# D1.1 Validated regional scale groundwater model Noardburgum

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## Table of Contents

# 1 Introduction

Vitens, the largest water supply company in the Netherlands, supplies 330 million $m^3$ of drinking water to domestic and industrial clients yearly. The main source for the production of this water is groundwater with salinity concentrations lower than 150 mg/L. In the province of Friesland, in the northern part of the Netherlands, problems have arisen with the abstraction of fresh groundwater due to salinization of wells by upcoming of brackish water. Public supply well field Noardburgum (Figure 1-1) was originally designed to produce 12 million $m^3$ of drinking water per year, but suffered heavily from salinization of the production wells in the 1980s, leading to a complete production stop from 1993 onwards. Ever since, Vitens is looking for options to increase drinking water production in the region.

The Freshkeeper concept was developed in the early 2000s as a solution for salinization of water wells and water well fields. The principle is that not only fresh groundwater is abstracted, but with a separate filter screen also the upconing brackish water. In that way, the fresh-brackish water interface is stabilized, preventing salinization of the fresh filter screen. The brackish groundwater can be disposed, for instance by injection into deeper aquifers, but it can also serve as an additional source for drinking water after desalination with reversed osmosis (RO).

A Freshkeeper combined with brackish water RO was applied during a field pilot in the northern well field of Noardburgum in 2009 and 2010. Shallow fresh and deeper brackish groundwater were abstracted within a multiple partially penetrating well equipped with two separate well screens, at a rate of 50 $m^3$/h each. The RO concentrate was injected at 190m depth, in a brackish water aquifer under a confining clay layer. While the goal was to stabilize the fresh-brackish water interface, the chosen operation even provoked a downconing of brackish water, indicating that the brackish water abstraction could be optimized further (i.e. a lower brackish water abstraction rate while still preventing upconing).

A second Freshkeeper pilot was started in 2014, aiming to further optimize Freshkeeper well design, monitoring and management, ultimately providing full and automated control of the fresh-brackish groundwater interface at the well field level. A new, “smart” Freshkeeper-well (Figure 1-2) was designed and installed, with two abstraction screens at a depth of 60 m (fresh groundwater) and 140m (brackish groundwater). The brackish water was not fed to an RO, but injected directly (unused) into the underlying aquifer. The smart part is in the measurement and control technology. Ultimately, the well itself will determine at what rate brackish water will be abstracted and injected, based on online measurements of the salinity of the groundwater. This pilot is continued in the SUBSOL project, with the goal to set the next steps to full scale Freshkeeper implementation and re-opening of the abandoned Noardburgum well field.

For full-scale application of the Freshkeeper, it is important to understand its effects on the salinity distributions in nearby well fields and on the positioning of the salinity front up north of the Noardburgum well field. One of the concerns is that full-scale Freshkeeper application at Noardburgum may result in increased salinity at the nearby well field Ritskebos, because of re-injected brackish water flowing to this well field via a by-pass in the underground. To this end, a regional scale groundwater model was built, validated and used to evaluate different scenarios of full-scale Freshkeeper application. This model and the scenario analysis are described in this report.

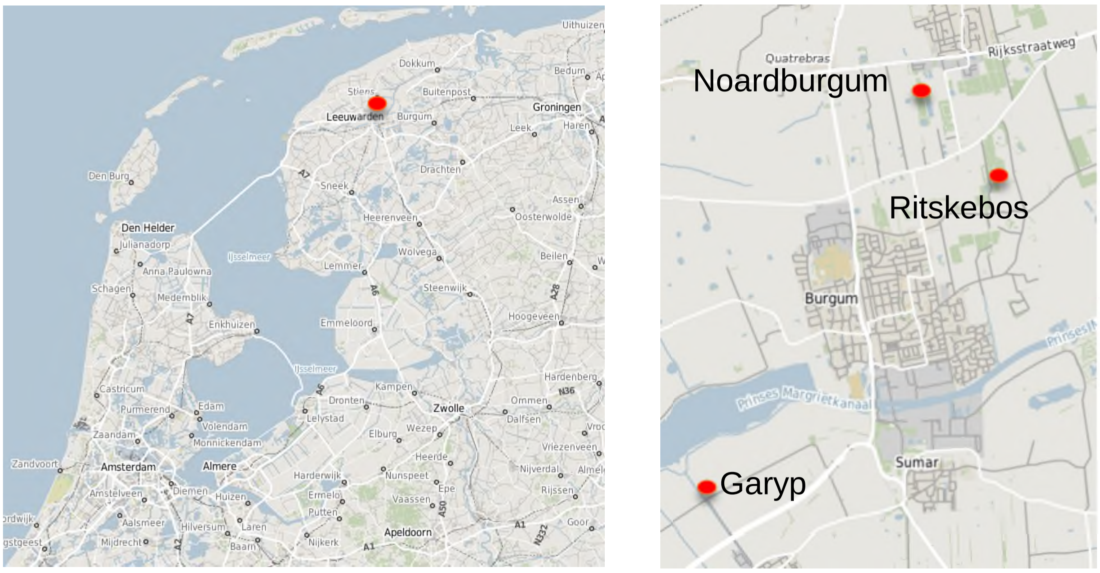


**Figure 1-1 Location of well fields Noardburgum (abandoned in 1993), Ritskebos and Garyp, in the northen part of the Netherlands**

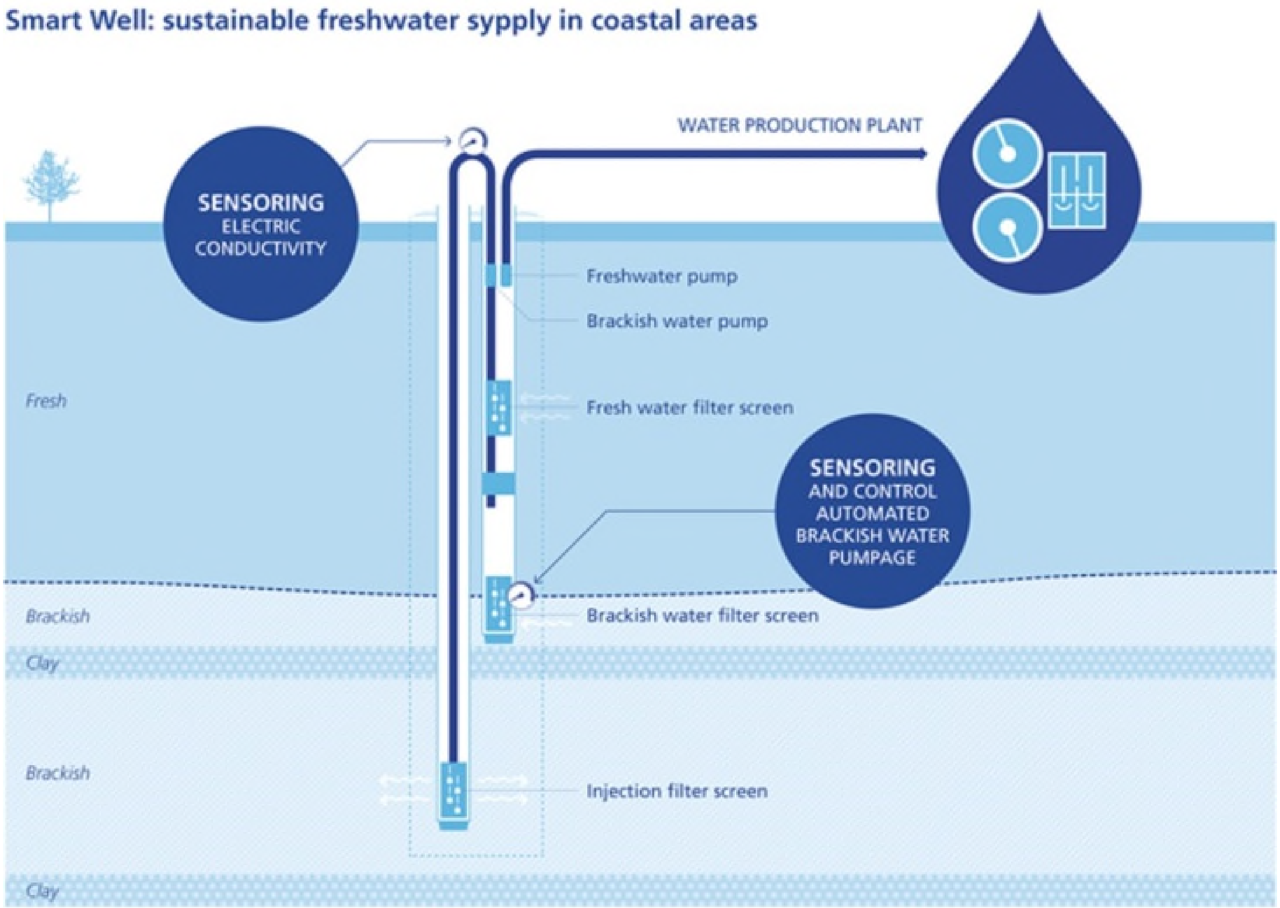


**Figure 1-2 Schematic of the smart Freshkeeper well at well field Noardburgum**

## 1.1 Objective

The objective of this study is to quantity the effects of full-scale Freshkeeper application at well field Noardburgum on the salinity distributions in nearby well fields and the positioning of the salinity front up north of the Noardburgum well field. To this end, a regional scale groundwater model was built, validated and used for evaluation of different scenarios of full-scale Freshkeeper application.

