]	Formation	Transmissivity (m^2/d) or resistance (d)	Information
Top aquitard	0	-60	Drenthe, Drachten, Urk	1000-3000 d	Boulder clay, clay, loam and fine to coarse sands
Target aquifer	-60	-150	Urk and Peize complex	5000 m^2/d	Mainly coarse to very coarse sands
First aquitard	-150	-160	(Peize) Tegelen	2000 d	6-10 m of clay and fine sands
Second aquifer	-160	-240	Peize complex, Waalre	1500-2500 m^2/d	Fine to coarse sands with small clay layers

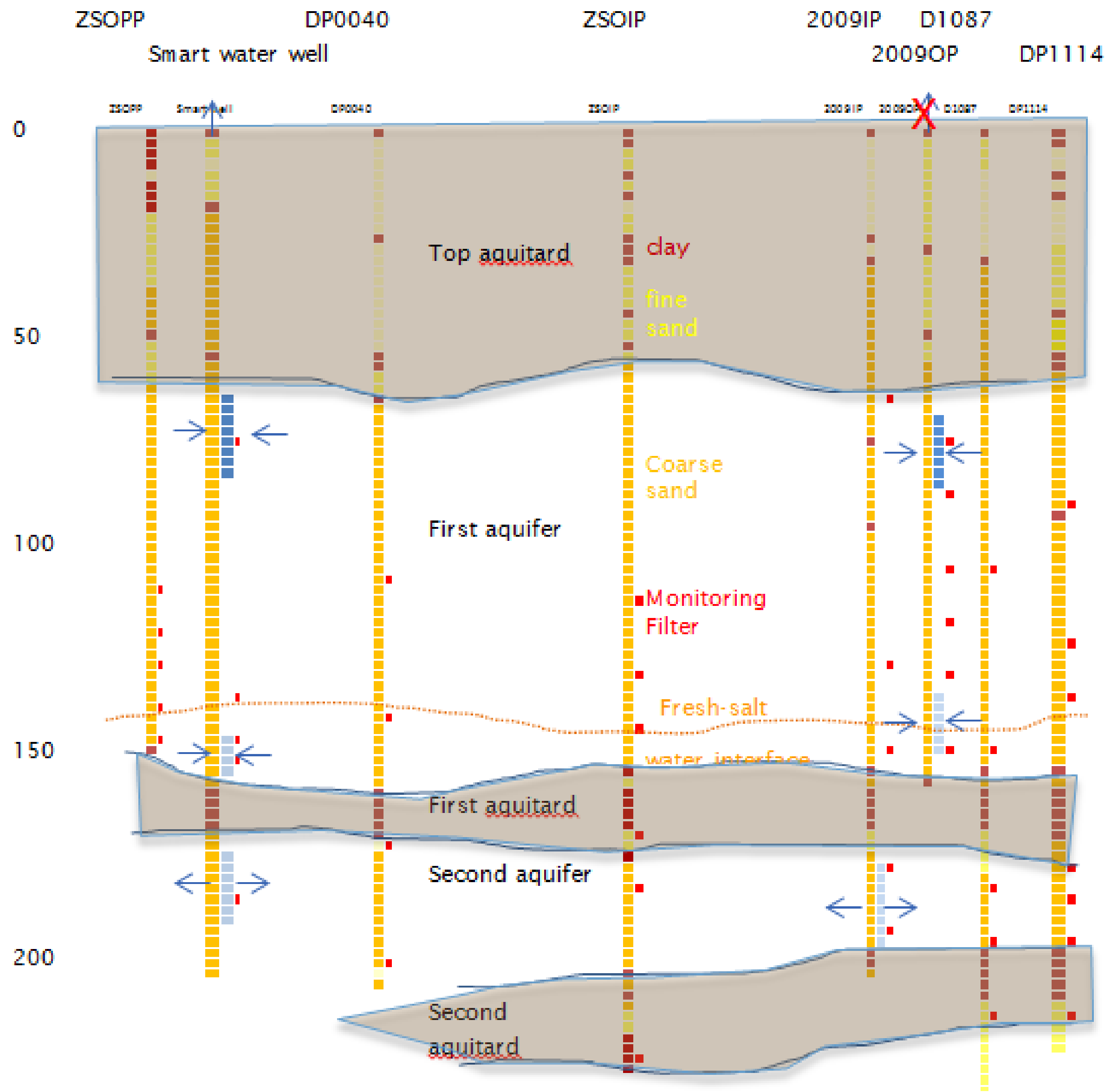

Figure 6: Integrated interpretation of the lithology and chloride stratification at the Noardburgum well field (Figure 4) at the start of the Freshkeeper pilot. The wells of the first Freshkeeper pilot (2009IP and 2009OP) were not in operation.

2.3. Ambient groundwater characterization

A detailed characterization of the ambient groundwater in the target aquifer was obtained by recording the electrical conductivities around the monitoring well screens in the target aquifer prior to and during operation of the 2014 – 2017 Freshkeeper pilot by geophysical borehole logging using a Robertson DIL-39 probe (‘EM-39’ (McNeill et al., 1990)). By pre-defining the relationship beween the measured EC and the chloride concentrations in the lab (Figure 7), this allows to determine the chloride stratification and the exact location of the fresh-salt interface within the target aquifer (Figure 8).

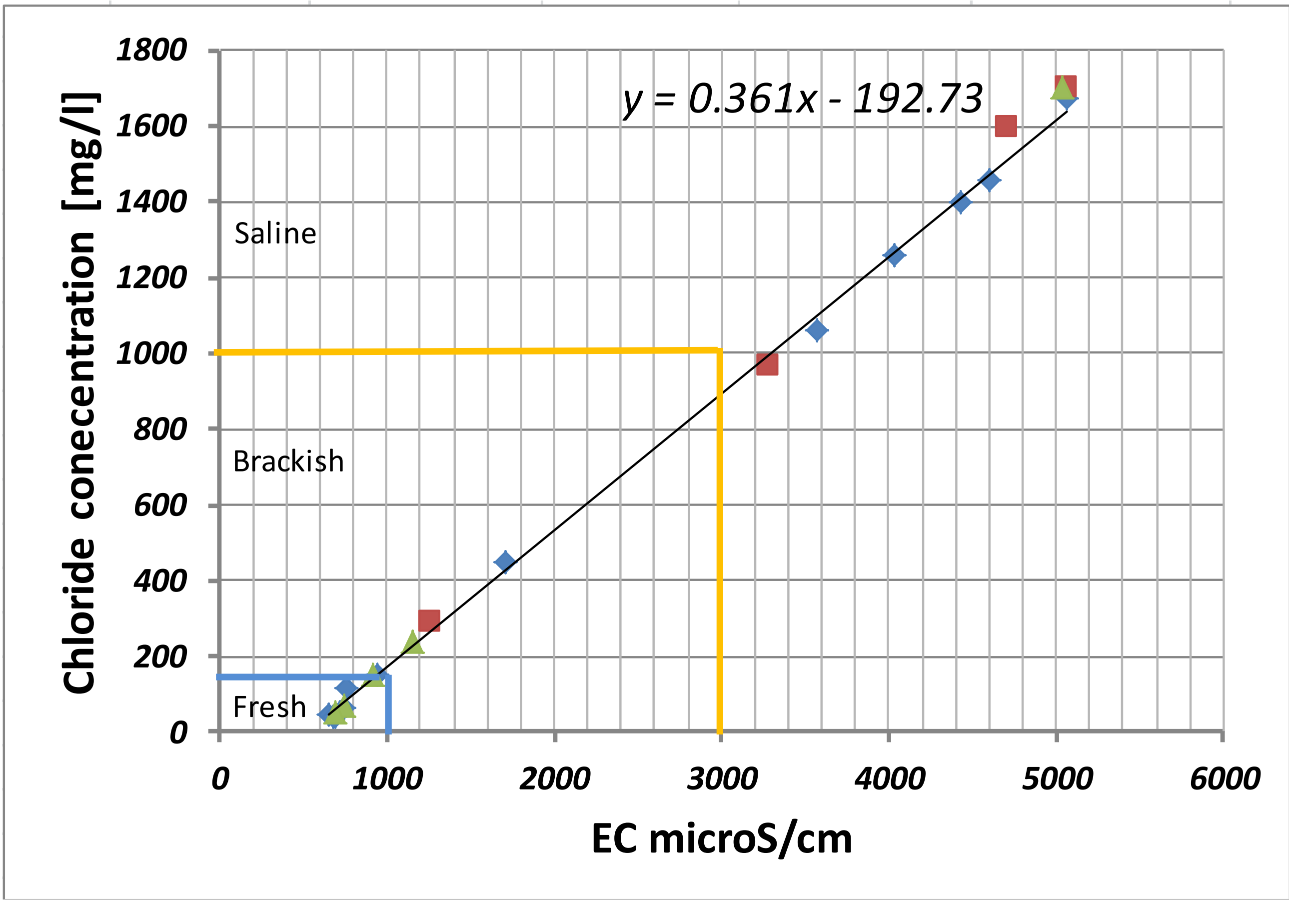

Figure 7: Relationship between chloride concentrations and EC determined from the lab-analyses of all samples taken around the fresh-salt interface.

The EM39-measurements indicate a sharp fresh-salt interface, with a mixing zone of only 10 m in depth (Figure 8). This interface is located within the shallow aquifer just above the confining Tegelen clay. Because of the steep gradient, the depth of the fresh-salt water interface is defined as the depth with a chloride concentration of 1000 mg/l or an EC of around 3000 µS/cm, corresponding with a depth of about 140 m BLS.

Right below the confining Tegelen clay layer, at a depth of about 160 m BLS, the chloride concentrations are lower (500 mg/L) than right above it, i.e. there is a chloride inversion. The chloride concentration increases again with depth within the deeper confined aquifer.

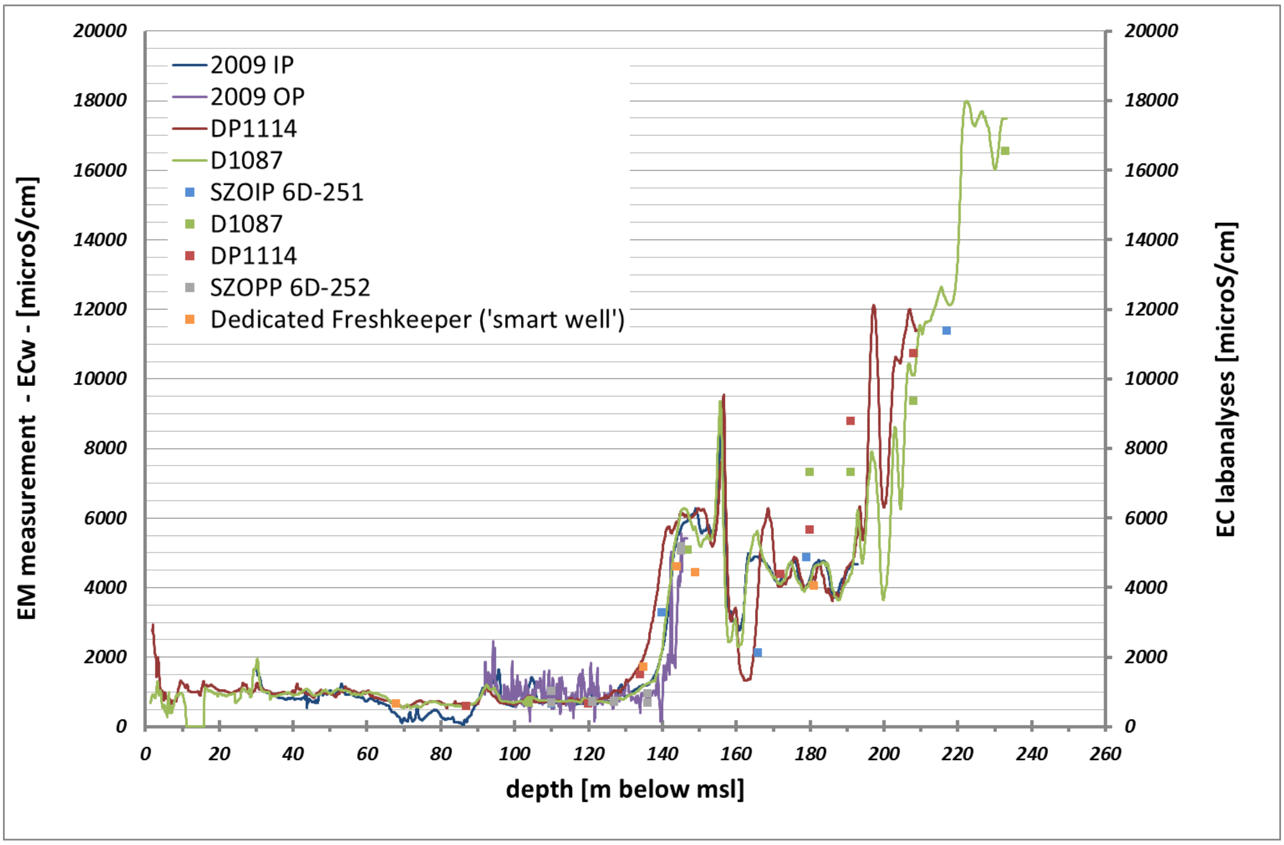

Figure 8: Electrical conductivity (EC) determined from EM39 measurements in monitoring wells (solid lines) and from lab analyses (dots), measured just before the pilot around the dedicated Freshkeeper. Water with a chloride concentration lower than 150 mg/L is considered fresh, water with a chloride concentration between 150 and 1000 mg/L is considered brackish, and water with a chloride concentration higher than 1000 mg/L is considered salt.

3. Freshkeeper pilot design

3.1. First Freshkeeper pilot: 2009 - 2013

The first Freshkeeper pilot in Noardburgum was performed in 2009/2013. Two well screens were installed to simultaneously extract fresh and brackish groundwater from the target aquifer, at a fixed rate of 50 m^3/h. An additional 25 m^3/h of freshwater was produced from the extracted brackish groundwater by applying reverse osmosis (brackish water reverse osmosis; BWRO). A separate infiltration well was placed near the Freshkeeper (Figure 4) with its screen in a deeper and more saline aquifer for the disposal of the BRWO concentrate, at a rate of 25 m^3/h. The pilot mainly focused on BWRO and the effects of BRWO concentrate disposal on the groundwater quality in the disposal aquifer.

The pilot was a success in terms of preventing salinization: simultaneous abstraction of fresh and brackish groundwater had provoked a downconing of the fresh-brackish water interface, i.e. a freshening of the production aquifer. This implied that the brackish water abstraction could be further minimized while still maintaining a stable fresh-brackish groundwater interface.

Results of this first Freshkeeper pilot have been described in various reports and proceedings, including Oosterhof et al., 2013; Raat et al., 2011 and Zuurbier et al 2016.

3.2. Second Freshkeeper pilot: 2014 onwards

In 2014, a follow-up Freshkeeper pilot was initiated at Noardburgum, with the goal to optimize freshkeeper design and operation: maximizing the freshwater recovery, while minimizing brackish water interception. This pilot was adopted by the SUBSOL project as one of the Reference applications and is subject of this report. Unlike the first pilot, the abstracted brackish groundwater was not used as a drinking water source, but was injected directly into the disposal aquifer.

Freshwater abstraction, brackish water abstraction and brackish water disposal were all combined within one borehole. For this, a dedicated well with three well screens was installed, at about 85 m distance southwest of the first Freshkeeper well (Figure 4):

- well screen #1 for the abstraction of freshwater at a rate of 70 m^3/h from the aquifer at a depth of 60-80 m BLS.
- well screen #2 for abstraction of brackish groundwater at adjustable rate of 5 – 23 m^3/h (default 13 m^3/h) from the aquifer at a depth of 143 - 154 m BLS
- One well screen for the disposal of intercepted brackish water in a deeper and more saline aquifer that is overlain by the Tegelen clay, at a depth of about 190 m BLS.

The following challenges were encountered during the design of the dedicated Freshkeeper with multiple integrated well screens:

- By standard, clay seals are installed in the borehole annulus where the well dissects natural clay layers, to prevent hydraulic connection between different aquifers. In addition, for this multi screen well, clay seals had to be installed at depths between the separate well screens, in order to prevent short-circuiting of groundwater via the gravel pack;
- The (submersible) brackish water pump had three additional requirements: (1) flow of water was not allowed when this pump was out of operation. (2) the pumps and other parts of the well had to be resistant to corrosion because of the contact with brackish or saline water. (3) the pump required both automated as well as manual control.
- The well needs had to be designed such that all required measurement- and control devices fitted within a single borehole (and within the well-chamber). The installation should allow an easy replacement or removal in case of defects and repair. Additionally, leaks in the borehole that are caused by the placement of monitoring equipment had to be prevented.

3.3. Dedicated Freshkeeper well design

The design of the dedicated Freshkeeper is presented in Figure 9. Additional and more specific information of the well and the subsurface is given in Appendix 1, including the technical drilling tests. The most important specifications and technical details were as follows:

- The well chamber has the standard lay-out of Vitens water supply;
- The borehole has a diameter of 900 mm in the first 145 m BLS and 700 mm below 145 m BLS.
- The diameter of the freshwater screen is 315 mm, of the brackish water extraction screen 250 mm and of the concentrate disposal screen 200 mm.
- A number of monitoring well screens were placed within borehole to monitor electrical conductivity (EC) and to monitor for well clogging. Due to the risks of well leakage or short-circuiting, the maximum number of monitoring wells within the borehole was 6. All monitoring screens have a diameter of 40 mm, except for one that has a diameter of 75 mm such that monitoring equipment (e.g. an EM-39 logger) would fit in..
- The submersible pump of the freshwater well screen has a fixed rate of 70 m^3/h. This makes the well screen less vulnerable to problems and saves costs of a frequency converter. In addition, it simplifies the management of the well field for the water company.
- The pump of the brackish water extraction well screen has an adjustable rate of minimum 5 to maximum 30 m^3/h. The pump of this well screen requires a high resistance to corrosion, since it extracts brackish or saline groundwater.

- During standstill, the infiltration well should be kept pressurized to prevent degassing of CO_2 from brackish water and subsequent gas clogging of the infiltration well.

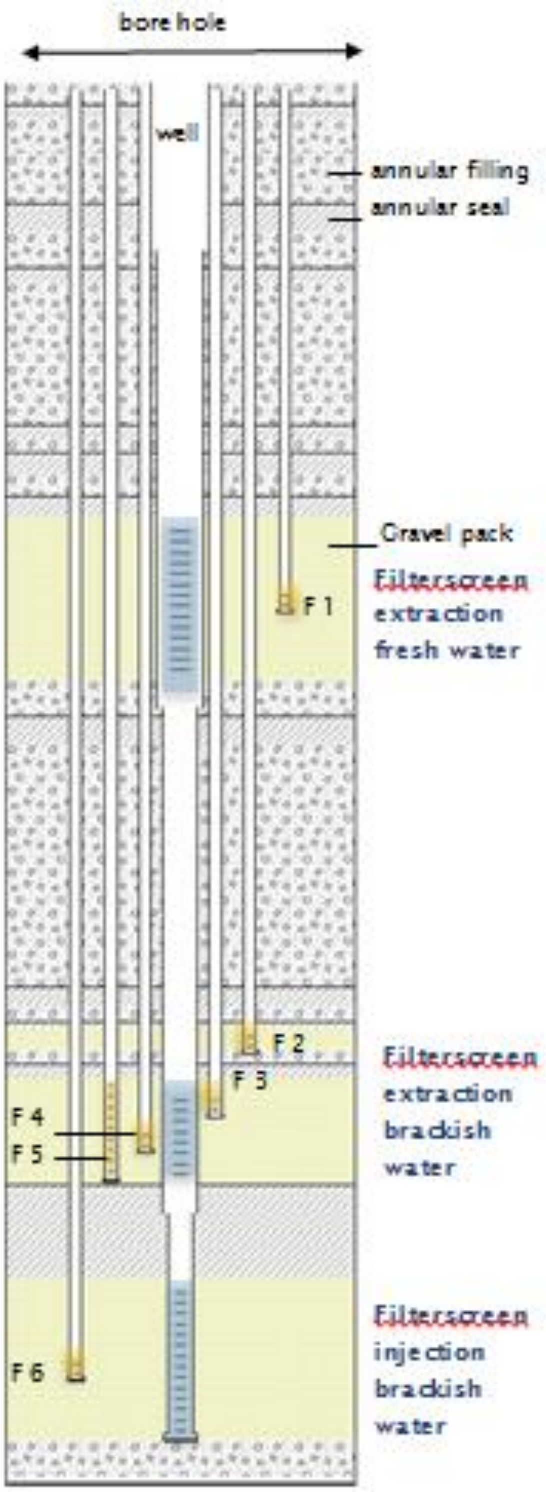

Figure 9: Lay out of the dedicated Freshkeeper with three well screens in one integrated borehole. The six monitoring well screens (F#) are also installed in the same borehole.

The dedicated Freshkeeper well was installied in October 2014 (prior to the SUBSOL project). .The total time span from drilling to start of production amounted to 4 months, as depicted in Table 2.

Table 2: Time schedule for the installation of the dedicated and integrated Freshkeeper.

Planning	Activities
Two weeks	Drilling of the well construction, and perform borehole measurements to define the depth of the fresh-saltwater interface and to determine the optimal placement of well screens.
Two weeks	Development of the well
One week	Rest
Three months	Placement of all well appliances and connection of the dedicated Freshkeeper to the piping of the drinking water company Vitens.

3.4. Monitoring wells

An extensive network of monitoring wells (Figure 4) was already available from the first Freshkeeper pilot and as such no additional monitoring wells were drilled. Monitoring well DP0040 (at 45 m distance from the dedicated Freshkeeper) was equipped with CTD-divers that automatically log water pressure and electrical conductivity. CTD-divers were installed in DP0040 at a depth of 108 m, 137 m, and 168 m BSL to measure the EC once every hour. with an hourly frequency. These measurements should render insight into the repsonse of the fresh-brackish water interface at distance from the Freshkeeper well.

In addition to this automated monitoring, water samples were taken multiple times from all monitoring well screens to determine the chloride concentration and the EC.

3.5. Photographic impression

A photographic impression of the dedicated Freshkeeper in Noardburgum is presented in Figure 10 and Figure 11.

Figure 10: Drilling of the dedicated Freshkeeper.

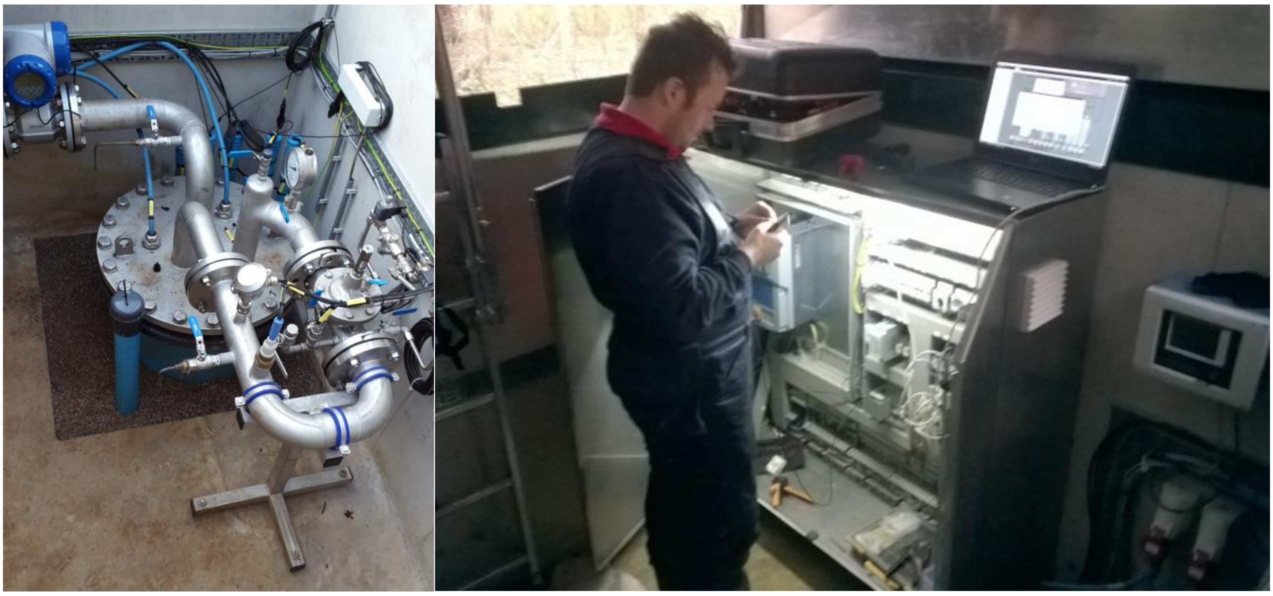

Figure 11: Left: Well chamber of the dedicated Freshkeeper. Right: John van der Klaauw (De Ruiter) is updating the control software in the well chamber.

4. Automated monitoring and control system

The objective of the real-time automated monitoring and control system is to minimize the abstraction of brackish water while still preventig upconing of brackish groundwater to the freshwater well screen. Therefore, the automated monitoring and control system should be able to stabilize the fresh-salt interface within the target aquifer. Additionally, it is important that the monitoring and control system is robust and able to meet and monitor all demands of the local authorities.

The monitoring system should provide sufficient insight in the behavior of the dedicated well and the groundwater system, to optimize the automated monitoring and control system and to formulate recommendations for the application of a dedicated Freshkeeper.

EC-sensors were installed in the borehole and in the well chamber, and were connected to an automated control system (Figure 12). The system is designed in such a way that the 3D-dynamics of the fresh-salt interface are monitored in real-time, based on real-time EC-measurements of recovered freshwater and of intercepted brackish groundwater. The automated monitoring and control system is further designed to regulate the discharges of the wells on the basis of the EC-measurements, in order to stabilize the position of the fresh-salt interface.

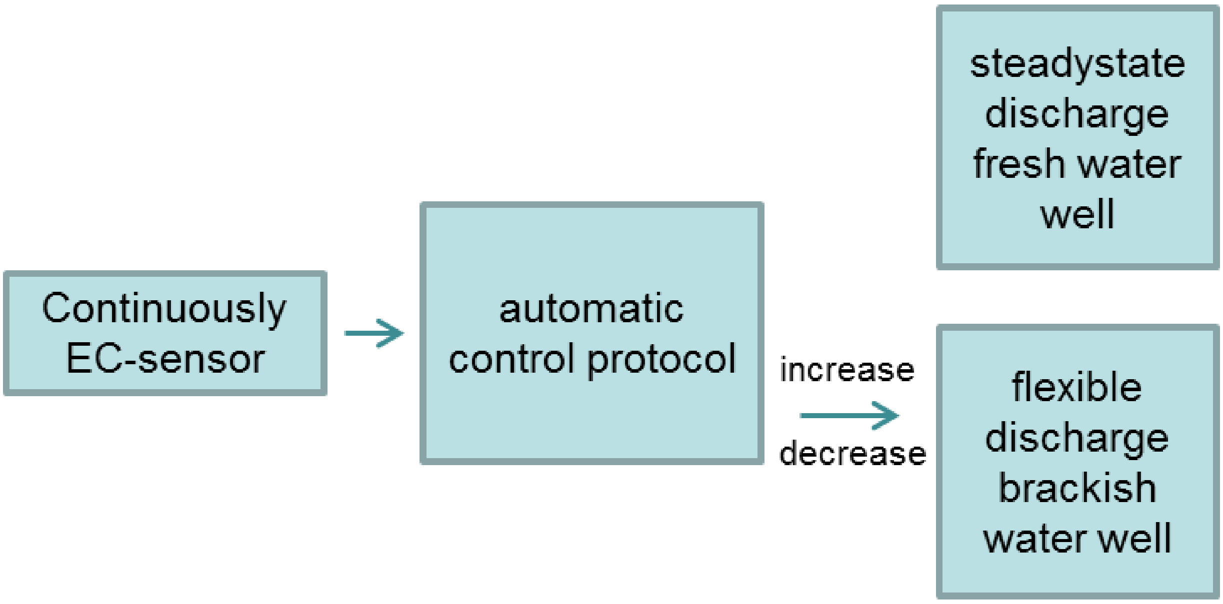

Figure 12: Lay-out of the automated monitoring and control system for the Freshkeeper.

4.1. Monitoring technique for the automated Freshkeeper

Several techniques for monitoring the EC and controlling the discharges were evaluated before the pilot. Based on the results presented in Table 3, it was concluded that simple EC-sensors were still most suited to monitor and subsequently control the fresh-salt interface with an automated control system. An eleborate discussion of all techniques is included in Appendix 2.

Table 3: Assessment of monitoring techniques for the automated control of the Freshkeeper based on electrical conductivity measurements.

Technique	Total costs (estimated)	Robustness	Proven technique?	Suitable for Noardburgum?	Result
Hydrogeophysical observatory	70.000**	Unknown	+/-	--	--
PECS	30.000*	+/-	+	+	+/-
Fibre optic cable	New technique*	Unknown	-	unknown	unknown
EC-sensor	15.000	+	+	+	+

** separate monitoring well is necessary, *separate monitoring well is preferred

The placement of EC-sensors in monitoring well screens is a proven technique and available from a wide prize range. An acquisition box for transferring data from the monitoring device to a computer is often required.

At the start of the pilot, the CTD-diver from Schlumberger was selected because it was assumed beneficial to select a supplier with an office in the Netherlands. This CTD-diver would be able to operate at depths of up to 300 m BLS, is resistant to corrosion, fits into a monitoring well screen of one inch in diameter, and additionally monitors the temperature and pressure (pressure only till a depth of 100 m BLS). The CTD-diver costs €1 500 per piece. The standard 'Diver' suffices for plain pressure level measurements and costs € 600 per piece. The installation of (free) diver-software is required to read the monitoring results.

Several problems occurred when applying these divers in the Freshkeeper well. Almost all divers malfunctioned multiple times after only a few months of operation, presumably due to corrosion (because of the placement in salt water) and high pressures (because of the placement below 100 m BSL). The connection between the sensor and the cable was especially fragile. In November 2016, these CTD divers were replaced by EC sensors, that had been tested in high-pressure lab during summer. These sensors were not able to measure temperature or pressure, however they proved reliable in supplying online EC data.

4.2. Layout of the automated monitoring and control system

The lay-out of the automated monitoring system with the EC-sensors in the dedicated Freshkeeper is presented in Figure 13. The measured EC of the recovered freshwater and the intercepted brackish water is sent as a signal to an acquisition box in the well chamber. From there, the signal is altered and sent to an online monitoring system. All data is saved online within the software control program Priva TC Manager and can be transferred from there to a remote computer through an online connection.

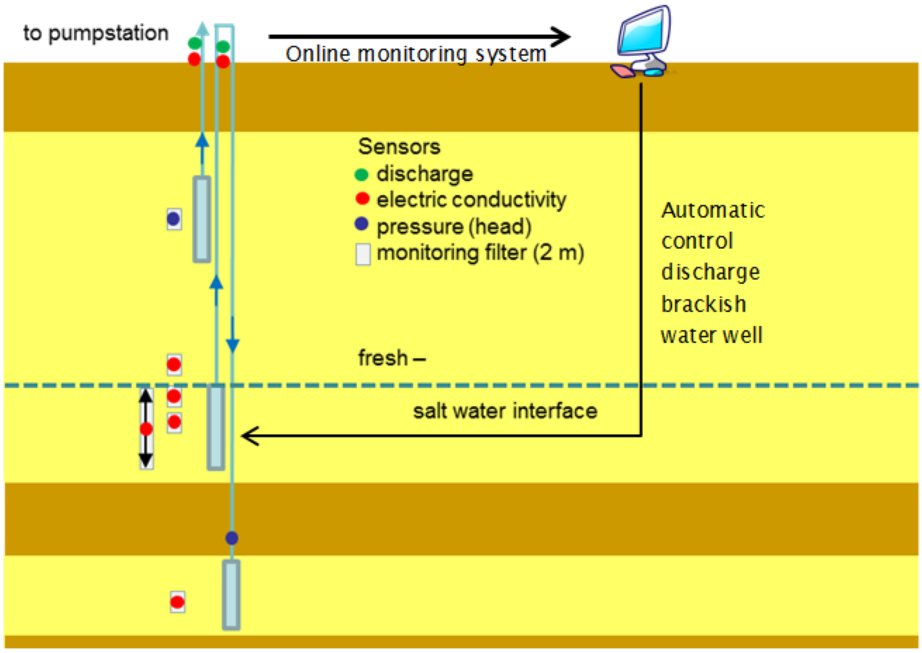

Figure 13: Lay-out of the automated monitoring and control system in the dedicated Freshkeeper.