# 2 Materials, methods and site description

Several groundwater models have been developed and applied for the Noardburgum and the surrounding well fields (Garyp, Ritskebos) in the past. These models, however, were not suited for evaluation of full-scale Freshkeeper application, either because density-driven groundwater flow was neglected (Triwaco models) or because their scale was too limited (local scale model Noardburgum). In 2016, as part of the SUBSOL project, all existing models were evaluated, and a first draft regional scale model was built. The evaluation and draft model are described in the MSc thesis by Geul (2016; Delft University of Technology), which formed the starting point for the model development and scenario analysis in this study.  presents the modelling strategy which was applied in this study, and which is described in this report.

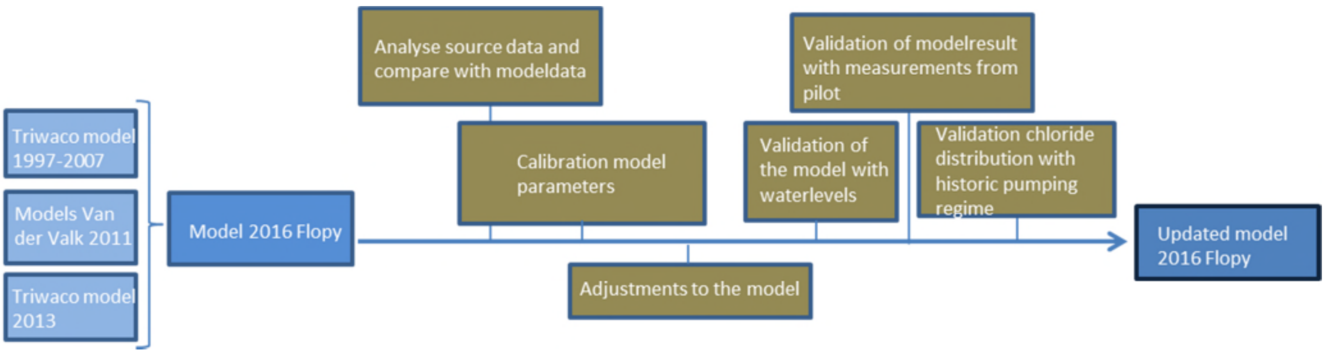


Figure 2-1 Scheme of modelling strategy

## 2.1 Short evaluation of existing Noardburgum groundwater models

**Triwaco model Noardburgum and Ritskebos**

The Triwaco model includes the well fields Noardburgum and Ritskebos and the surrounding area (De Graaf et al., 2007). The model was setup in the Microfem finite element code by Milfac (1996) and Rus (1997). This model is available in the Triwaco graphical user interface which allows for the use of the conceptual model and parameter distributions with different resolutions and connection to simulation programs (Royal Haskoning, 2004; www.triwaco.com).

In 2007, salinity distributions (chloride) and solute transport were added to the Triwaco model (De Graaf et al., 2007). The aim was to gain insight into the cause of the salinization of the Noardburgum well field. Also, model predictions of the average chloride concentration of the both well fields were made.

**Local SEAWAT model Noardburgum**

As part of his MSc research at Delft University of Technology, van der Valk (2011) set up three models for Noardburgum, with the aim to gain insight into the relevant salinization processes on a local (well) and intermediate (well field) scale. Van der Valk used the SEAWAT code because of its ability to simulate three-dimensional variable density groundwater flow coupled with multi-species solute transport. This allows for accurate description of the groundwater flow movement taking into account the density differences between fresh and saline water (buoyancy effects and upconing). The three models are:

- Small scale (well) model. This model was used to gain insight in local flow around the Freshkeeper well. Also, the effects of the well field configuration on upconing was determined using this model;
- Cross sectional model. This model was used to simulate the historic salt intrusion (10,000 years ago - now). The modelling results were used to define the spatial distribution of chloride for the intermediate scale model.
- Intermediate (well field) scale model. This model was used to evaluate salinization at the process in the Noardburgum well field.

**Revision of Triwaco model (2013)**

In 2013, a modelling study was performed with the Triwaco model to assess the fate of the injected brackish water from the (then planned) second “smart”Freshkeeper (van der Linde, 2014; MSc thesis Delft University of Technology). A model sensitivity analysis was performed for extent of the clay layer (aquitard) at the base of the production aquifer (Tegelen clay) and for (the transmissivity of) the injection aquifer. The presence of the Tegelen clay layer over a large area was found to have a large influence on the model outcomes. This clay layer has been found in deep drillings, but its extend is largely unknown. To be safe in terms of model predictions, Van der Linde (2014) included the extend of this clay layer and the injection depth of the brackish water in the subsequent modelling.

Initially, the effects of density differences 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). At the end of this study, SEAWAT simulations were carried out that did account for density differences and dispersion. It was concluded that density differences and dispersion cannot be neglected when modelling groundwater flow in the Noardburgum area.

**Draft regional scale model (Noardburgum FloPy 2016)**
In 2016, as part of the SUBSOL project, a first (draft) regional scale model capable of modelling density-driven groundwater flow was built for Noardburgum and surrounding well fields. The model was set up using FloPy (Bakker et al. 2016), a Python package to create, run, and post-process MODFLOW-based models, including SEAWAT and MT3D. The model setup (hydrogeology) was copied from the Triwaco 2013 model, and all models were run with MODFLOW, MT3D and the SEAWAT module. This first (draft) regional scale model is described in the MSc thesis by Geul (2016; Delft University of Technology), and formed the starting point of model development as described in this report.

## 2.2 Well fields Noardburgum and Ritskebos

Groundwater abstraction at well fields Noardburgum and Ritskebos started in the 1950s. Both well fields were gradually enlarged and by the late 1970s total water abstraction peaked to 25 million cubic meters per year (Figure 2-2). Water is abstracted from the top aquifer; well screens are generally positioned at a depth of 60 to 90 mbsl (meter below sea level). As a result of the large (fresh) groundwater withdrawal, brackish water that resided in the lower part of the production aquifer gradually moved upwards, resulting in a s increase in chloride concentration in the production well wells. In 1990, water produced from well field Noardburgum exceeded the 150 mg/L chloride drinking water limit, and in 1994 Vitens had to seize production and close down this well field. Also, production at Ritskebos was limited and wells with deeper filter screens were closed.

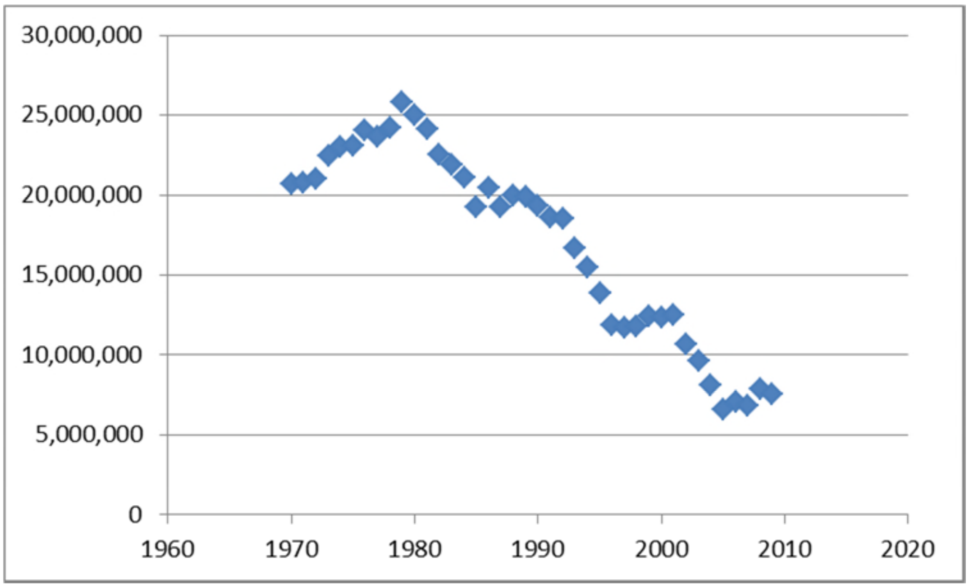


Figure 2-2 Total drinking water production (m3/year) from well fields Noardburgum and Ritskebos

# 3 Data evaluation: geology, salinity, recharge

Available data on (hydro)geology, salinity distributions, groundwater recharge and water wells is presented and evaluated. This data forms the basis of the regional scale groundwater model and its parameterization.

## 3.1 Geology and hydrogeology

Available data on (hydro)geology included:

- Borehole descriptions, well field Noardburgum (Vitens);
- Borehole descriptions and geology model results REGIS V 2.1 (Dutch national geology database; www.dinoloket.nl) ;
- Grondwaterkaart van Nederland, Harlingen/ Leeuwarden (report; TNO, 1987) ;
- Regional MIPWA-groundwater model V2.2 (Berendrecht et al, 2007);
- Pumping tests, well field Noardburgum (IWACO, 1979);
- IJking FLOP-model in het nader onderzoek verzilting pompstation 'Storm' te Noardburgum (report; IWACO, 1986);
- IJking Iwaco-model (report; Iwaco, 1997).

Table 3-1 summarizes the geology (based on the source data) and presents the parameters included in the model.

Table 3-1 Geology and hydrogeolgy at the well fields Noardburgum and Ritskebos

| Aguifer / Aquitard | Top [mbsl] | Bottom [mbsl] | Geological Formation | Transmissivity / resistance (MODEL) | Transmissivity / resistance (DATA) | Information |
|---|---|---|---|---|---|---|
| Top aquitard | 0 | 60 | Drenthe, Drachten, Urk | 60 m/d; 800d | 400-900 $m^2$/d ; 1000-3000 d | Boulder clay, clay, loam and fine to coarse sands |
| Aquifer #1 | 60 | 150 | Urk and Peize complex | 5200$m^2$/d | 5000 $m^2$/d | Mainly coarse to very coarse sands |
| Aquitard #1 | 150 | 160 | (Peize) Tegelen | 1300 d | 2000d | 6-10 m of clay and fine sands |
| Aquifer #2 | 160 | 240 | Peize complex and Waalre | 2500 $m^2$/d | 1500 – 2500 $m^2$/d | Fine to coarse sands with small clay layers |

The top aquitard (0 – 60 mbsl) consists of clay and sand layers from the Drenthe, Drachten and Urk formations. A boulder clay of 1 to 3 m thick is generally present at surface level (Watergebiedsplan, 2015). At different locations a second clay layer is present at a depth of approx. 50 mbsl. The majority of this aquitard is made up of fine and coarse sands. The first aquifer (60 – 150 mbsl) consists mainly of coarse sands from the Urk and Peize formation. Locally the sand can be fine to coarse. This aquifer is the production aquifer, with well screens are generally positioned at a depth of 60 to 90 mbsl. The first aquitard (150 – 160 mbsl) is often referred to as Tegelen clay (also Peize formation) and was found in all bore desriptions of the Noardburgum and Ritskebos well fields. The aquitard consists of 6- 10 meters of clay and fine sands. Figure 3-1 shows a hydrogeological cross-sections along both well fields. In the cross-sections, the Tegelen clay is not depicted as a seperate layer but part of the Peize formation.

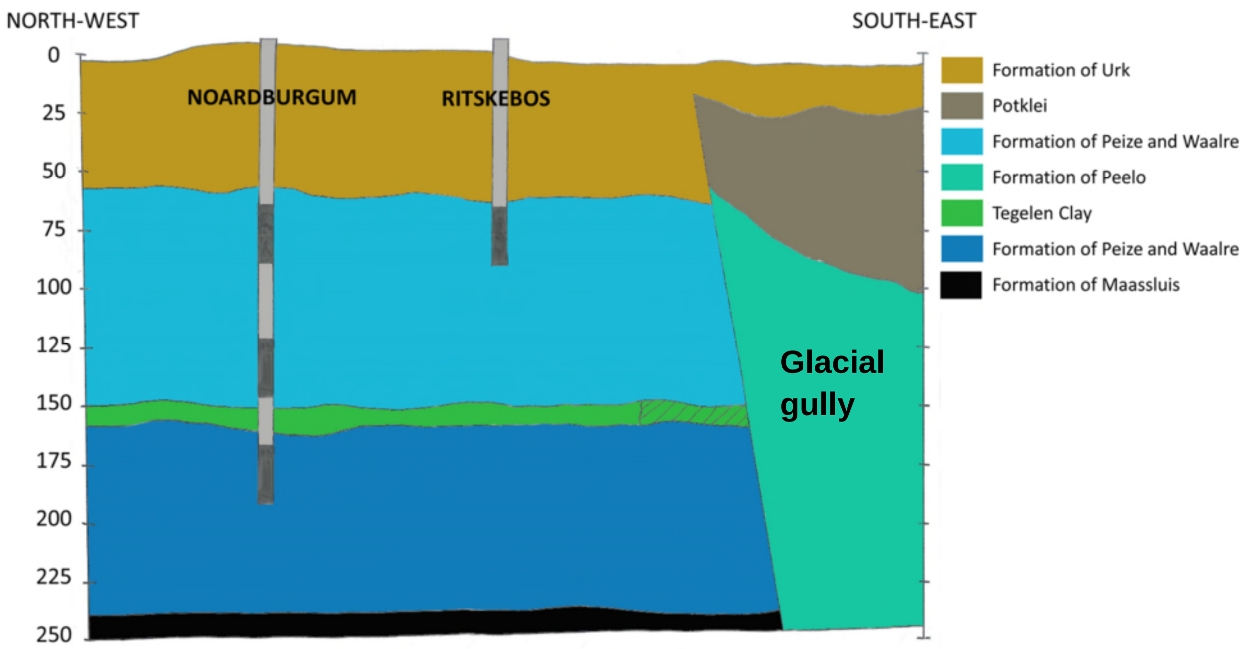


**Figure 3-1 Geology crossection along the well fields Noardburgum and Ritskebos (from: Geul, 2016)**

An important geological feature in the area is a large glacial gully, which was formed during the Elsterien ice age (465,000 – 418,000 years ago), when Scandinavian land ice reached the Northern part of what now is the Netherlands. East of Noardburgum a tunnel (U-shaped) valley of several hundred meters deep formed (Figure 3-1), most likely as a result of glacial erosion, and was later on filled up with sands and clays. The top part of tunnel shaped valley is filled with 80 meters of ‘Potklei’, a glaciolacustrine deposit of compacted clay with a black or brownish colour. Potklei can be found in the northern part of the Netherlands and in East Germany (Ehlers et al., 1984). Friction caused by the glacial erosion is thought to have left a (loamy) clay layer at the flanks of the tunnel valley, impermeable to horizontal flow. The upper part of the glacial tunnel valley is considered impermeable to groundwater flow, while the bottom part is moderately permeable.

The glacial gully cuts through the Tegelen clay that separates the production aquifer of Noardburgum and Ritskebos from the brackish water injection aquifer, effectively connecting both aquifers. One of the concerns is that full-scale Freshkeeper application at Noardburgum may result in increased salinity at Ritskebos, because of re-injected brackish water flowing to Ritskebos via this by-pass formed by the glacial gully.