Pressure heads are monitored to determine the infiltration pressure and the occurrence of well clogging. The signal from the Schlumberger EC-sensors to the acquisition box appeared to be too weak for a cable of more than 100 meters in length, and was interrupted by the signal of the pump inverter of the brackish water well screen. Consequently, the brackish water well had to be turned off every hour for 10 minutes to enable the transfer of information form the EC-sensor to the acquisition box. This problem was solved by the placement of the new EC-sensors in November 2016.

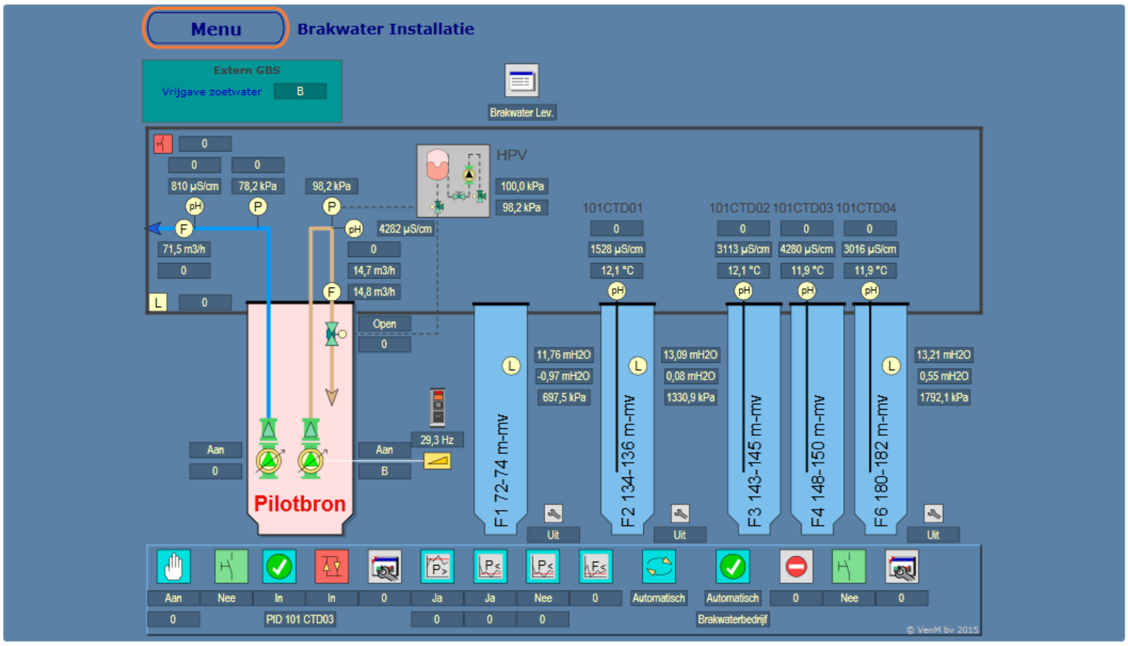

Figure 14: Interface of the on-line monitoring and control system Priva TC Manager.

4.3. Monitoring devices

The monitoring devices eventually used in the dedicated Freshkeeper are presented in Table 4. The frequency of the EC-measurements and of the data transfer to the acquisition box was determined in the monitoring program and should be equal for all sensors and all monitoring equipment.

Table 4: Parameters to be monitored, frequency of measurements, monitoring equipment, and location of installation.

Parameter	Frequency	Equipment	Location of installation
Discharge	Continuously	Flow meter	In the well chamber
EC	Continuously	EC meter	In the well chamber
EC	Hourly	CTD-diver*	In the monitoring well screen
Block EC	Manually set	CTD-diver*	In the long monitoring well screen. The vertical position of the diver can be adjusted manually.
Pressure head	Continuously	Pressure transmitter	In the freshwater well and brackish water well
Pressure head	Hourly	Diver**	In the monitoring screen next to the freshwater well

* These CTD-divers appeared to be irresistant to corrosion or high pressures. Therefore, these sensors have been replaced in November 2016.
** Pressure transmitter from the company Schlumberger.

4.4. Automated control

The discharge of all pumps is automatically controlled by the EC measurements of the sensors present in the monitoring well screens. In the software, the control can easily be altered from one sensor to the other. The resulting discharge follows from a predefined relationship between the measured EC and the discharge, based on the first measurements of the Freshkeeper pilot (Figure 15).

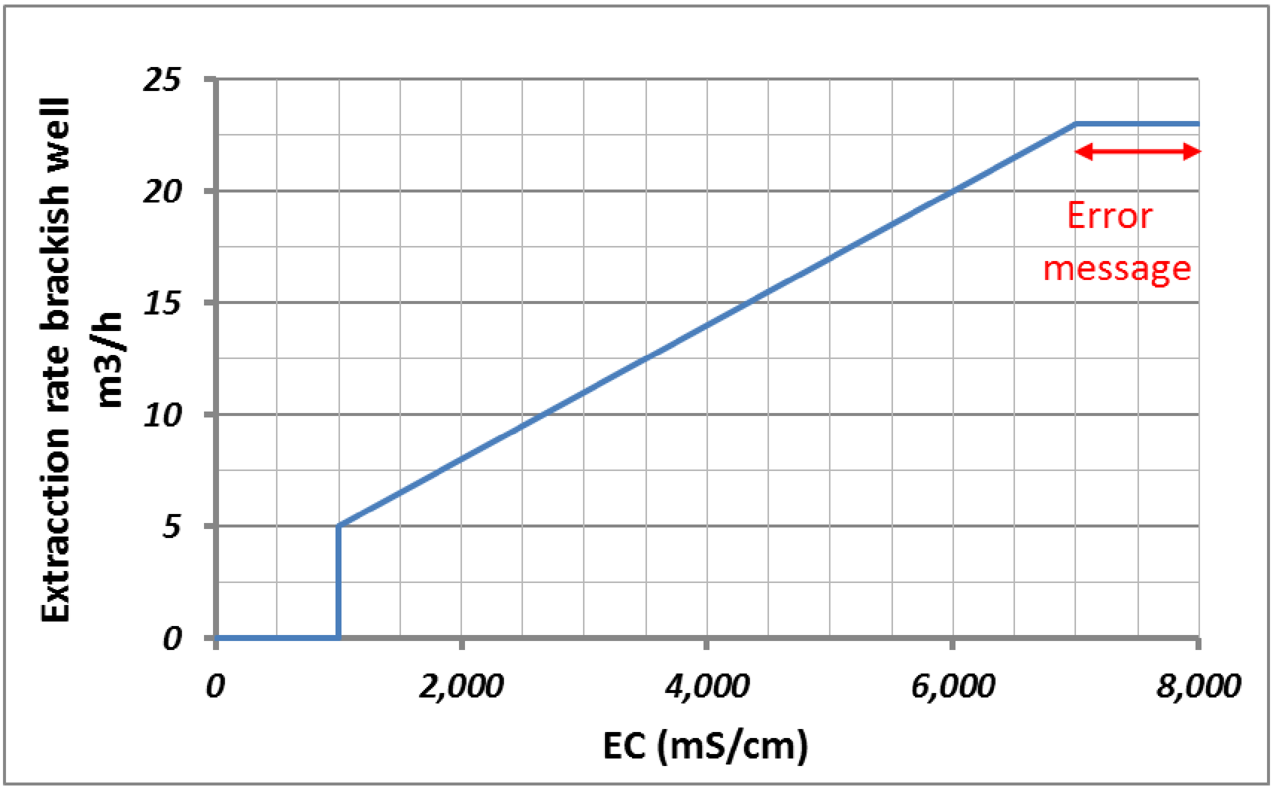

Figure 15: The relationship between the rate of brackish water interception and the EC measured in the second well screen of the dedicated Freshkeeper that intercepts brackish water, determined from the first measurements of the Freshkeeper pilot.

The higher the EC, the higher the discharge of the well screen that intercepts brackish water.

- At an EC < 1 000 mS/cm, the brackish water pump is turned off until the EC again reaches a value of > 2 000 mS/cm.
- At an EC > 7 000 mS/cm, a warning signal will be sent, since the maximum allowable EC of water disposed to the brackish water target aquifer is 7 000 mS/cm. Operators can then make decisions how to proceed. Based on modeling and practical experience, it seems very unlikely that EC at one of the monitoring screens is to exceed the 7 000 mS/cm value.

5. System repsonse to diffentent abstraction regimes

In order to (1) test and evaluate the monitoring system and (2) attain a better understanding of the local groundwater system and its repsonse to different abstraction regimes, a series of test were run between June 2015 and November 2016. After this testing (i.e. from November 2016 onwards), the pilot has been running in its standard modus of operation, i.e. freshwater and brackish water abstraction of 71 m^3/h and 13m^3/h, repectively.

5.1. Scenarios

Different operation scenarios have been tested with the dedicated Freshkeeper from June 2015 till November 2016 (Table 5). The scenarios were defined to understand the effect of the dedicated Freshkeeper on the local chloride stratification. The first scenario was defined on the basis of the results of the first Freshkeeper pilot. After operation of the first four scenarios, water surrounding the brackish groundwater well screen was still fresh. Therefore, as part of the fifth scenario, the brackish groundwater extraction well was turned off for almost half a year and only the fresh water well was operating. Figure 16 shows the discharges of the pumps in the fresh and brackish water well from June 2015 till August 2016.

Table 5: Operation scenarios of the dedicated Freshkeeper during the test period.

Scenario	Period	Fresh water recovery [m3/h]	Brackish water extraction and disposal [m3/h]
1	26 June 2015 – 20 August 2015	71 (steady state)	13 (steady state)
2	20 August 2015 – 1 October 2015	off	off
3	1 – 29 October 2015	71 (steady state)	13 (steady state)
4	29 - 30 October 2015*	71 (steady state)	5-25 (variable)
5	30 October 2015 – 18 November 2015 & 24 December 2015 - 27 July 2016	71 (steady state)	out
6	22 July 2016 – November 2016	off	off

*this period only lasts for two days because the sensors below a depth of 100 m malfunctioned on 30-10-2015.

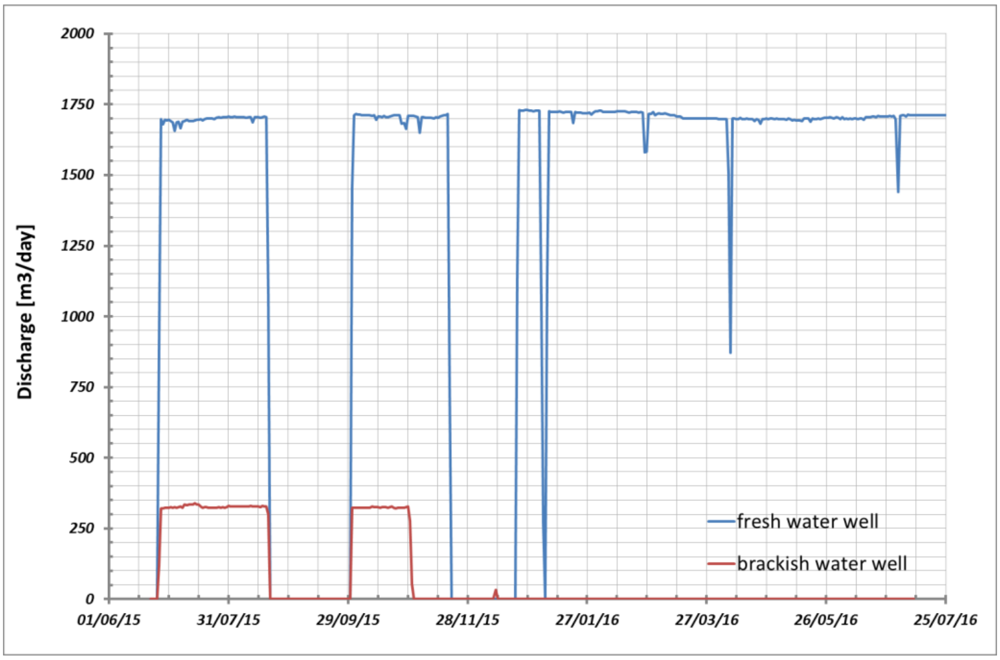

Figure 16: Discharge of the fresh and brackish water well during the pilot.

5.2. EC monitoring data

The automated control unit described in Chapter 0 was in use during the pilot. Not all sensors were operating properly during the pilot, resulting in gaps in the monitoring data.

All EC-measurements are presented in Appendix 2, which were subjected to the following influences:

- The cables of the sensors have been (re)moved several times during the monitoring period for two reasons: to take water samples from the monitoring screen for the lab; and to replace the cables by new ones. The measured EC was usually slightly affected after replacement of the sensor.
- One of the pumps was shortly taken out of production several times, resulting in peaks in the measurements.

In addition to the EC-measurements, water samples have been taken from the monitoring screens of the dedicated Freshkeeper, DP0040 and SZOPP. This was done in May 2015 (before the start of the recovery), in October 2015, in February 2016 and in July/ August 2016. Block-measurements have been performed in March, November, and December 2015 in the long monitoring screen of the dedicated Freshkeeper, along the brackish screen. The measured EC has been verified and adjusted to the EC of the lab-analyses.

At the start of the third scenario, the drawdown of the groundwater level was frequently monitored in the monitoring wells for several days. This was done because of the concern that the low water level in a pond (a pingo remnant formed in periglacial times) 450 m South of the dedicated Freshkeeper would be the unexpected effect of the operating Freshkeeper.

5.3 Effects of pumping regimes near the Freshkeeper well

Figure 17 and Figure 18 show the EC-measurements of the sensor in the dedicated Freshkeeper. Some patterns are observed, indicated by the numbered items in both figures:

1. At the start of the pilot, groundwater at depth of the brackish second filter screen indeed is brackish (F3 at 144 mBSL; 4600 µS/cm). However, at 135mBSL, groundwater is already fresh (<2000 µS/cm);
2. When water is abstracted from both the fresh and brackish well screens with a discharge rate of 70 m^3/h and 13 m^3/h, respectively, the fresh-salt interface moves downward. See F3 at the top of the brackish water well and, to a lesser extent, F2, 10 m above the top of the brackish water well;
3. The EC in F3 gradually decreases over time when both wells are extracting. When extractions stop, EC restores to the original value within just a couple of days. This pattern is repeated at subsequent extractions and similar behavior can be observed (but to a lesser extent) in F4. We doubt, however, that this fast recovery to initial EC values resembles the recovery of the fresh-brackish interface, which should be a much slower process. Instead, it is assumed that water mixes in the borehole once the wells stop extracting and that there is a preference flow from deeper (more saline) water through the borehole. Note that this process is not visible in Figure 17. Therefore, it is recommended to monitor this in the coming months.

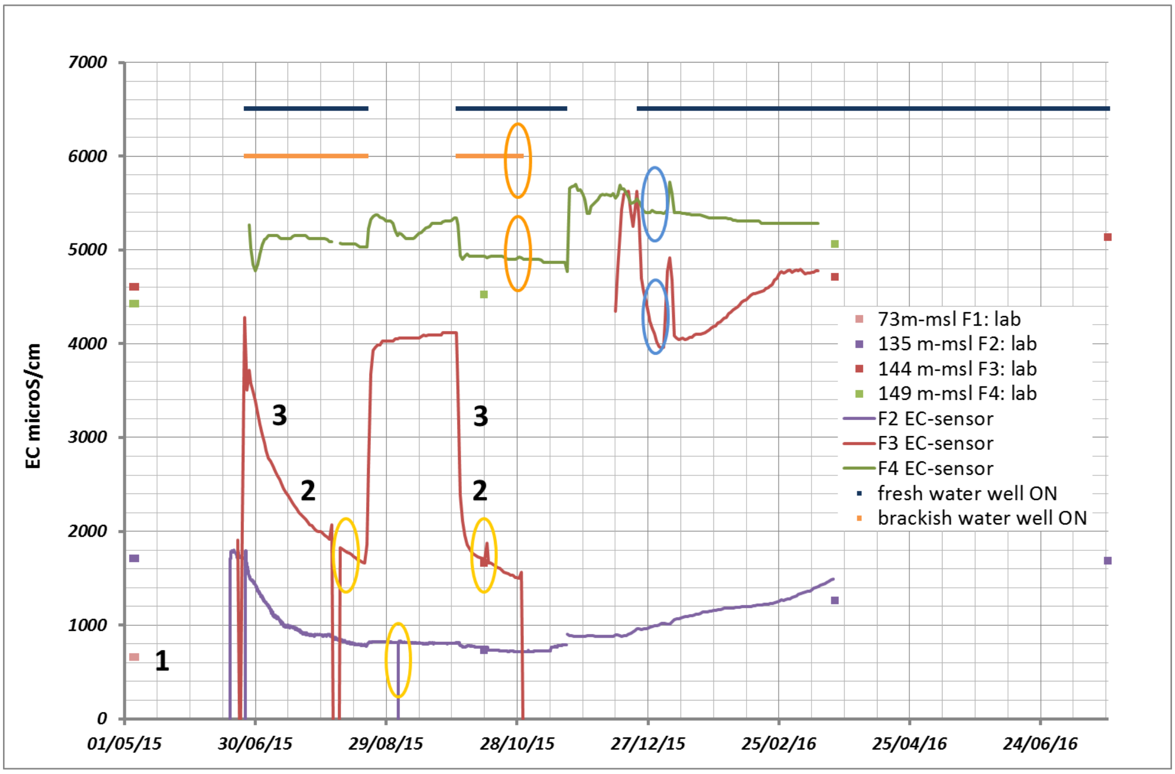

Figure 17: EC-measurements in the monitoring screens of the dedicated Freshkeeper. Blue circles: moments when the freshwater well was out of operation. Orange circles: moments when the EC-sensor was removed from the monitoring screen or when water samples were taken.

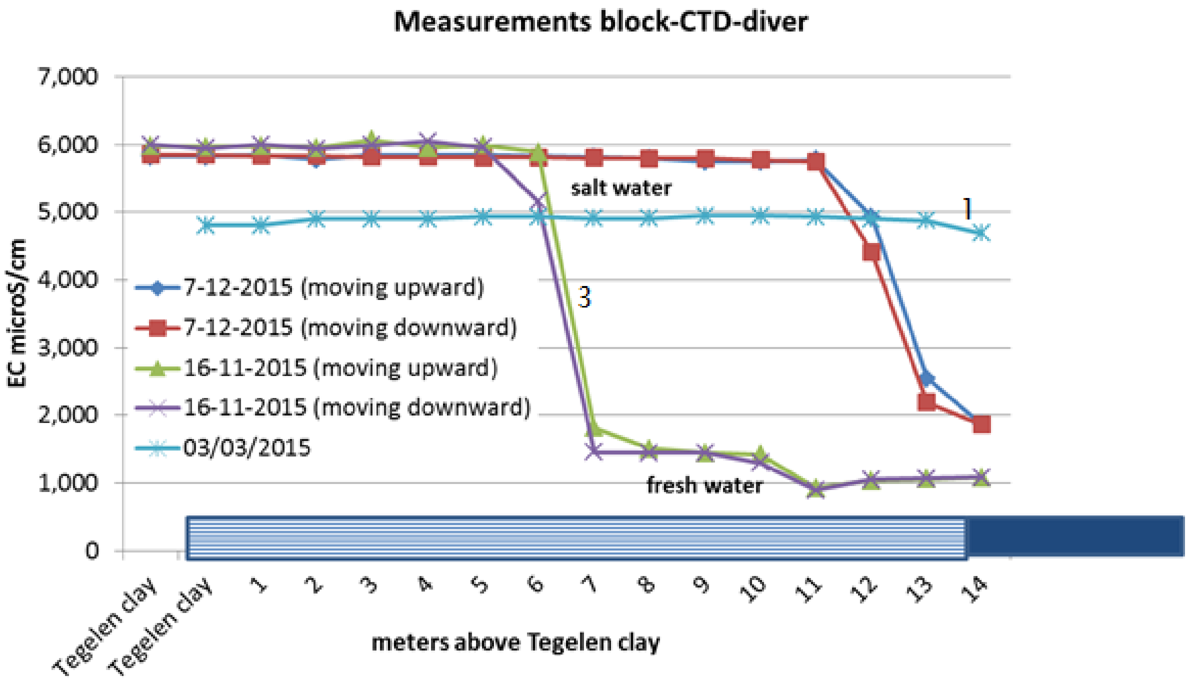

Figure 18: Block measurements in the long monitoring well screen along the brackish screen of the dedicated Freshkeeper.

EC measurements in the nearby monitoring wells is presented in Appendix 3. Using this data and data of chloride concentrations, the response of the fresh-brackish water interface in the Freshkeeper well, at 10 meters distance and at 45 meter distance was deduced (Figure 19). Clearly, the effects of different pumping regimes are strongest in the Freshkeeper well: depth of the interface may shift over 10 m of depth. At 45 m distance, the interface stays within limits of 2 meters depth.

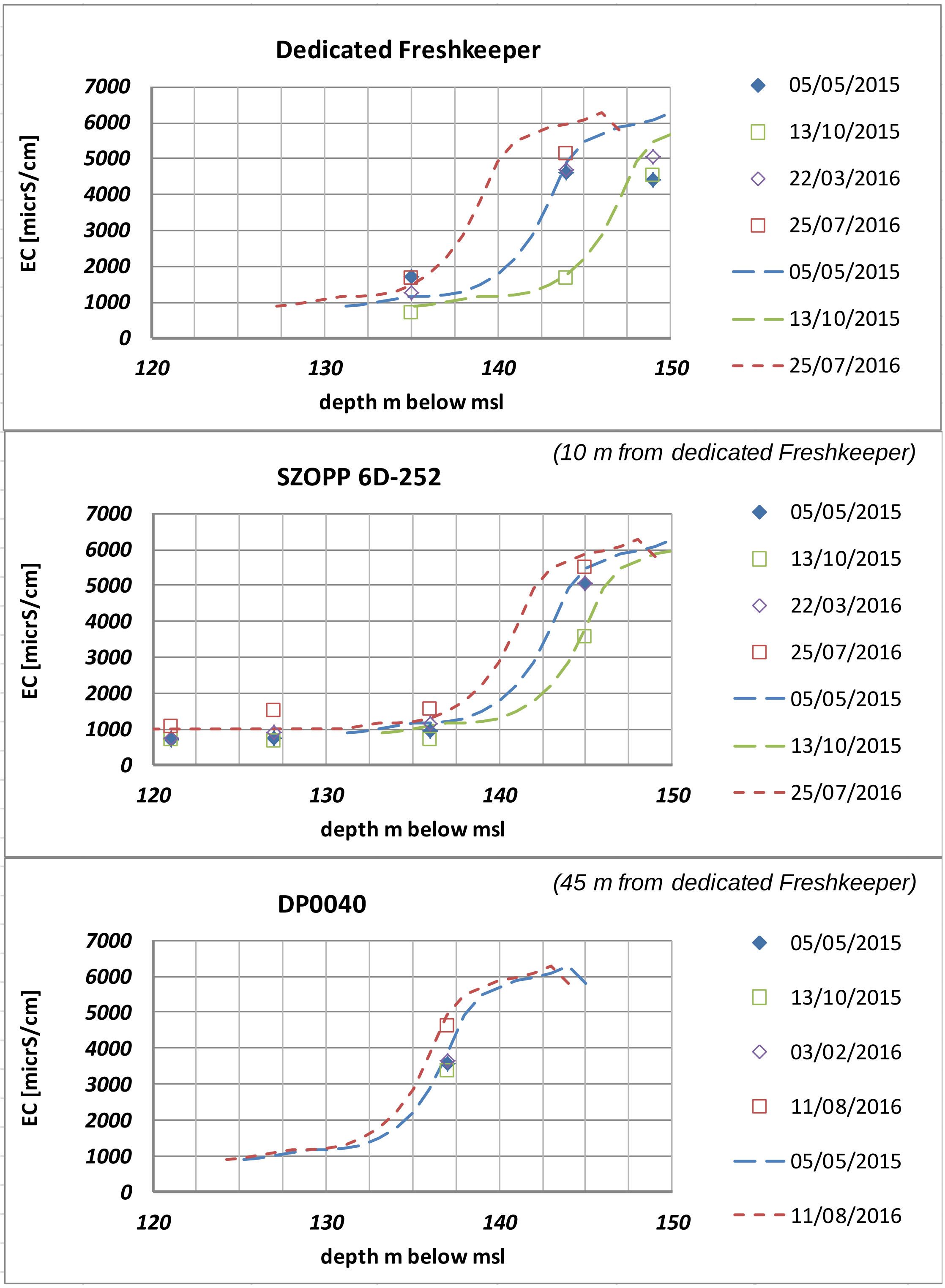

Figure 19: The EC-stratification (with depth) at different moments in the dedicated Freshkeeper ('smart water well') and two monitoring wells.

5.4 Effects of pumping regimes at distance from the Freshkeeper well

Under normal operation, the freshwater well screen and the brackish well screen are both extracting, and the brackish water abstraction has a strong effect on the electrical conductivity in that screen. This effect decreases at a distance of 10 m from the dedicated Freshkeeper and is almost non-existent at a distance of 45 m (DP0040) from the dedicated Freshkeeper. At this mode of operation (70m^3/h fresh; 13 m^3/h brackish), both wells have an equal influence on the pressure head in PD0040 at 137 mBSL. This may implie that the cone of extraction of the freshwater pump may deeper at larger distance from the Freshkeeper well. In other words: the freshwater well may provoke an upward movement of the fresh-brackish interface at larger distance, ultimately (several years) resulting in brackish water flowing towards this well.

This hypotheses is supported by changes in EC in monitoring wells at 100 m (D1087) and 125 m (DP1114): the fresh-brackish water interface has shifted over larger distances than well DP0040 (Figure 20).. In addition, this upconing was also detected in EM39 measurements that were performed in November 2016 at wells D1087 en DP1114 (Appendix 3).

In conclusion: the effects of pumping regimes on the fresh-brackish water interface may change with distance from the well. It is therefore recommended to monitor this interface at multiple monitoring wells and preferebly both by online EC measurement, as well as occasional geophysical measurements (EM39).

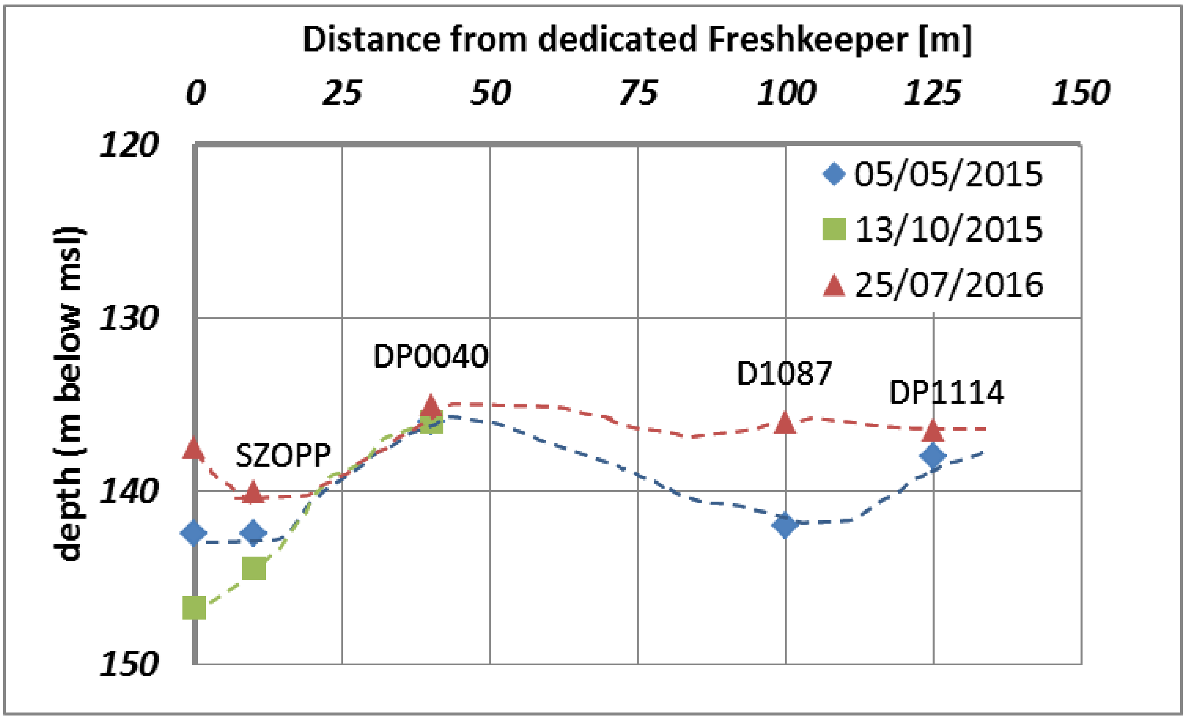

Figure 20: Level of fresh-salt interface (3000 µS/cm) at different moments and different distances from the dedicated Freshkeeper ('smart water well').

5.3. Optimalisation of the control technique

Because of malfunctioning of the original CTD-divers, we were only able to test the automated control settings (section 4.4) for one month. During this month, the automated control unit worked properly.

The automated control unit used input EC signals from sensors installed in monitoring wells in the gravel pack, at the depth of the brackish water screen. A more robust way to control the brackish water would be to use EC measurements of the abstracted brackish water. This would be an integrated signal, with less dynamics and artifacts, but with the disadvantage that it can only measure when the brackish water pump is in operation. Alternatively, online EC measurements from monitoring wells in close vicinity could be used or an integrated signal from all sensors nearby.

6. Groundwater flow and transport models

Groundwater flow models have been set up for the Noardburgum well field, both at local and regional scale. The local scale model has been used to evaluate pilot results both for the 2009 – 2013 pilot as well as the 2014 pilot (SUBSOL reference site). Regional scale models have been used, amongst others, to evaluate effects of deep well injection of BWRO concentrate (2009 – 2013 pilot) and intercepted brackish groundwater (2014 pilot) on salinity of nearby well fields. See Rijpkema and Van Doorn (2017) for evaluation of regional effects of full scale application of the 2014 Freshkeeper setup.

6.1. Local model for the first Freshkeeper pilot

Van der Valk (2011) has made several groundwater models for the Noardburgum well field. These have been applied to increase our understanding of relevant salinization processes at Noardburgum, both on a large and a small scale (van der Valk, 2011):

- Small scale model, to gain insight into local processes in the vicinity of the Freshkeeper well. In addition, this model allows to determine the effects of the well field configuration on upconing.
- Cross-sectional model, which is used to gain insight into the salinization process of the Noardburgum well field. The model is used to simulate the historic salt intrusion (from 10.000 years ago till now). The results of the model are used to make a spatially distributed chloride concentration distribution, that is subsequently used in the large scale model.
- Large scale model, which is used to gain insight into the salinization process of the Noardburgum well field.

6.2. Regional scale models

A Triwaco-groundwater, including a solute transport module, has been set up by De Graaf et al. (2007). The model based on the Microfem-model developed by Milfac (1996) and IWACO (1997) and includes the well fields of Noardburgum and Ritskebos. De Graaf et al. (2007) used the model to make projections of salinity concentrations in the Ritskebos well field.

Using the TRIWACO model, Van der Linde (2014) assessed the effects of brackish water disposal at Noardburgum on the nearby well field Ritskebos. The modelling started with a sensitivity analysis for the aquitard at the base of the aquifer (Tegelen clay), with the extractions and the deep aquifer situated below this aquitard. The presence of a second aquitard over a large area within the deep aquifer turned out to have a large influence on the results. This aquitard was found in a deep drilling, but the extend is largely unknown. Therefore, it was decided to include the extend of this aquitard and the injection depth of the brackish water in the subsequent modelling.

Initially, the influence of density variations on the groundwater flow were neglected and only advective transport was considered (using the finite element groundwater flow simulation program Triwaco-FLAIRS and the path line program TRACE (Royal Haskoning 2009)). Later on, simulations were carried out that did account for the influence of density and dispersion, using the model code SEAWAT (Guo and Langevin, 2002). It was concluded that density differences and dispersion cannot be neglected when modelling groundwater flow in the Noardburgum area. Since, the SEAWAT code has been used to model groundwater flow at Noardburgum, both for local as regional scale modeling. Geul (2016) and Rijpkema and Van Doorn (2017, SUBSOL D1.1) further modified the regional scale Noardburgum SEAWAT model to its final version using the software Flopy (www.flopy.com).