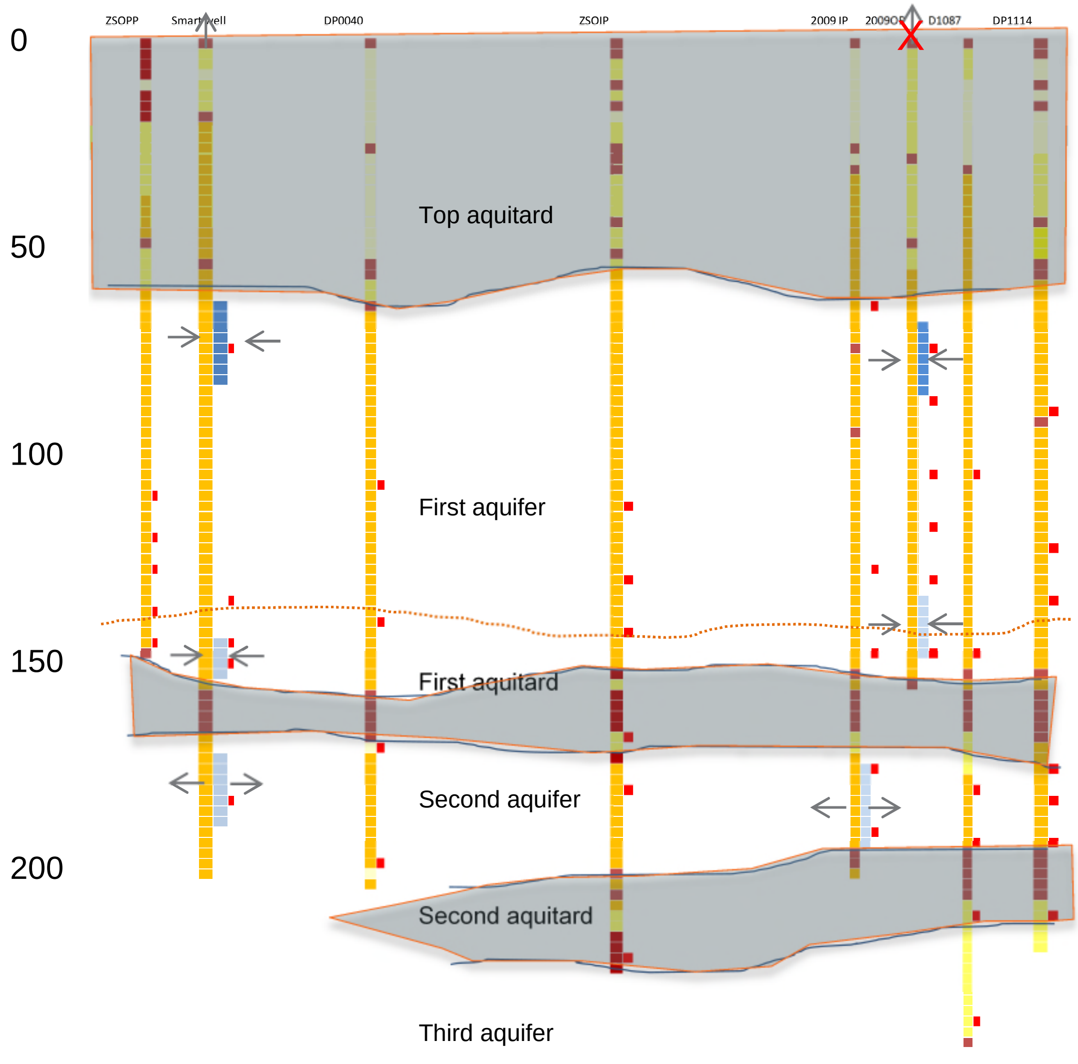


**Figure 3-2 Cross section at the well field Noardburgum interpreted from borehole descriptions. Dashed orange lines are monitoring and pumping wells installed for the 2009 and 2014 Freshkeeper pilots.**

## 3.2 Salinity distributions

### Well fields Noardburgum and Ritskebos

Chloride concentrations in pumping wells and monitoring filters are available from the 1950s onwards, both at Noardburgum (pumping wells until 1994) and Ritskebos. Figure 3-3 shows the chloride concentration of the raw water of the Noardburgum and Ritskebos well fields. Chloride concentrations increased from the 1950s onwards, until production was stopped in Noardburgum in 1994 and, at the same time lowered at Ritskebos. It is clearly visible that both well fields extracted fresh water at the start of the extraction.

Figure 3-4 shows the Electrical Conductivity (EC) with depth for some wells in Noardburgum, as measured in 2014 just before the start of the Freshkeeper pilot. Measurements indicate that most of the production aquifer is fresh and that brackish water is only present at the bottom of the aquifer, below a depth of 140 mbsl. There are no signs of (remnants of) saline water that upconed in the past.

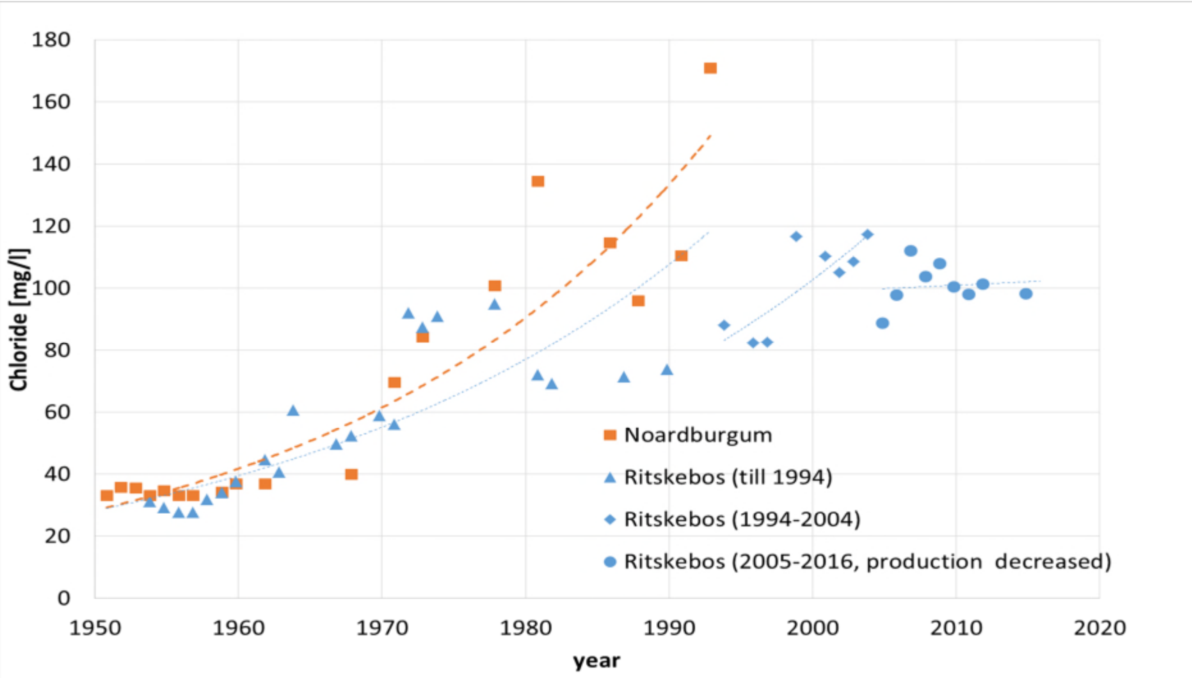


**Figure 3-3 Mean chloride concentrations of the wells at the well fields Noardburgum and Ritksebos from the 1950s onwards.**