6.3. Local model for the second Freshkeeper pilot

A local Noardburgum model has been derived from the 2017 regional model by Rijpkema and Van Doorn (2017). The following adjustments have been made:

- The chloride stratification has been adjusted to mimic chloride stratification around the dedicated Freshkeeper, DP0040 and SZOPP 6D-252 (Table 6).
- The top and bottom of the layer with the well screens are adjusted to the exact depth and length of the well screens.
- The well extraction and infiltration rates have been adjusted to the actual discharges during the pilot.
- The model cells have been refined to 1 m directly around the well.

Table 6: Average of the chloride stratification at the wells (dedicated Freshkeeper, ZSOPP and DP0040).

Top-bot [m below msl]	Chloride concentration [mg/L]	Model layer
0-130	Varies between 50 and 60	1 to 9
130-135	150	10
135-140	600	11
140-144	1500	12
144-154 (brackish water well)	1500	13
154-160 (Tegelen clay layer)	1500	14
160-170	700	15+16
170 – 240	Increases from 1500 to 6000	17-22

The model was validated using the results of Freshkeeper testing between June 2015 and November 2016 (Chapter 5), in particular using data of:

- The vertical movement of the fresh-salt interface at the dedicated Freshkeeper (F3: monitoring screen at 144 m BLS), DP0040 (monitoring screen at 137 m BLS) and ZSOPP (monitoring screen at 135 m BLS);
- The reduced variation in chloride concentration at F2, the monitoring screen from the dedicated Freshkeeper at 135 m BLS;
- The greater upward movement of the fresh-salt interface at monitoring screen D1087 relative to the monitoring screen of DP1114 above 140 m BLS.

The model results are presented for the two monitoring screens of the dedicated Freshkeeper near the fresh-salt water interface in Figure 21. An important parameter (both in the local model as wells as the regional scale model) is the vertical permeability. Model runs were performed with two different values for the vertical permeability: 0.2 * horizontal permeability (Figure 21, top row.) and 0.5* horizontal permeability (Figure 21, bottom row).

Clearly, field test data are best represented by the model when using an anisotropy of 5, i.e. $k_V = 0.2*k_H$), in particular when brackish water is abstracted. When the brackish water pump is out of operation, the modeled concentrations are much lower then does observed. The observed steep increase in chloride concentrations, however, is questionable and may be attributed to an artifact in the pilot, i.e. preferential flow from the deeper (more saline) pats of the aquifer through the borehole during times when the the brackish water pump is out of operation, but the freshwater pump is still running.

Based on these local scale evaluations an anisotropy factor of 5, i.e. $k_V = 0.2*k_H$ was set both for the local scale model, as well as the full scale model.

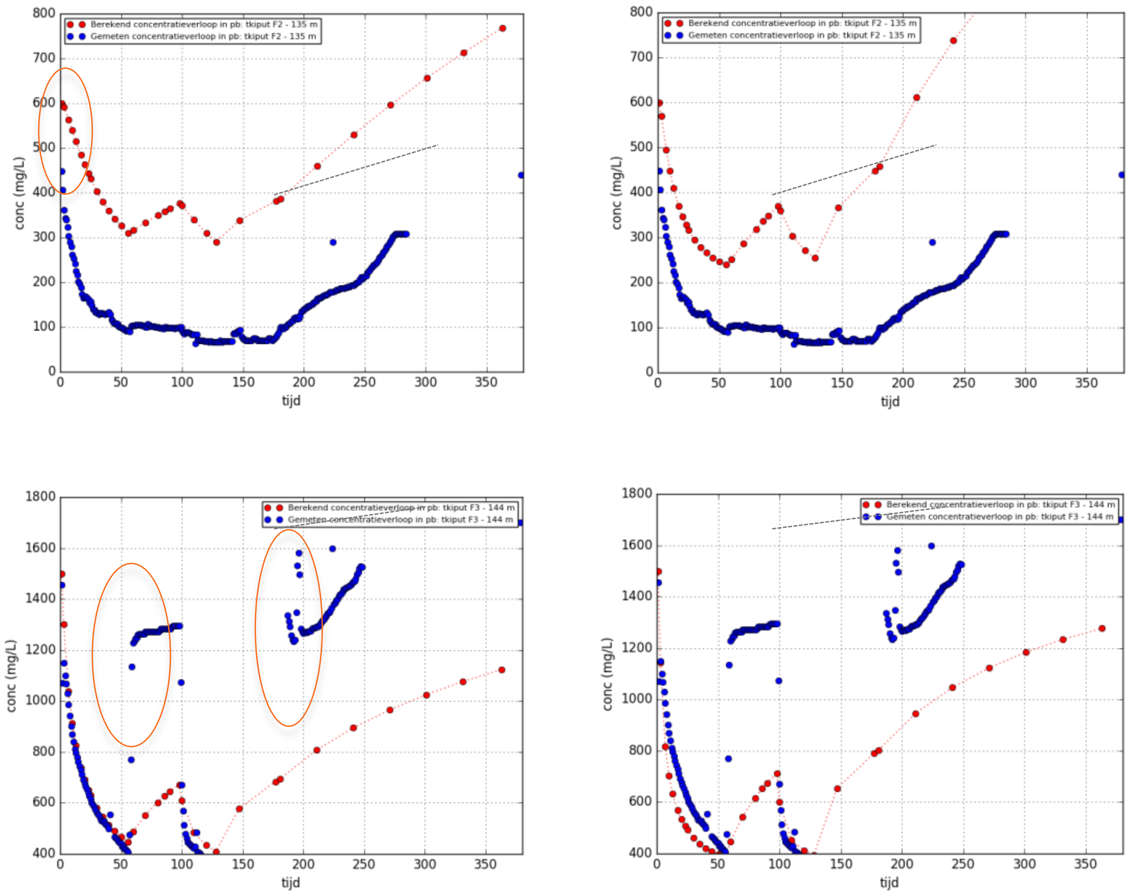

Figure 21: Calculated (red) and Observed (blue) chloride concentration in the dedicated Freshkeeper at monitoring screen F2 at 135 m BSL (top) and F3 at 144 m BSL (bottom). Left: the vertical hydraulic conductivity (Kv) is equal to 20% of the horizontal hydraulic conductivity. Right: the vertical hydraulic conductivity (Kv) is equal to 50% of the horizontal hydraulic conductivity.

7. Summary and conclusions

- A Freshkeeper well with dedicated filter screens for freshwater abstraction, brackish water abstraction and brackish water disposal was designed and installed.
- 6 monitoring screens, 3 well screens and 2 submersible pumps were placed within one single borehole. To prevent short-circuiting of water through the gravel pack, clay seals were installed in the annulus between monitoring and well screens.
- The Freshkeeper well operated as planned, producing 70m^3/h freshwater from the top filter screen ((60 – 80 mBLS) since the start of the pilot. This water was distributed to the nearby drinking water production plant.
- Brackish groundwater was abstracted from the second well screen (143 – 154 mBSL), at an adjustable rate of 5 to 23 m^3/h This water was injected in the underlying aquifer at approx. 190 mBSL.

- An automated control unit (ACU) was designed and installed in the well chamber. This unit connects to the EC monitoring devices in the Freshkeeper well, as well as with remote computers (online)
- Through the ACU, the brackish water abstraction rate could be set automatically as a function of electrical conductivity measured at depth of the brackish water abstraction screen.
- The ACU functioned properly, but could be tested for one month only because of malfunctioning of the CTD-divers that were initially installed.
- Problems with the CTD divers included corrosion, leakage and bad cable connections. The divers were eventually replaced by simple EC sensors, that function properly.

- Between between June 2015 and November 2016 several pumping regimes were induced, in order to test the hydrological system's repsonse to well operation.
- The results were used to validate the local and regional scale groundwater models, in particular the anisotropy factor (k_H/k_V).
- Close to the Freshkeeper well, the fresh-brackish interface could shift over 10 meters depth, depending on brackish water abstraction rate. This effect diminished to only about 1 – 2 meters at 45 meters distance. However, at larger distance, again a larger interface shift was observed.
- It was concluded that the effects of pumping regimes on the fresh-brackish water interface may change with distance from the well. It is therefore recommended to monitor this interface at multiple monitoring wells and preferebly both by online EC measurement, as well as occasional geophysical measurements (EM39).

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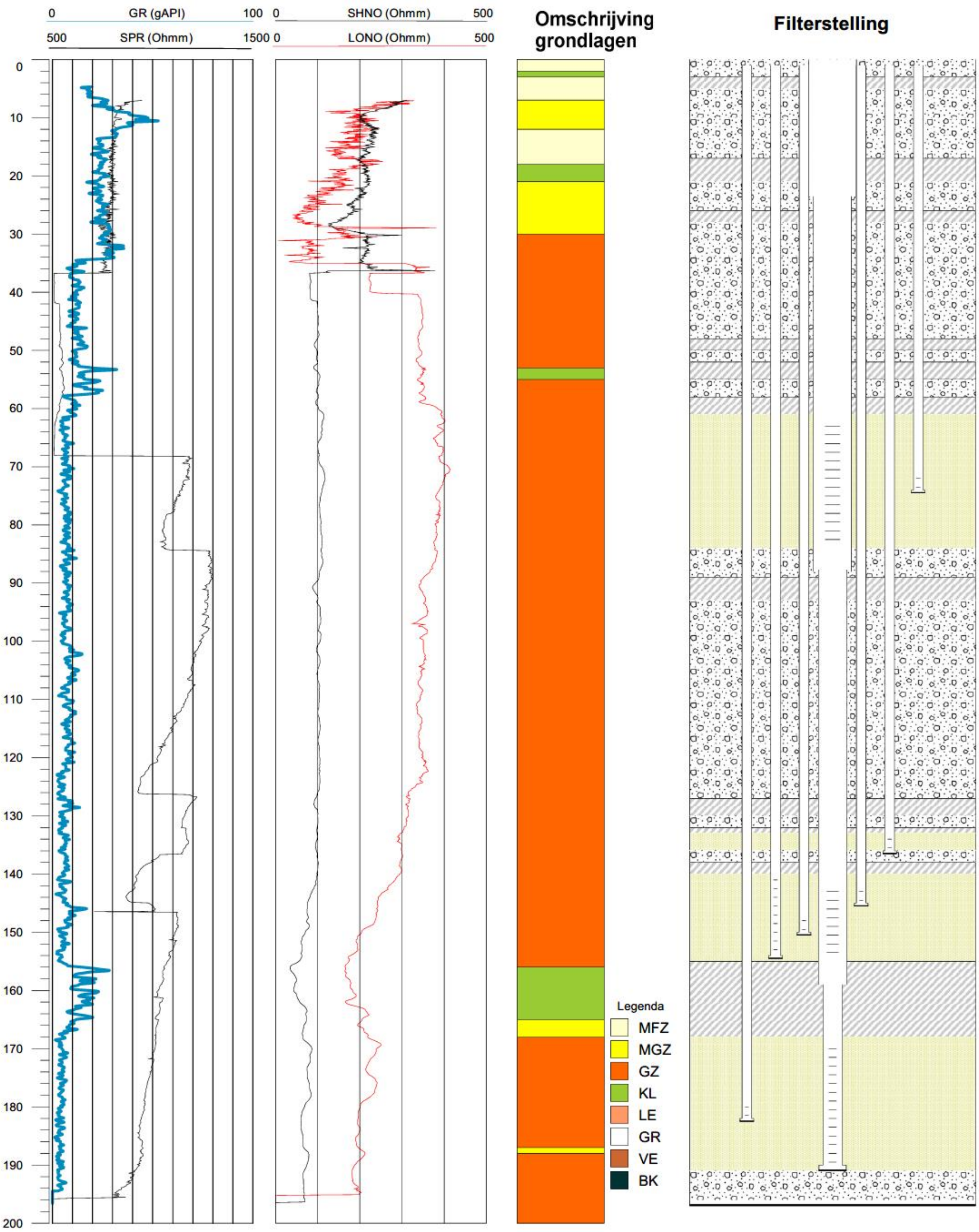
www.triwaco.com

www.flopy.com

Appendix 1: Specific information of the dedicated Freshkeeper

Plaatsnaam:	Noardburgum	x-coördinaat:	240682
Straatnaam:	Van Grinterstraat 1	y-coördinaat:	585589
Putnaam:	Slimme Put	maaiveldhoogte:	
opdrachtgever:		datum:	10/07/2014
		boorgatdiameter:	900/700 mm
boorbedrijf:	BAM Nelis de Ruiter		

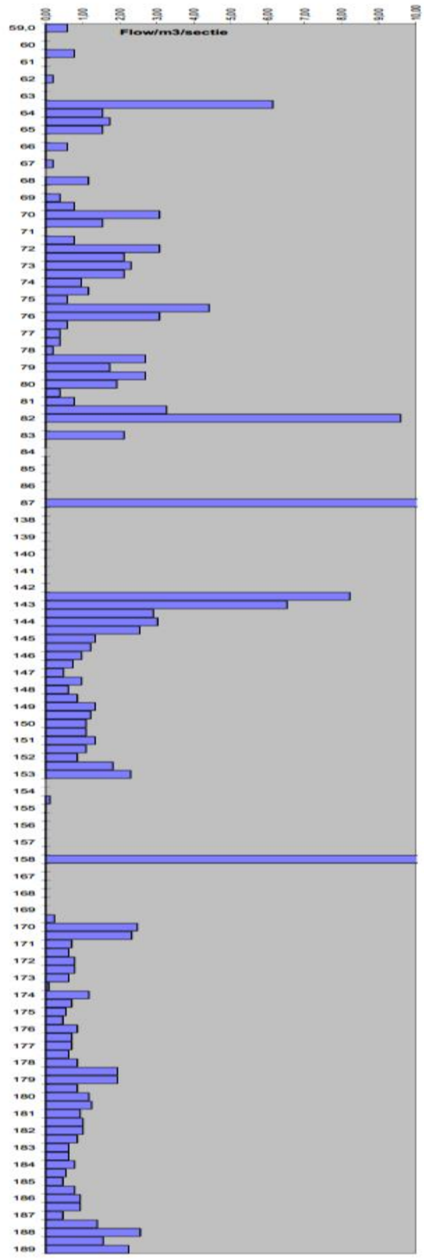


BAM Nelis De Ruiter bv

bam infra

POMPSTATION :					Noordburgum			Put Nummer:		Slimme put	
Flowmeting :					1			Datum	:	3-11-2014	
Opmerking								geen			

filter	Q	af pomp.	Ø	factor	impuls	Q M3/uur	Q in %	impuls	M3/uur	Q per mtr afpomping	Q in % totaal
	120	1,07			625	120,00	100,00	0,00	0,00	0,00	0,00
59,0			315	1	625	120,00	100,00	3,00	0,58	0,54	0,48
59,5			315	1	622	119,42	99,52	-7,00	-1,34	-1,26	-1,12
60			315	1	629	120,77	100,64	-3,00	-0,58	-0,54	-0,48
60,5			315	1	632	121,34	101,12	4,00	0,77	0,72	0,64
61			315	1	628	120,58	100,48	-11,00	-2,11	-1,97	-1,76
61,5			315	1	639	122,69	102,24	-4,00	-0,77	-0,72	-0,64
62			315	1	643	123,46	102,88	1,00	0,19	0,18	0,16
62,5			315	1	642	123,26	102,72	-3,00	-0,58	-0,54	-0,48
63			315	1	645	123,84	103,20	-1,00	-0,19	-0,18	-0,16
63,5			315	1	646	124,03	103,36	32,00	6,14	5,74	5,12
64			315	1	614	117,89	98,24	8,00	1,54	1,44	1,28
64,5			315	1	606	116,35	96,96	9,00	1,73	1,61	1,44
65			315	1	597	114,62	95,52	8,00	1,54	1,44	1,28
65,5			315	1	589	113,09	94,24	-6,00	-1,15	-1,08	-0,96
66			315	1	595	114,24	95,20	3,00	0,58	0,54	0,48
66,5			315	1	592	113,66	94,72	-1,00	-0,19	-0,18	-0,16
67			315	1	593	113,86	94,88	1,00	0,19	0,18	0,16
67,5			315	1	592	113,66	94,72	0,00	0,00	0,00	0,00
68			315	1	592	113,66	94,72	6,00	1,15	1,08	0,96
68,5			315	1	586	112,51	93,76	-5,00	-0,96	-0,90	-0,80
69			315	1	591	113,47	94,56	2,00	0,38	0,36	0,32
69,5			315	1	589	113,09	94,24	4,00	0,77	0,72	0,64
70			315	1	585	112,32	93,60	16,00	3,07	2,87	2,56
70,5			315	1	569	109,25	91,04	8,00	1,54	1,44	1,28
71			315	1	561	107,71	89,76	-1,00	-0,19	-0,18	-0,16
71,5			315	1	562	107,90	89,92	4,00	0,77	0,72	0,64
72			315	1	558	107,14	89,28	16,00	3,07	2,87	2,56
72,5			315	1	542	104,06	86,72	11,00	2,11	1,97	1,76
73			315	1	531	101,95	84,96	12,00	2,30	2,15	1,92
73,5			315	1	519	99,65	83,04	11,00	2,11	1,97	1,76
74			315	1	508	97,54	81,28	5,00	0,96	0,90	0,80
74,5			315	1	503	96,58	80,48	6,00	1,15	1,08	0,96
75			315	1	497	95,42	79,52	3,00	0,58	0,54	0,48
75,5			315	1	494	94,85	79,04	23,00	4,42	4,13	3,68
76			315	1	471	90,43	75,36	16,00	3,07	2,87	2,56
76,5			315	1	455	87,36	72,80	3,00	0,58	0,54	0,48
77			315	1	452	86,78	72,32	2,00	0,38	0,36	0,32
77,5			315	1	450	86,40	72,00	2,00	0,38	0,36	0,32
78			315	1	448	86,02	71,68	1,00	0,19	0,18	0,16
78,5			315	1	447	85,82	71,52	14,00	2,69	2,51	2,24
79			315	1	433	83,14	69,28	9,00	1,73	1,61	1,44
79,5			315	1	424	81,41	67,84	14,00	2,69	2,51	2,24
80			315	1	410	78,72	65,60	10,00	1,92	1,79	1,60
80,5			315	1	400	76,80	64,00	2,00	0,38	0,36	0,32
81			315	1	398	76,42	63,68	4,00	0,77	0,72	0,64
81,5			315	1	394	75,65	63,04	17,00	3,26	3,05	2,72
82			315	1	377	72,38	60,32	50,00	9,60	8,97	8,00
82,5			315	1	327	62,78	52,32	-7,00	-1,34	-1,26	-1,12
83			315	1	334	64,13	53,44	11,00	2,11	1,97	3,80
83,5			315	1,04112	323	59,57	49,64	-3,00	-0,55	-0,52	-0,46
84			315	1,04112	326	60,12	50,10	0,00	0,00	0,00	0,00
84,5			315	1,04112	326	60,12	50,10	-10,00	-1,84	-1,72	-1,54
85			315	1,04112	336	61,96	51,64	-16,00	-2,95	-2,76	-2,46
85,5			315	1,04112	352	64,91	54,10	-44,00	-8,11	-7,58	-6,76
86			315	1,04112	396	73,03	60,86	-30,00	-5,53	-5,17	-4,61
86,5			315	1,04112	426	78,56	65,47	-48,00	-8,85	-8,27	-7,38
87			315	1,04112	474	87,41	72,84	474,00	87,41	81,70	72,84
verloop			315	1,04112	0	0,00	0,00	-567,00	-104,56	-97,72	-57,15
138			250	1,58751	567	68,58	57,15	-1,00	-0,12	-0,11	-0,10
138,5			250	1,58751	568	68,70	57,25	-7,00	-0,85	-0,79	-0,71
139			250	1,58751	575	69,54	57,95	-4,00	-0,48	-0,45	-0,40
139,5			250	1,58751	579	70,03	58,36	-10,00	-1,21	-1,13	-1,01
140			250	1,58751	589	71,24	59,36	-10,00	-1,21	-1,13	-1,01
140,5			250	1,58751	599	72,45	60,37	-17,00	-2,06	-1,92	-1,71
141			250	1,58751	616	74,50	62,08	-11,00	-1,33	-1,24	-1,11
141,5			250	1,58751	627	75,83	63,19	-5,00	-0,60	-0,57	-0,50
142			250	1,58751	632	76,44	63,70	-10,00	-1,21	-1,13	-1,01
142,5			250	1,58751	642	77,65	64,70	68,00	8,22	7,69	6,85
143			250	1,58751	574	69,42	57,85	54,00	6,53	6,10	5,44
143,5			250	1,58751	520	62,89	52,41	24,00	2,90	2,71	2,42
144			250	1,58751	496	59,99	49,99	25,00	3,02	2,83	2,52
144,5			250	1,58751	471	56,96	47,47	21,00	2,54	2,37	2,12
145			250	1,58751	450	54,42	45,35	11,00	1,33	1,24	1,11
145,5			250	1,58751	439	53,09	44,25	10,00	1,21	1,13	1,01
146			250	1,58751	429	51,88	43,24	8,00	0,97	0,90	0,81
146,5			250	1,58751	421	50,92	42,43	6,00	0,73	0,68	0,60
147			250	1,58751	415	50,19	41,83	4,00	0,48	0,45	0,40
147,5			250	1,58751	411	49,71	41,42	8,00	0,97	0,90	0,81
148			250	1,58751	403	48,74	40,62	5,00	0,60	0,57	0,50
148,5			250	1,58751	398	48,14	40,11	7,00	0,85	0,79	0,71
149			250	1,58751	391	47,29	39,41	11,00	1,33	1,24	1,11
149,5			250	1,58751	380	45,96	38,30	10,00	1,21	1,13	1,01
150			250	1,58751	370	44,75	37,29	9,00	1,09	1,02	0,91
150,5			250	1,58751	361	43,66	36,38	9,00	1,09	1,02	0,91
151			250	1,58751	352	42,57	35,48	11,00	1,33	1,24	1,11
151,5			250	1,58751	341	41,24	34,37	9,00	1,09	1,02	0,91
152			250	1,58751	332	40,15	33,46	7,00	0,85	0,79	0,71
152,5			250	1,58751	325	39,31	32,76	15,00	1,81	1,70	1,51
153			250	1,58751	310	37,49	31,24	19,00	2,30	2,15	1,91
153,5			250	1,58751	291	35,19	29,33	0,00	0,00	0,00	0,00
154			250	1,58751	291	35,19	29,33	0,00	0,00	0,00	1,21
154,5			250	1,65566	291	33,75	28,12	1,00	0,12	0,11	0,10
155			250	1,65566	290	33,63	28,03	-2,00	-0,23	-0,22	-0,19
155,5			250	1,65566	292	33,86	28,22	-8,00	-0,93	-0,87	-0,77
156			250	1,65566	300	34,79	28,99	-13,00	-1,51	-1,41	-1,26
156,5			250	1,65566	313	36,30	30,25	-32,00	-3,71	-3,47	-3,09
157			250	1,65566	345	40,01	33,34	-42,00	-4,87	-4,55	-4,06
157,5			250	1,65566	387	44,88	37,40	-33,00	-3,83	-3,58	-3,19
158			250	1,65566	420	48,71	40,59	420,00	48,71	45,52	40,59
verloop			250	1,65566	0	0,00	0,00	-487,00	-56,48	-52,78	-31,40
167			200	2,48156	487	37,68	31,40	-4,00	-0,31	-0,29	-0,26
167,5			200	2,48156	491	37,99	31,66	-4,00	-0,31	-0,29	-0,26
168			200	2,48156	495	38,30	31,92	-6,00	-0,46	-0,43	-0,39
168,5			200	2,48156	501	38,76	32,30	-4,00	-0,31	-0,29	-0,26
169			200	2,48156	505	39,07	32,56	-11,00	-0,85	-0,80	-0,71
169,5			200	2,48156	516	39,92	33,27	3,00	0,23	0,22	0,19
170			200	2,48156	513	39,69	33,08	32,00	2,48	2,31	2,06
170,5			200	2,48156	481	37,22	31,01	30,00	2,32	2,17	1,93
171			200	2,48156	451	34,89	29,08	9,00	0,70	0,65	0,58
171,5			200	2,48156	442	34,20	28,50	8,00	0,62	0,58	0,52
172			200	2,48156	434	33,58	27,98	10,00	0,77	0,72	0,64
172,5			200	2,48156	424	32,81	27,34	10,00	0,77	0,72	0,64
173			200	2,48156	414	32,03	26,69	8,00	0,62	0,58	0,52
173,5			200	2,48156	406	31,41	26,18	1,00	0,08	0,07	0,06
174			200	2,48156	405	31,34	26,11	15,00	1,16	1,08	0,97
174,5			200	2,48156	390	30,17	25,15	9,00	0,70	0,65	0,58
175			200	2,48156	381	29,48	24,57	7,00	0,54	0,51	0,45
175,5			200	2,48156	374	28,94	24,11	6,00	0,46	0,43	0,39
176			200	2,48156	368	28,47	23,73	11,00	0,85	0,80	0,71
176,5			200	2,48156	357	27,62	23,02	9,00	0,70	0,65	0,58
177			200	2,48156	348	26,92	22,44	9,00	0,70	0,65	0,58
177,5			200	2,48156	339	26,23	21,86	8,00	0,62	0,58	0,52
178			200	2,48156	331	25,61	21,34	11,00	0,85	0,80	0,71
178,5			200	2,48156	320	24,76	20,63	25,00	1,93	1,81	1,61
179			200	2,48156	295	22,82	19,02	25,00	1,93	1,81	1,61
179,5			200	2,48156	270	20,89	17,41	11,00	0,85	0,80	0,71
180			200	2,48156	259	20,04	16,70	15,00	1,16	1,08	0,97
180,5			200	2,48156	244	18,88	15,73	16,00	1,24	1,16	1,03
181			200	2,48156	228	17,64	14,70	12,00	0,93	0,87	0,77
181,5			200	2,48156	216	16,71	13,93	13,00	1,01	0,94	0,84
182			200	2,48156	203	15,71	13,09	13,00	1,01	0,94	0,84
182,5			200	2,48156	190	14,70	12,25	11,00	0,85	0,80	0,71
183			200	2,48156	179	13,85	11,54	8,00	0,62	0,58	0,52
183,5			200	2,48156	171	13,23	11,03	8,00	0,62	0,58	0,52
184			200	2,48156	163	12,61	10,51	10,00	0,77	0,72	0,64
184,5			200	2,48156	153	11,84	9,86	7,00	0,54	0,51	0,45
185			200	2,48156	146	11,30	9,41	6,00	0,46	0,43	0,39
185,5			200	2,48156	140	10,83	9,03	10,00	0,77	0,72	0,64
186			200	2,48156	130	10,06	8,38	12,00	0,93	0,87	0,77
186,5			200	2,48156	118	9,13	7,61	12,00	0,93	0,87	0,77
187			200	2,48156	106	8,20	6,83	6,00	0,46	0,43	0,39
187,5			200	2,48156	100	7,74	6,45	18,00	1,39	1,30	1,16
188			200	2,48156	82	6,34	5,29	33,00	2,55	2,39	2,13
188,5			200	2,48156	49	3,79	3,16	20,00	1,55	1,45	1,29
189			200	2,48156	29	2,24	1,87	29,00	2,24	2,10	1,87



Blad 1 van 2

Capaciteitsproef bronnen

Project naam	**Freshkeeper**	Datum proef	**30 oktober 2014**
Plaats project	**Noardburgum**	MV t.o.v. NAP/bouwpeil	
Opdrachtgever	**Vitens**	Bron t.o.v. MV	**0,86 m**
Naam bron	**Slimme put**	PB 1 t.o.v. MV	**0,86 m**
		PB 2 t.o.v. MV	**0,86 m**
Projectnummer	**3220390**	PB 3 t.o.v. MV	**0,86 m**
		PB 4 t.o.v. MV	**0,86 m**
		PB 5 t.o.v. MV	**0,86 m**
		PB 6 t.o.v. MV	**0,79 m (Ø75mm)**

Ontwerpdebiet (Qontwerp): 120,00 m³/h | **Specifiek debiet [m³/h/m]: 112,15**

tijd	debiet		waterstand bron	peilbuis 1	peilbuis 2	peilbuis 3	peilbuis 4	peilbuis 5	peilbuis 6	opmerkingen
[min]		[m³/h]	[m - b.b.]	[m - b.b.]	[m - b.b.]	[m - b.b.]	[m - b.b.]	[m - b.b.]	[m - b.b.]	
0	0%	0,00	4,61	4,63	4,59	4,64	4,62	4,62	4,56	
2	50%xQontwerp	60,00	5,08	5,06	4,63	5,05	5,04	4,95	4,92	
5	50%xQontwerp	60,00	5,10	5,09	4,65	5,06	5,06	4,96	4,95	
10	50%xQontwerp	60,00	5,11	5,08	4,65	5,07	5,06	4,96	4,96	
20	50%xQontwerp	60,00	5,11	5,09	4,65	5,08	5,07	4,96	4,96	
30	50%xQontwerp	60,00	5,10	5,10	4,66	5,08	5,07	4,96	4,96	
40	50%xQontwerp	60,00	5,11	5,11	4,67	5,08	5,07	4,96	4,96	
50	50%xQontwerp	60,00	5,11	5,11	4,67	5,08	5,07	4,97	4,97	
60	50%xQontwerp	60,00	5,11	5,11	4,67	5,08	5,07	4,97	4,97	
62	Qontwerp	120,00	5,64	5,60	4,72	5,52	5,49	5,35	5,35	
65	Qontwerp	120,00	5,66	5,61	4,73	5,54	5,52	5,37	5,37	
70	Qontwerp	120,00	5,67	5,63	4,75	5,56	5,52	5,38	5,38	
80	Qontwerp	120,00	5,67	5,64	4,76	5,57	5,52	5,38	5,38	
90	Qontwerp	120,00	5,67	5,64	4,76	5,57	5,53	5,39	5,39	
100	Qontwerp	120,00	5,68	5,64	4,76	5,57	5,54	5,41	5,41	
110	Qontwerp	120,00	5,68	5,64	4,77	5,57	5,54	5,41	5,41	
120	Qontwerp	120,00	5,68	5,64	4,77	5,57	5,54	5,41	5,41	
122	150%xQontwerp	180,00	6,18	6,07	4,80	5,94	5,86	5,75	5,75	
125	150%xQontwerp	180,00	6,21	6,11	4,81	5,98	5,92	5,76	5,75	
130	150%xQontwerp	180,00	6,22	6,13	4,83	6,00	5,94	5,76	5,76	
140	150%xQontwerp	180,00	6,23	6,15	4,84	6,01	5,95	5,77	5,76	
150	150%xQontwerp	180,00	6,23	6,15	4,85	6,04	5,96	5,78	5,77	
160	150%xQontwerp	180,00	6,24	6,15	4,85	6,03	5,96	5,78	5,78	
180	150%xQontwerp	180,00	6,24	6,16	4,86	6,04	5,98	5,79	5,79	
0	0%	0,00								stopproef
2	0%	0,00	4,78	4,77	4,72	4,76	4,77	4,73	4,66	
5	0%	0,00	4,66	4,70	4,63	4,71	4,70	4,70	4,62	
10	0%	0,00	4,61	4,64	4,58	4,66	4,65	4,64	4,56	
20	0%	0,00	4,57	4,60	4,53	4,62	4,61	4,60	4,52	
30	0%	0,00	4,56	4,58	4,52	4,62	4,59	4,59	4,51	
40	0%	0,00	4,53	4,56	4,50	4,59	4,58	4,59	4,50	
50	0%	0,00	4,52	4,55	4,48	4,59	4,56	4,56	4,48	
60	0%	0,00	4,51	4,52	4,46	4,57	4,56	4,56	4,47	

Appendix 2: Various monitoring techniques for enabling the automated monitoring and control of the Freshkeeper

Subsurface monitoring Device (SMD)

A subsurface monitoring device consists of 2 components:

- An electrical array with a number of electrodes in the borehole;
- An acquisition box with the electronic modules at the surface and an embedded computer to monitor the electronics and to create 3D-images. The software can also be used to control the wells;

The estimated cost of the system, including the software and control program, is € 50 000.