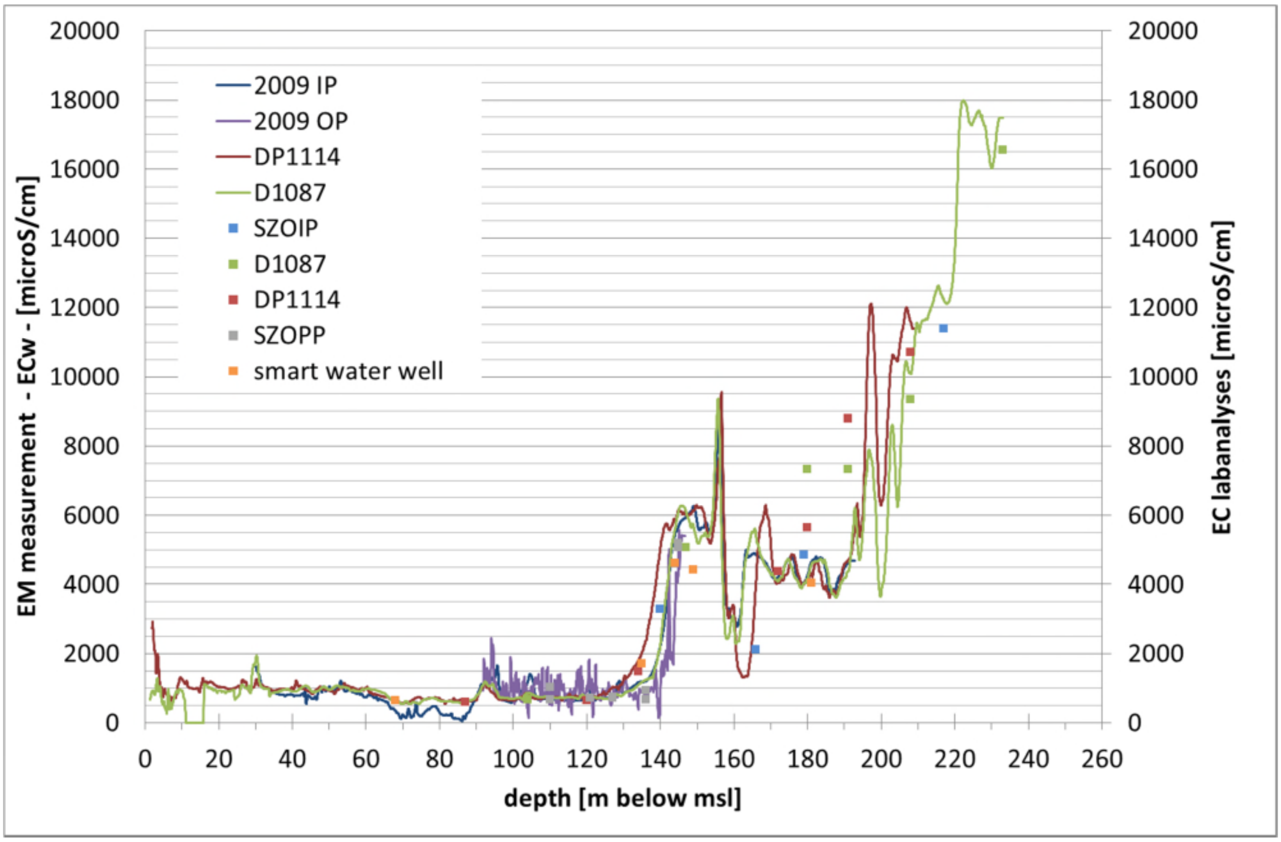

Figure 3-4 Electrical Conductivity versus the depth in 2014, just before start of the Freshkeeper pilot. EC measured with EM39-probe and in water samples .

### Regional chloride distributions

An extensive monitoring survey was executed in 2016 at all the monitoring filters in the production aquifer and deeper aquifers, both in the well fields and their surroundings. Focus was on salinity (EC and chloride). Results of this monitoring campaign were compared with the chloride distributions as modelled by Geul (2016). This 3D concentration pattern was obtained by running his model up to the year 2016, with chloride distributions of 1985 as the starting point.

The measurements indicate that chloride is not distributed in an uniform pattern. Especially in the Noardburgum well field, depth of the fresh/brackish interface varies on short distance. Another inconvenience is that at outside of the well field, data availability is low, and we have severe doubts whether an interpolated distribution (based on sparse measurements) will render better initial conditions than those defined by Geul (2016). Instead it was recommended not to adjust the initial concentration in the model but to perform additional scenario analyses with a worst-case initial concentration.

## 3.3 Groundwater recharge

The following data (sources) relevant to define groundwater recharge in the model were evaluated:

- Digital map of surface water levels (Wetterskip Fryslan);
- Watergebiedsplan (Report; Wetterskip Fryslan, 2015) ;
- Information (e-mail) from Wetterskip Fryslan about water supply and water drainage in the surface water system;
- Model files of the national/regional groundwater model MIPWA 2.2 (Berendrecht et al, 2007):
    - Surface water system: waterlevel, bottom level and soil resistance;
    - Location of infiltration area's and seepage area's;
    - Groundwater recharge;
    - Location of urban area's.

In Geul's 2016 model (Noardburgum FloPy 2016), groundwater recharge is a combination infiltration of the surfacewater system and the net precipitation. The surface water system was implemented in the Triwaco model, but resistances were set so high, that the surface water system did not contribute to additional recharge.

In the model, groundwater recharge was set to 450 – 500 mm/year in the vicinity of the well fields, 180 mm/year in the urban areas, and 300 mm/year in the other area. These values were defined in 1997-2007 and correspond with a scenario of 22 million $m^3$ water abstraction per year.The recharge from the surface water system, however, is reliant on the abstraction rates of the well fields. Present day, total abstraction is approx. 7 million $m^3$/year, and therefor recharge is also presumed lower. It is recommended to use MODFLOW's GHB package to model recharge from surface waters and to adjust MODFLOW's Recharge package to the actual net precipitation.

# 4 Noardburgum FloPy 2017 model

The (draft) regional scale, density-driven groundwater model set up by Geul (2016), was updated and validated, taking into account reccomendations in Chpater 3. The updates model is refered to as **Noardburgum FloPy 2017**. This chapter describes the updates and validation results.

## 4.1 Model discretisation

The Noardburgum FloPy 2017 model was programmed in such a way, that it is easy to run the model with different model areas and cell sizes. Parameter information is coupled to the center of each model cell, allowing the model to be easily re-build with new model discretions. The model always has to be run stationary for the whole area with a cell size of 50 m by 50 m to generate the boundary conditions for a local model calculation.

The dimensions of the regional model are X-coordinate: 189,000 m – 203.000 m (14 km), and Y-coordinate: 572.000 m – 590.000 m (18 km). For the scenario analysis, the gridsize was set to 12.5 by 12.5 m for a large area around the well fields (4 km by 6.5 km). The model was run for 50 years with time steps of one year. All model parameters (recharge, wells et cetera) were stationary in the model. As a test, runs with smaller grid sizes and time steps were performed, but this did not have a significant effect on the model results. The model was divided into 22 model layers, with a thickness varying between 5 and 20 metres (Table 4-1).

The northern, western and southern model boundaries were set at distances larger than 3 x sqrt(KDC) from the well fields. The eastern border was positioned In the glacial gully (750m east of the western flank). Hydraulic heads and chloride concentrations were set to constant (fixed) values at all boundaries. The positioning of the eastern border was double checked by moving it an additional 1250m further east; this did not have an effect on water levels in the first aquifer, which was a verification that the eastern boundary was set correct.

Table 4-1 Model layers of the regional scale Noardburgum model (Noardburgum FloPy 2017)

| Layer | Top (m-msl) | Bottom (m-msl) | Thickness (m) | Aquifer/ aquitard |
|---|---|---|---|---|
| 1 | 0 | -10 | 10 | aquitard 1 |
| 2 | -10 | -35 | 25 | aquitard 1 |
| 3 | -35 | -60 | 25 | aquitard 1 |
| 4 | -60 | -75 | 15 | aquifer 1 |
| 5 | -75 | -90 | 15 | aquifer 1 |
| 6 | -90 | -100 | 10 | aquifer 1 |
| 7 | -100 | -110 | 10 | aquifer 1 |
| 8 | -110 | -120 | 10 | aquifer 1 |
| 9 | -120 | -130 | 10 | aquifer 1 |
| 10 | -130 | -135 | 5 | aquifer 1 |
| 11 | -135 | -140 | 5 | aquifer 1 |
| 12 | -140 | -145 | 5 | aquifer 1 |
| 13 | -145 | -150 | 5 | aquitard 2 |
| 14 | -150 | -160 | 10 | aquifer 2 |
| 15 | -160 | -165 | 5 | aquifer 2 |
| 16 | -165 | -170 | 5 | aquifer 2 |
| 17 | -170 | -175 | 5 | aquifer 2 |
| 18 | -175 | -185 | 10 | aquifer 2 |
| 19 | -185 | -196 | 11 | aquifer 2 |
| 20 | -196 | -204 | 8 | aquifer 2 |
| 21 | -204 | -223 | 19 | aquifer 2 |
| 22 | -223 | -240 | 17 | aquifer 2 |

## 4.2 Calibration using water levels

Since 2000, groundwater levels in both well fields are monitored with pressure-sensors. Only monitoring filters with more than 300 measurements per year over a period of 4 years were selected. 133 monitoring filters met this criterium. The average groundwater levels are determined using the whole measurement period.