Some points of interests are:

- The data has to be analysed in the applied software program.
- It is unknown whether the monitoring system was successfully implemented till a depth of 200 m BSL.
- Discussion with the system's installer clarified that the equipment of the well and the vertical flow of brackish water through the well might influence the electrodes. Therefore, the system requires either the placement of a screen between the electrodes and the equipment, or the installation of a separate monitoring borehole. Both solutions will result in an additional cost of € 25 000.

Permanent Electrode Cables System (PECS)

The permanent electrode cables system ('zoutwachter') is a proven technique that is already in use for several decades.Several (around 13) electrodes are placed on a cable in a borehole at a distance specified by the user. The electrodes are in contact with the soil and measure the soil resistance at every point. One of the disadvantages of the system is that once the electrodes are installed, they can't be removed or replaced. Another disadvantage is that the equipment takes several weeks to prepare and the dimensions of the cables have to be given to the manufacturer in advance, since adjustments to the dimensions are not possible after installation.The company Vitens has experienced sensor malfunctioning and a late response time of the manufacturer.

CVES electrodes vertically placed

Continuous vertical electrical soundings (CVES) electrodes are normally placed at surface level. The penetration depth of the signal into the subsurface depends on the separation distance of the electrodes. Over the past years, a pilot was conducted by the VU University with CVES electrodes placed vertically in a borehole till a depth of 3 m BSL. The objective was to create a 3D-image of the EC-value in the aquifer. In consultation with the VU University, the technique was considered too premature for implementation at a depth of 150 m BSL.

Fiber optic cable

The fiber optic cable was mainly used at the beginning of this pilot for temperature measurements because it has a high resistance to corrosion and high pressures. However, the use of this cable for EC-measurements was still in development at the start of the pilot. The technique is therefore considered only as additional monitoring for testing the equipment.

EC-sensors

The placement of EC-sensors in monitoring well screens is a proven technique and available from a wide prize range. An acquisition box for transferring data from the monitoring device to a computer is often required for translation of the signal.

At the start of the pilot, the CTD-diver from Schlumberger was selected because it was assumed beneficial to select a supplier with an office in the Netherlands. The CTD-diver can operate till a depth of 300 m BSL, is resistant to corrosion, fits into a monitoring well screen of one inch in diameter, and additionally monitors the temperature and pressure (pressure only till a depth of 100 m BSL). The CTD-diver costs €1 500 per piece. The standard 'Diver' suffices for plain pressure level measurements and costs € 600 per piece. The installation of (free) diver-software is required to read the monitoring results.

Alternative (unsuitable) EC monitoring techniques

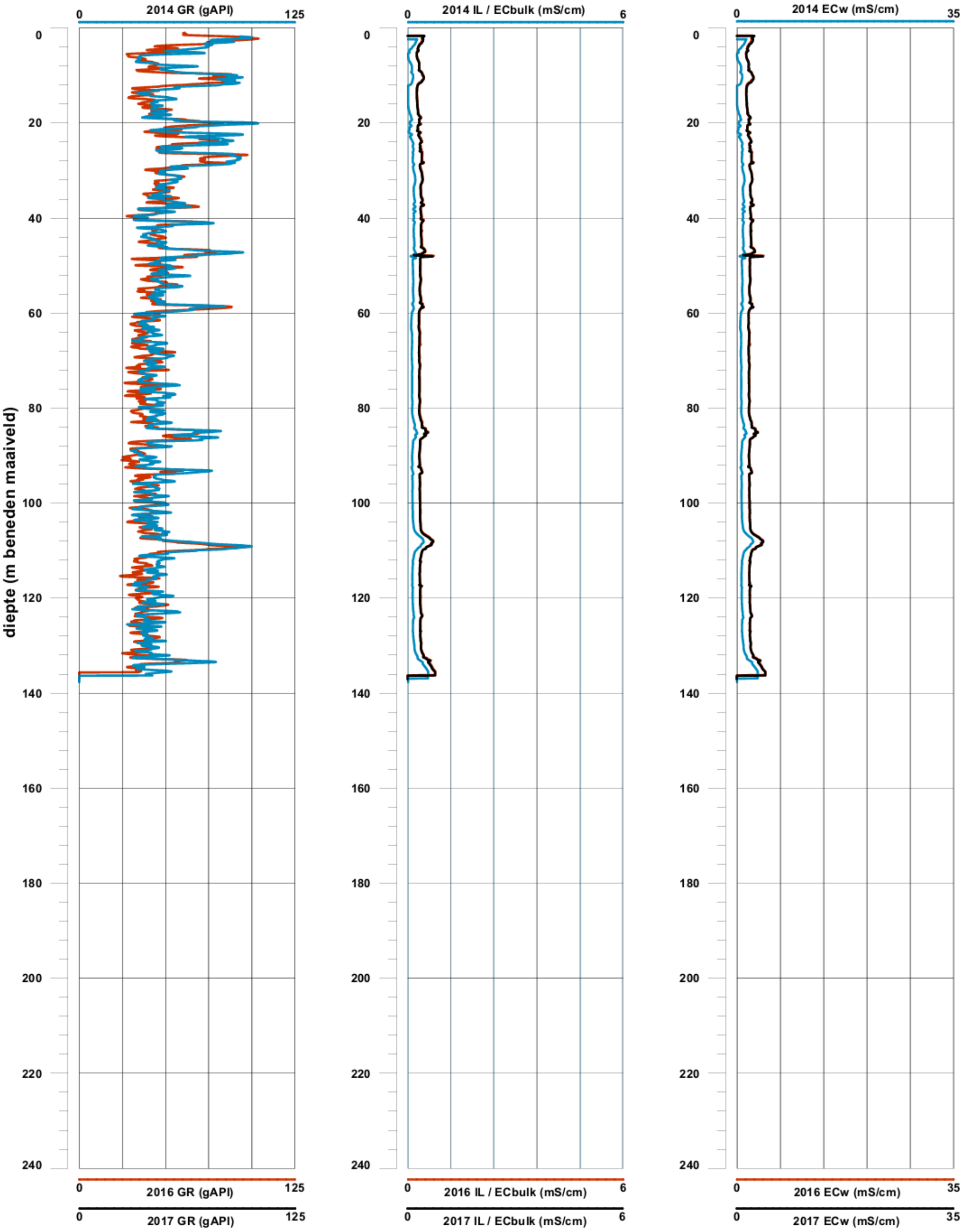
- EM39 borehole measurements. Soil resistance is measured along the borehole with a short and long probe. The amount of measurements depends on the depth of the monitoring filers. The signal reaches 35 cm outside of the borehole. The monitoring screen requires a minimal diameter of 2.5 inch. In the Netherlands, costs for borehole measurements are approximately € 1 500 – 2 000 per day.
- Groundwater quality analysis. These measurements are usually required for calibration of the aforementioned monitoring techniques.

Appendix 3: EC-measurements

Bijlage

Plaatsnaam:	Noordbergum	**Opdrachtgever:**	Vitens
Straatnaam:	Dokter Ypeijlaan	**Boorbedrijf:**	-
RD - coördinaten:	X: 196150, Y: 581150	**Naam put:**	B06D0293
Maaiveldhoogte:	1.5 m NAP (AHN)	**Boormethode:**	-
Datum:		**Diameter boorgat:**	-

Deltares
Enabling Delta Life

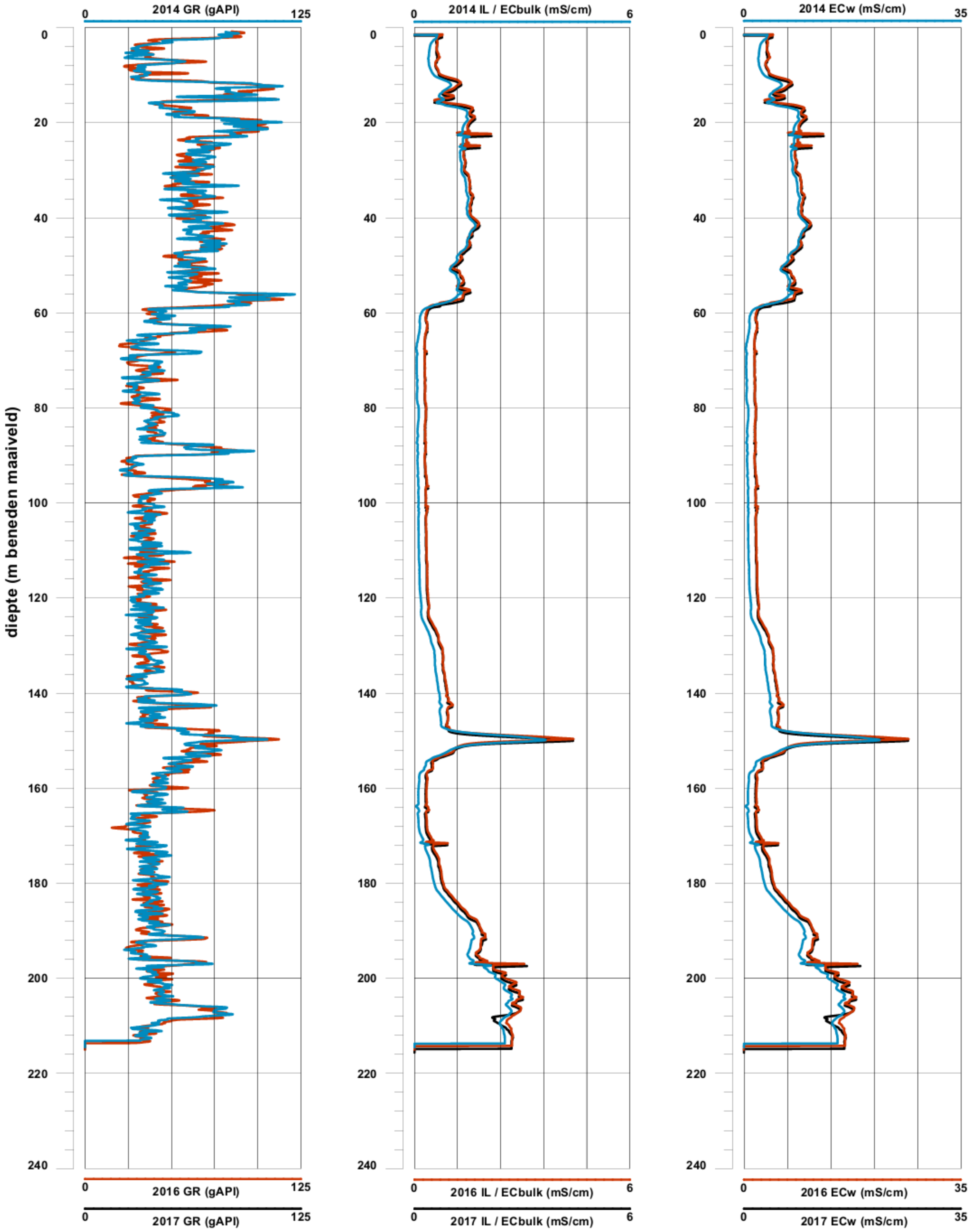


Bijlage

Plaatsnaam: Noordbergum
Straatnaam: Rijksstraatweg
RD - coördinaten: X: 196822, Y: 581770
Maaiveldhoogte: 0.8 m NAP (AHN)
Datum:

Opdrachtgever: Vitens
Boorbedrijf: -
Naam put: B06D0294
Boormethode: -
Diameter boorgat: -

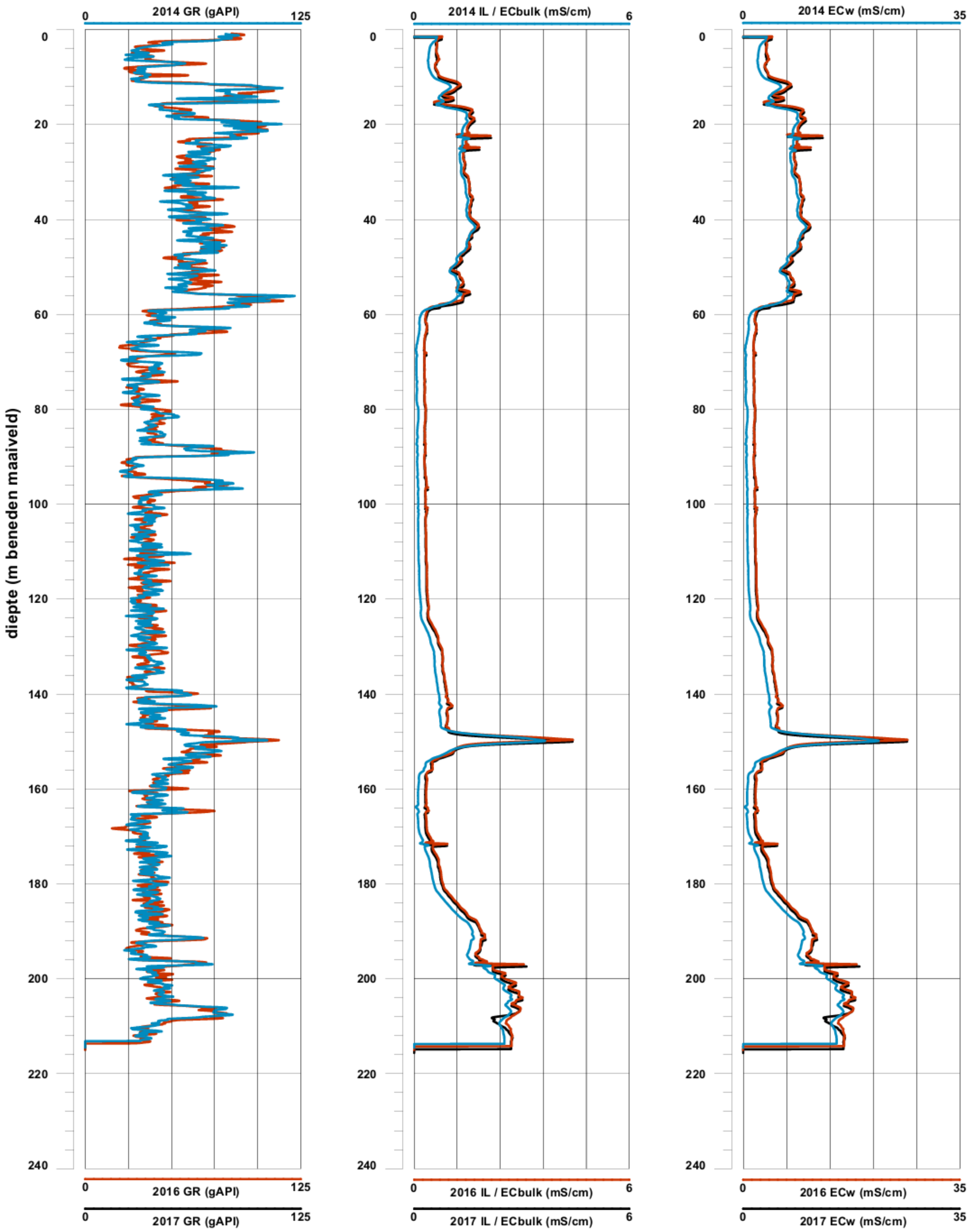
Deltares
Enabling Delta Life



Bijlage

Plaatsnaam:	Noordbergum	**Opdrachtgever:**	Vitens
Straatnaam:	Rijksstraatweg	**Boorbedrijf:**	-
RD - coördinaten:	X: 196822, Y: 581770	**Naam put:**	B06D0294
Maaiveldhoogte:	0.8 m NAP (AHN)	**Boormethode:**	-
Datum:		**Diameter boorgat:**	-