A number of calibration model runs were executed, to test wether some of the adjustments made to the model were valid. For each run, only one parameter was varied and the mean water level was compared with the calibration set. provides a summary of these tests.

Table 4-2 Calibration of theNoardburgum FloPy 2017 model, based on information of the source data

| Scenario | Resistance GHB-package | Use of DRN-package | Resistance first aquitard | Kh and Kv aquitard 1, layer 1 | Groundwater recharge | Mean residu in aquitard 1 (groundwater level) | Mean residu in aquifer 1 |
|---|---|---|---|---|---|---|---|
| 1 (reference scenario) | Not in use | no | 800 days | kH = kV = 0.1 m/day | 1.2 mm/day | +50 cm | 0 cm |
| 2 | 150 days | no | 800 days | kH = kV = 0.1 m/day | 1 mm/day | +30 cm | -12 cm |
| 3 | Not in use | Yes, 150 days | 800 days | kH = kV = 0.1 m/day | 1 mm/day | +16 cm | -30 cm |
| 4 | 150 days | no | 400 days | kH = kV = 0.1 m/day | 1 mm/day | +30 cm | +1 cm |
| 5 | 150 days | no | 800 days | kH = kV = 1.0 m/day | 1 mm/day | +26 cm | +14 cm |
| 6 | 600 days | no | 800 days | kH = kV = 0.1 m/day | 1 mm/day | +20 cm | -17 cm |
| 7 | 150 days | no | 800 days | kH = kV = 0.5 m/day | 1 mm/day | +27 cm | +10 cm |

## 4.3 Model adjustments

Based on insights obtained from the data evaluation (Chapter 3) and calibration runs (section 4.2) four of the model packages in the 2016 model were adjusted.

**LPF package**

The hydrogeological parameters in the model were adjusted as follows:

- First aquitard (model layer 1-3):
    - Model layer 1: kD adjusted to 10 $m^2$/d;
    - Model layers 2 and 3: not adjusted;
- First aquifer:
    - kD not adjusted;
    - kV adjusted from 0.1*kH to 0.2*kH. This implies that there is less vertical anisotropy in the aquifer. This wass done, based on the verification of the model with the pilot (section 0);
    - Second aquitard: not adjusted, although the resistance in the model seems an underestimation, and the scenario analysis are thus a worst-case approach.

To be able to perform non- stationary model calculations the storage coefficient was added to the model (Van der Gun, 1979).

**Recharge and GHB package**

As explained in section 3.3, the recharge in model does not correspond with the current abstraction rates. In the Noardburgum FloPy 2017 model,  recharge from surface water is modeled through the GHB package. Surface water levels were taken from the Triwaco model and verified with data provided by Wetterskip Fryslan (water authority). These were well matched. The resistance of the bottom of the surface water was set to 150 days (based on the calibration). This corresponds to values set in the MIPWA model. A water supply plan is in force in the region, meaning that surface water can infiltrate from the waterways. As it is likely that soil resistance will increase due to infiltration, resistance to all infiltrating waterways was increased by a factor of 10. During calibration this proved to be a plausible factor.

Recharge resulting from precipitation (i.e. precipitation minus evapotranspiration was set to 1 mm/d, similar to the values set in MIPWA (360 mm/year). In urban areas, recharge is likely to be lower, because of interception. Recharge in urban areas was thus set to 0.5 mm/d.

These adjustment (GHB package, recharge) resulted in an average recharge of about 1.3 mm/d for the whole model area. This is in line with previous calculations with the MIPWA model.

**Well package**

The Noardburgum FloPy 2016 model was not up to date with the Ritskebos well field. 28 abstraction wells are still used at Ritskebos, all having approximately the same capacity and in operation for about the same number of hours per day. Therefore, the total flow rate of 7 million $m^3$/year was distributed evenly over the 28 active wells.

There are no wells anymore at Noardburgum, except for the two pilot (Freshkeeper) wells. For the scenario runs with full-scale Freshkeeper application (2 million $m^3$ / year), wells were placed according to the existing infrastructure as much as possible (see Table 4-3).

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Table 4-3 Locations and characteristics of the (future) smart water wells at well field Noardburgum

| Name well | Exists | x | y | Well type | Abstraction / injection rate [m³/d] | Depth [mbsl] |
|---|---|---|---|---|---|---|
| Freshkeeper 2009 - abstraction | Yes<br>“” | 195748<br>“” | 581550<br>“” | Fresh<br>Brackish | 1360<br>280 | 63 - 73<br>143 -149 |
| Freshkeeper 2009 - injection | Yes | 195774 | 581560 | Injection | 280 | 170 -190 |
| Freshkeeper 2014 | Yes<br>“”<br>“” | 195703<br>“”<br>“” | 581456<br>“”<br>“” | Fresh<br>Brackish<br>Injection | 1360<br>280<br>280 | 63 -73<br>143 -149<br>170 -190 |
| Freshkeeper new #3 | No<br>“”<br>“” | 195782<br>“”<br>“” | 581076<br>“”<br>“” | Fresh<br>Brackish<br>Injection | 1360<br>280<br>280 | 63 -73<br>143 -149<br>170 -190 |
| Freshkeeper new #4 | No<br>“”<br>“” | 195740<br>“”<br>“” | 581257<br>“”<br>“” | Fresh<br>Brackish<br>Injection | 1360<br>280<br>280 | 63 - 73<br>143 -149<br>170 -190 |

**SSM package**

The following chloride concentrations were imposed to the model for boundary conditions:

- Recharge from precipitation: 70 mg/l;
- Recharge from the surface water system: 65 mg/l;
- Re-injection of (abstracted) brackish water: 2000 mg/l.

**BTN package**

The initial chloride concentration was kept similar to the Noardburgum FloPy 2016 model. However, in order to perform scenario analysis with a worst-case initial concentration approach, chloride concentrations in model layers 11, 12 and 13 was increased with 800 mg/L. This 800 mg/L was based on the maximum difference between the chloride concentration in the Noardburgum FloPy 2016 model and the measured chloride concentration (section 3.2).

## 4.4 Validation of Noardburgum FloPy 2017

The updated model was validated in three ways: (1) using water levels from the calibration set (section 4.2), (2) using chloride data from the Freshkeeper pilot, and (3) using historic chloride data from water abstracted at well fields Noardburgum and Ritskebos.

**Water level calibration set**

Table 4-4 summarizes, per aquifer, the modeled versus observed water levels. For Aquifer #1, modeled water levels are generally in line with observed water levels. In the second aquifer the differences between the model and the measured water levels are larger, still acceptable from a modeling perspective. The poorer results for Aquifer #2 partly reflect the less detailed information that is available for this (deep) aquifer. Also, chloride concentrations at this depth are higher and therefore play a dominant role in calculating the water levels. Uncertainties in the chloride concentration on depth translate into uncertainties in the water level. Comparing model results and measurements is more difficult here, because the measured water level in a saline environment must be translated to a water level in a freshwater environment. This conversion is often inaccurate.

**Table 4-4 Validation of Noardburgum FloPy 2017 with the water level calibration set**

| Aquifer/ aquitard | Number of filters | Mean difference (m) | Mean absolute difference (m) |
|---|---|---|---|
| Top of first aquitard | 72 | 0.04 | 0.31 |
| First aquitard | 24 | -0.35 | 0.79 |
| First aquifer | 25 | -0.06 | 0.15 |
| Second aquitard | 2 | 0.10 | 0.29 |
| Second aquifer | 10 | -0.26 | 0.33 |

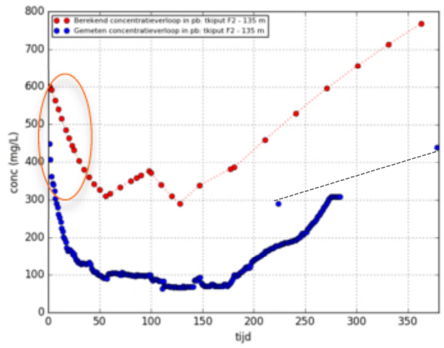
**Comparison of the model with the pilot smart water well**

In order to validate the model using the chloride concentration measurements from the Freshkeeper pilot ( 2015-2016), some adjustments were made to the groundwater model:

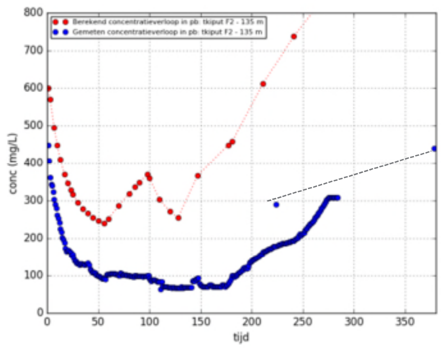
- Chloride distribution was adjusted to chloride concentrations measured along the ”smart” Freshkeeper well and monitoring wells DP0040 and SZOPP6D-252 (Table 4-5);
- The top and bottom of the model layers were adjusted to the exact depths and lengths of the Freshkeeper (observation) filters;
- The abstraction and injection rates were set non-stationary in the model, just as the well actually functioned;
- The model discretisation was refined to cells of 1 by 1 m in close vicinity of the Freshkeeper well.

**Table 4-5 Mean chloride stratification, based on the measurements in the pilot along the Freshkeeper well and in monitoring wells DP0040 and ZSOPP.**

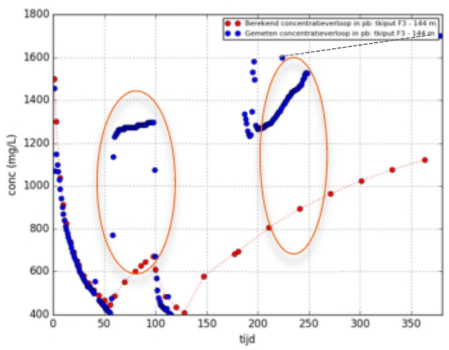
| Depth [mbsl] | Model layer | Chloride concentration [mg/L] |
|---|---|---|
| 0-130 | 1 to 9 | 50 – 60 |
| 130-135 | 10 | 150 |
| 135-140 | 11 | 600 |
| 140-144 | 12 | 1500 |
| 144-154 | 13 | 1500 |
| 154-160 | 14 | 1500 |
| 160-170 | 15+16 | 700 |
| 170 – 240 | 17 to 22 | 1500 – 6000 |



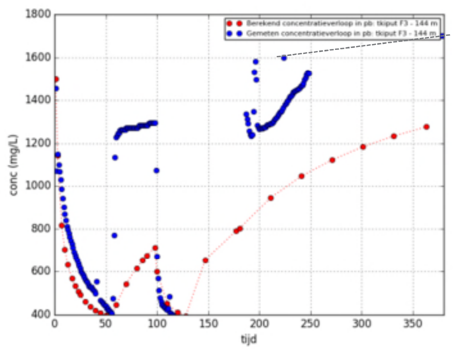

SMART WATER WELL F2 / 135M-MSL: KV FIRST AQUIFER IS 0.2*KH




SMART WATER WELL F2 / 135M-MSL: KV FIRST AQUIFER IS 0.5* KH




SMART WATER WELL F3 / 144M-MSL: KV FIRST AQUIFER IS 0.2*KH




SMART WATER WELL F3 / 144M-MSL: KV FIRST AQUIFER IS 0.5*KH

**Figure 4-1 Calculated chloride concentration with the groundwatermodel and calculated chloride concentrations, based on the EC-measurements in two monitoring filters (Filter 2 and 3) of the smart water well. Blue dots: based on EC measurements. Blue line: based on water analysis. Red dots: based on model result.**

In Figure 4-1, for two monitoring filters, modeled and observed chloride concentration are plotted. This has been done for model runs with a different vertical anisotropy, namely kV = 0.2 * kH and kV = 0.5 * kH. The following observations were made:

- In the upper figures (filter 2), the initial chloride concentration does not match the actual measured concentration (600 mg / l vs. 450 mg / l). This is because the average stratification of the three wells is included in the model and the stratification on a distance of 40 m varies. Nevertheless, the model represents the same trend as measured in the pilot;
- In the lower figures (filter 3), the model does not simulate the “jumps” that are visible in the measurements. These jumps seem to coincide with preferential flow from the deeper (salt) part of the first watering package during and after deployment of the well. If this effect is ignored, the model calculates the measured concentration trend at an anisotropy of kV = kH * 0.2 reasonable. With an anisotropy of kV = 0.5 * kH (right figure), the model slightly overestimated  the dynamics in chloride. It is thus recommended to change the anisotropy factor to 5 (kV = kH * 0.2).

**Historic extraction rates and chloride concentration**

Figure 4-2 shows the modeled chloride concentrations of the production water (Noardburgum and Ritskebos combined) when total abstraction is set to 22 million $m^3$/year. This amount of water was abstracted (on average) by the two well fields (11 million $m^3$/year each) between 1970 and 1990.

Modeled chloride concentration increased rapidly to 150 mg/L within 5 years after the start of the production. Thereafter, a constant yearly increase of +2 mg /L is observed. This trend is in the same order as observed in the historic date from the well fields: +2.5 mg/L per year (Figure 3-3). The model result and historic measurements cannot be compared in absolute terms, because the model simulation was performed with the current initial chloride distribution, and not the 1960s distribution.

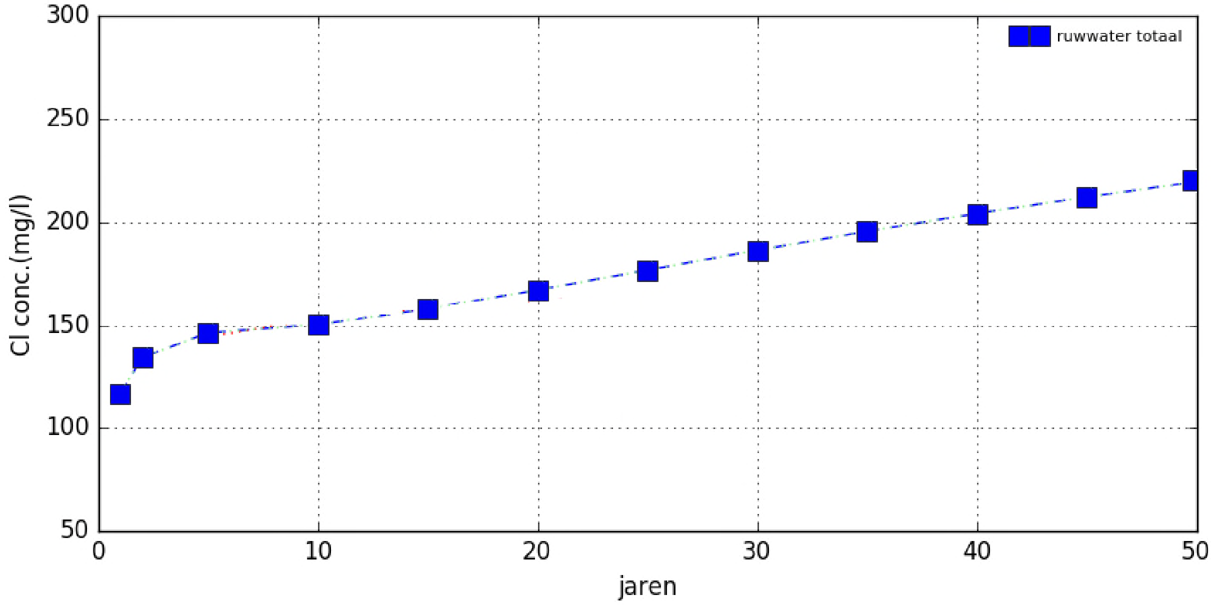



**Figure 4-2 Calculated chloride concentration of the raw water of the well fields Noardburgum and Ritskebos together. The discharges are based on the historic extraction rates.**

# 5 Scenario analysis for full-scale Freshkeeper application

The updated model **Noardburgum FloPy 2017** was used to evaluate different scenarios to increase drinking water production in the region with 2 million $m^3$ per year. Vitens has several options to increase production, including (1) increase production in well field Ritskebos, (2) restart production at well field Noardburgum (i.e. application of Freshkeeper at full-scale) or a combination of both. Focus of the evaluations were the effects on the regional salinity distributions (i.e. prevention of salinization) and on the salinity concentrations in surrounding well fields. One of the concerns is that full-scale Freshkeeper application at Noardburgum may result in increased salinity at Ritskebos, via the by-pass through the glacial gully.