Deltares
Enabling Delta Life



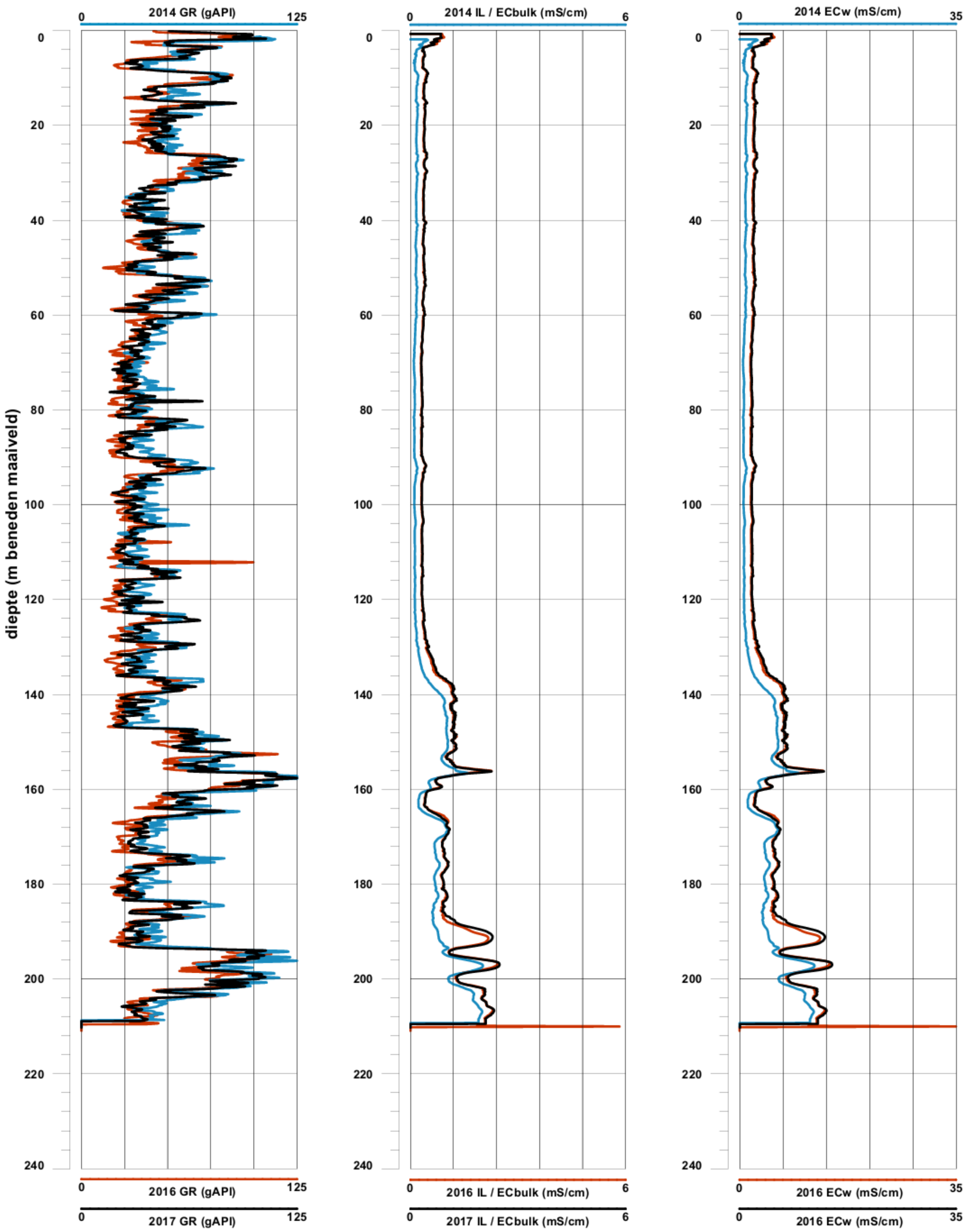
SubSol

Bijlage

Plaatsnaam: Noordbergum
Straatnaam: Pompstation Vitens
RD - coördinaten: X: 195799, Y: 581585
Maaiveldhoogte: 1.6 m NAP (AHN)
Datum:

Opdrachtgever: Vitens
Boorbedrijf: -
Naam put: B06D1114
Boormethode: -
Diameter boorgat: -

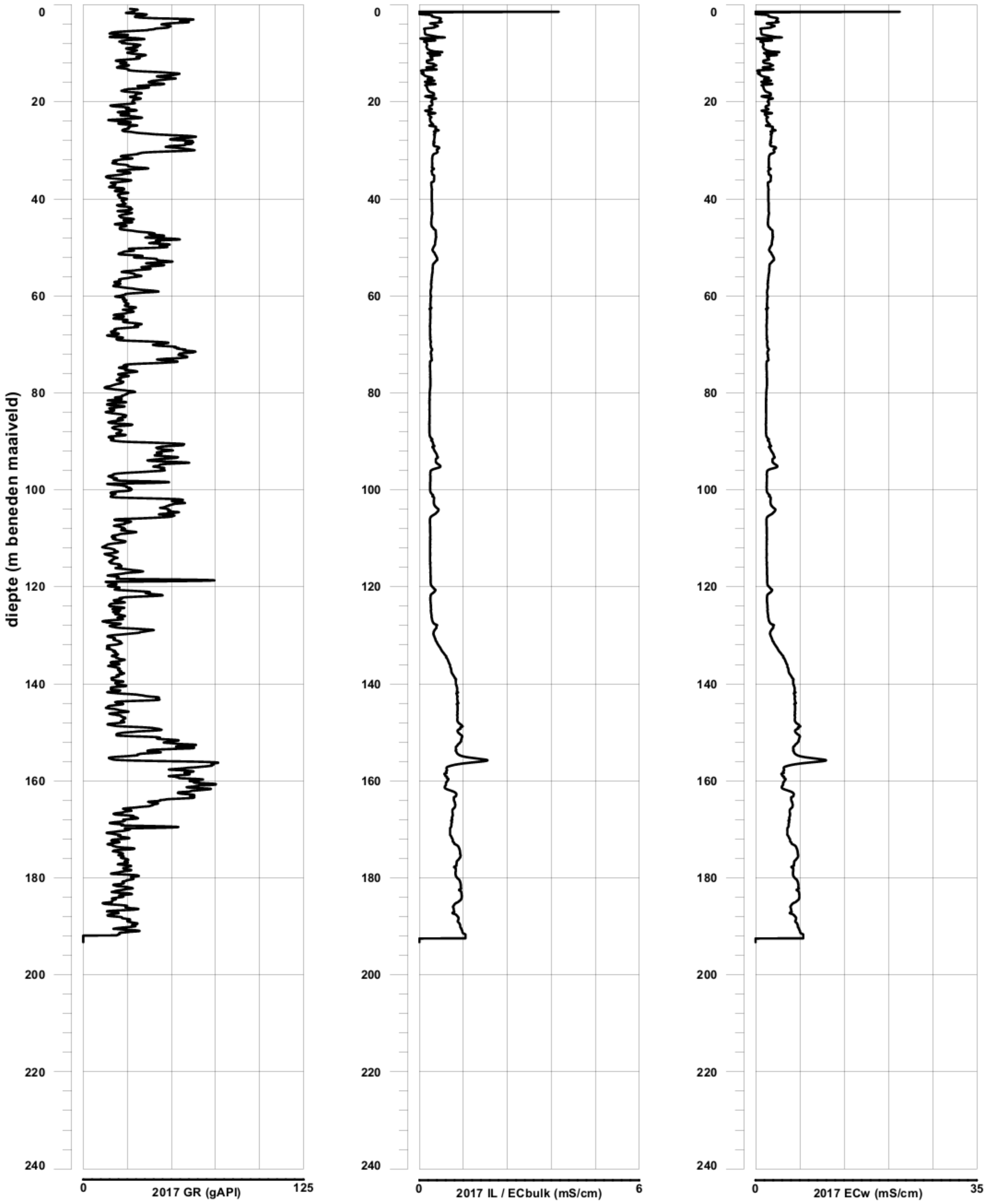
Deltares
Enabling Delta Life



Bijlage

Plaatsnaam:	Noordbergum	**Opdrachtgever:**	Vitens
Straatnaam:	Pompstation Vitens	**Boorbedrijf:**	-
RD - coördinaten:	X: 195775, Y: 581560	**Naam put:**	Injectieput
Maaiveldhoogte:		**Boormethode:**	-
Datum:		**Diameter boorgat:**	-

Deltares
Enabling Delta Life



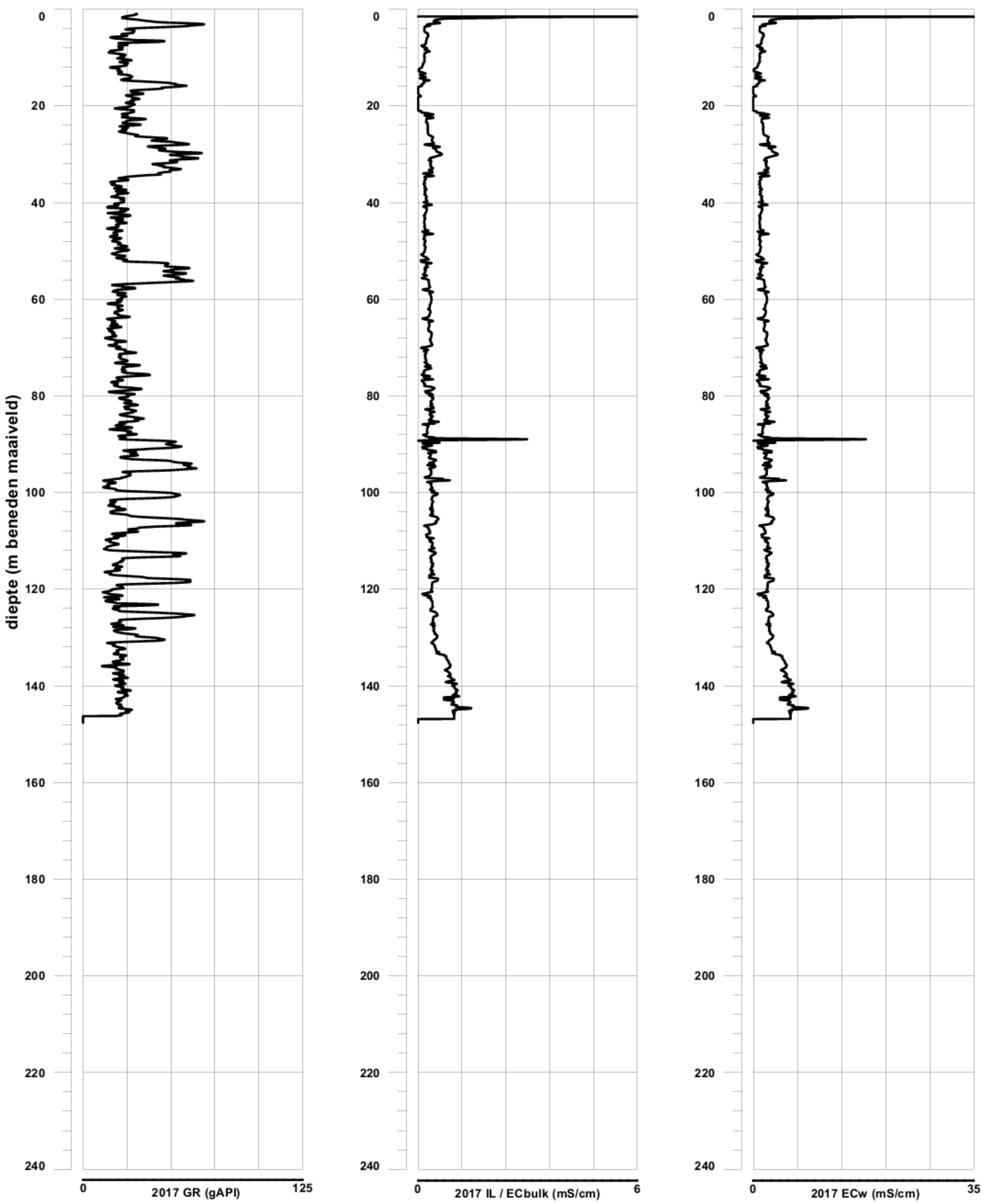
SubSol

Bijlage

Plaatsnaam: Noordbergum
Straatnaam: Pompstation Vitens
RD - coördinaten: X: 195748, Y: 581549
Maaiveldhoogte:
Datum:

Opdrachtgever: Vitens
Boorbedrijf: -
Naam put: Onttrekkingsput
Boormethode: -
Diameter boorgat: -

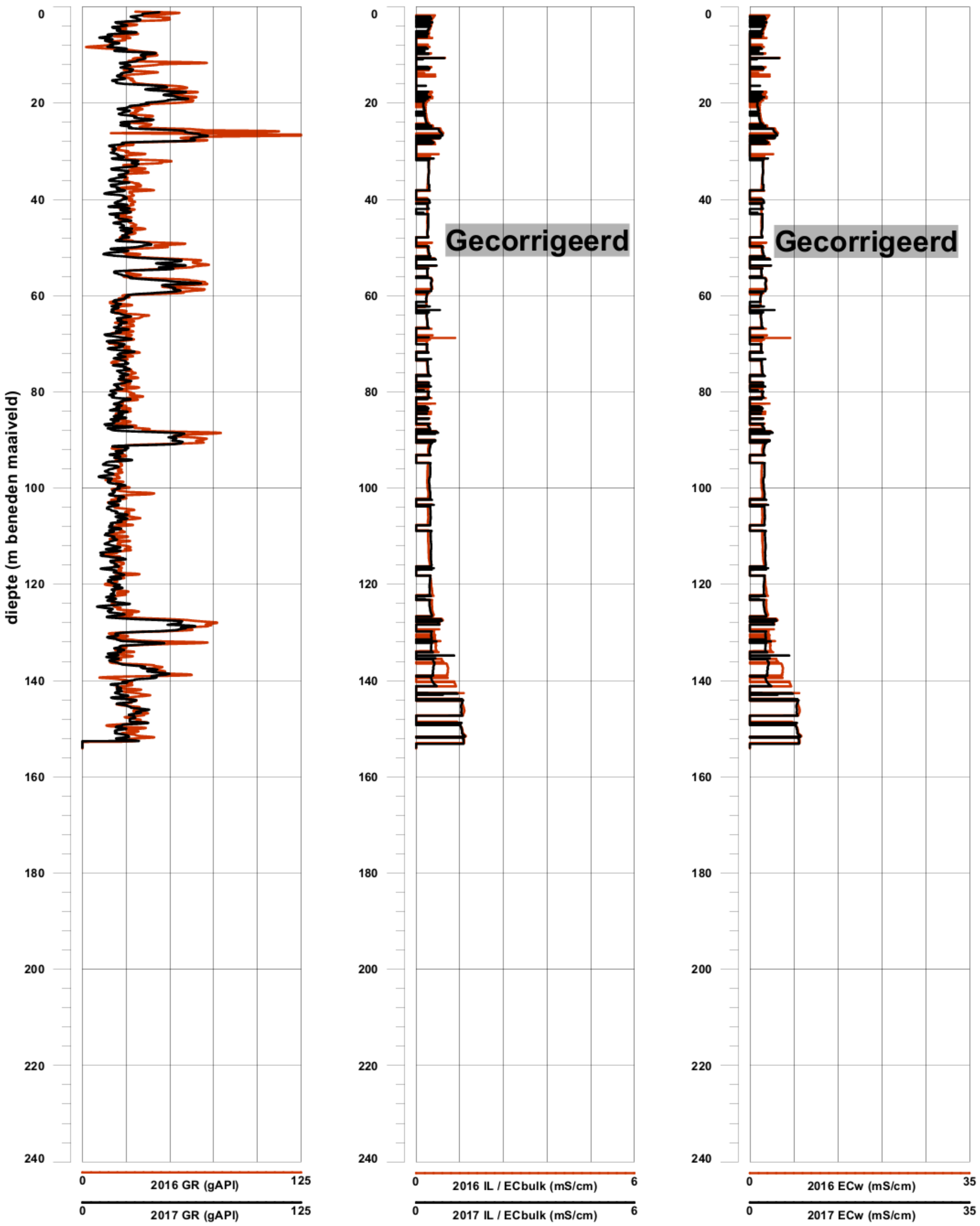
Deltares
Enabling Delta Life



Bijlage

Plaatsnaam: Noordbergum
Straatnaam: Pompstation Vitens
RD - coördinaten: X: 195714, Y: 581472
Maaiveldhoogte: 1.6 m NAP (AHN)
Datum:

Opdrachtgever: Vitens
Boorbedrijf: -
Naam put: Slimme put
Boormethode: -
Diameter boorgat: -



Bijlage

Plaatsnaam: Noordbergum
Straatnaam: Pompstation Vitens
RD - coördinaten: X: 195714, Y: 581472
Maaiveldhoogte: 1.6 m NAP (AHN)
Datum:

Opdrachtgever: Vitens
Boorbedrijf: -
Naam put: Slimme put
Boormethode: -
Diameter boorgat: -

Deltares
Enabling Delta Life