## 5.1 Assesment criteria

The main criterium for Vitens is that 2 million $m^3$/year fresh water can be sustainable produced at from Noardburgum and/or Ritskebos. The definition of sustainability for this specific case is (Table 5-1):

*"The full scale Freshkeeper s considered sustainable if the chloride concentration of the mixed production water (Ritskebos + Noardburgum) does not exceed 150 mg/L in the next 50 years, assuming that groundwater abstraction rates and climatic conditions remain equal."*

**Table 5-1 Defined assesment criteria**

| Assesment criteria | Chloride concentration |
|---|---|
| Trend chloride concentration well field Noardburgum | < 150 mg/L after 50 years |
| Trend chloride concentration well field Ritskebos | < 150 mg/L after 50 years |
| Trend chloride concentration of raw water well fields Noardburgum + Ritskebos | < 150 mg/L after 50 years |

## 5.2 Scenario definitions

Table 5-2 summarizes the different scenarios that were evaluated. Vitens ideally opts for a production increase of 2 million $m^3$ per year, totaling 9 million $m^3$ year. This can be achieved from Ritskebos alone, or by a combination of Ritskebos and Noardburgum (Freshkeeper). Abstracted brackish water is directly injected into the second aquifer in all Freshkeeper scenarios, except one. In this scenario D., the abstracted brackish water (0.4 million $m^3$/y) is desalinated with a reverse osmosis (50% recovery), rendering 0.2 million $m^3$/y (fresh) permeat and 0.2 million $m^3$/y BWRO concentrate. This concentrate is then reinjected into the aquifer aquifer, as was piloted in 2009. The Reference scenario and the full scale (2 Mm3/y) Freshkeeper scenario have both also been modelled with the worst-case initial chloride concentrations.

**Table 5-2 future scenario's and discharge rates per well field**

| | Noardburgum | | | RTSKB | Total |
|---|---|---|---|---|---|
| | Freshwater [$Mm^3$/y] | Brackish [$Mm^3$/y] | Injection [$Mm^3$/y] | Freshwater [$Mm^3$/y] | Freshwater [$Mm^3$/y] |
| A. Reference scenario** | 0 | 0 | 0 | 7 | 7 |
| B. 2$Mm^3$/y (standard) production NB | 2 | 0 | 0 | 7 | 9 |
| C. 2$Mm^3$/y Freshkeeper production NB** | 2 | 0.4 | 0.4 | 7 | 9 |
| D. 2$Mm^3$/y combined Freshkeeper and brackish water reverse osmosis (BWRO) | 2 | 0.4 | 0.2 | 7 | 9 |
| E. +2$Mm^3$/y production RTSKB | 0 | 0 | 0 | 9 | 9 |
| F. 1 $Mm^3$/y Freshkeeper NB, +1 $Mm^3$/y RTSKB | 1 | 0.2 | 0.2 | 8 | 9 |

*NB = well field Noardburgum, RTSKB = well field Ritskebos. Well field Ritskebos has only wells with one filter. ** these scenarios were also been modelled with the worst-case initial chloride concentration.

## 5.3 Scenario results

Appendix 2 presents the modelling results for all scenarios. Appendix 3 presents the results for the model scenarios with the worst-case initial chloride concentration. The following can be concluded:

**A. Reference scenario.** The fresh-brackish water interface at Noardburgum will gradualy move downwards towards the Tegelen clay. This was expected as the area as a whole is an infiltration area and in this scenario no water is abstracted at Noardburgum. The chloride concentrations in aquifer #1 will slighly increase towards 70 mg/L; this is because the precipitation was set to have a chloride concentration of 70 mg/L. Chloride concentrations in the production water (100% Ritskebos) will stablize at approx. 115 mg/L.

**B. 2 million $m^3$/y "standard" production at NB**. Chloride concentrations at Noardburgum will increase fast, as expected. After about 20 years, chloride concentrations slowly decrease. This is due to the chloride distribution in the model: after some time the water is attracted from an area with a lower chloride concentration. It is questionable whether this will occurs in the real world. Even though chloride concentrations in the production water (Noardburgum:Ritskebos = 2:7) is at 120mg/L (thus below drinking water limits), this is considered a risky scenario.

**C/D. 2 million $m^3$/y Freshkeeper NB**. This scenario was modelled with and without the use of brackish water reverse osmose (BWRO). When BWRO is applied in the model, half of the abstracted brackish water is converted into fresh permeat water (chloride concentration practically 0 mg/L) and half into BWRO concentrate, which has a chloride concentration twice that of the abstracted brackish groundwater. With the use of BWRO treatment, half the volume of water will be injected in the second aquifer, i.e. 0.2 million $m^3$/y compared to 0.4 million $m^3$/y in the standard Freshkeeper. Injecting a lower volume of water indeed renders lower chloride concentrations at both Noardburgum and Ritskebos after 50 years. In both scenarios, there is an increase in chloride concentrations at Ritskebos (Figure 5-1 and Figure 5-2), because of reinjected brackish water reaching this well field via the glacial gully by-pass. This increase commences 10 year later (i.e. after 40 years) in scenario D., as in this scenario a smaller volume of brackish water is reinjected (yet with a higher salinity). For the same reasons, chloride concentrations in the production water (Noardburgum:Ritskebos = 2:7) are also lower in scenario D.

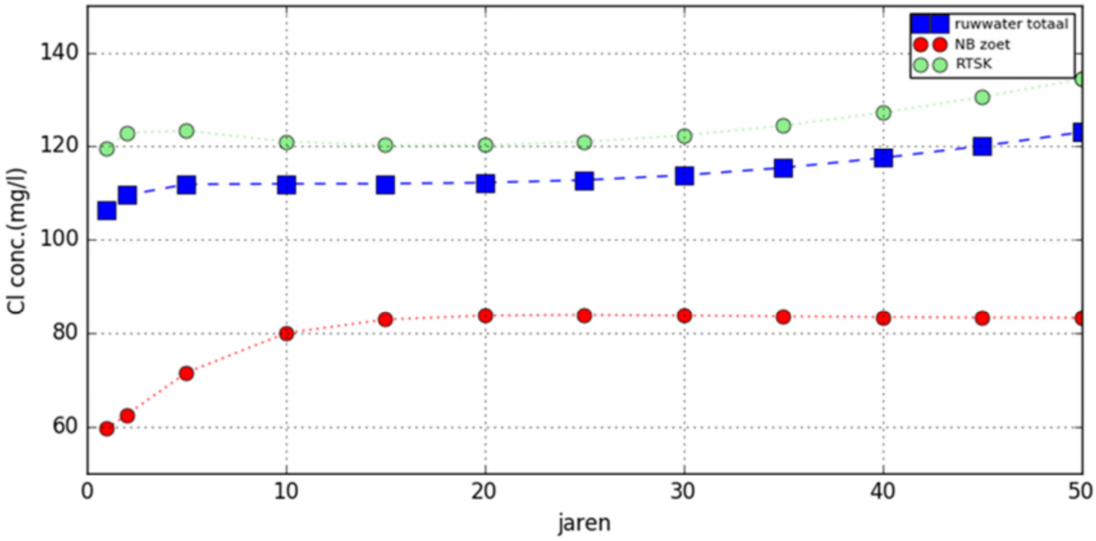



**Figure 5-1. Chloride concentrations in scenario C. 2Mm3/y Freshkeeper production NB. Concentrations in Noardburgum are stable at approx. 82 mg/L, while concentrations at Ritskebos gradually increase after 30 years because of reinjected brackish water reaching this well field via the glacial gully by-pass.**

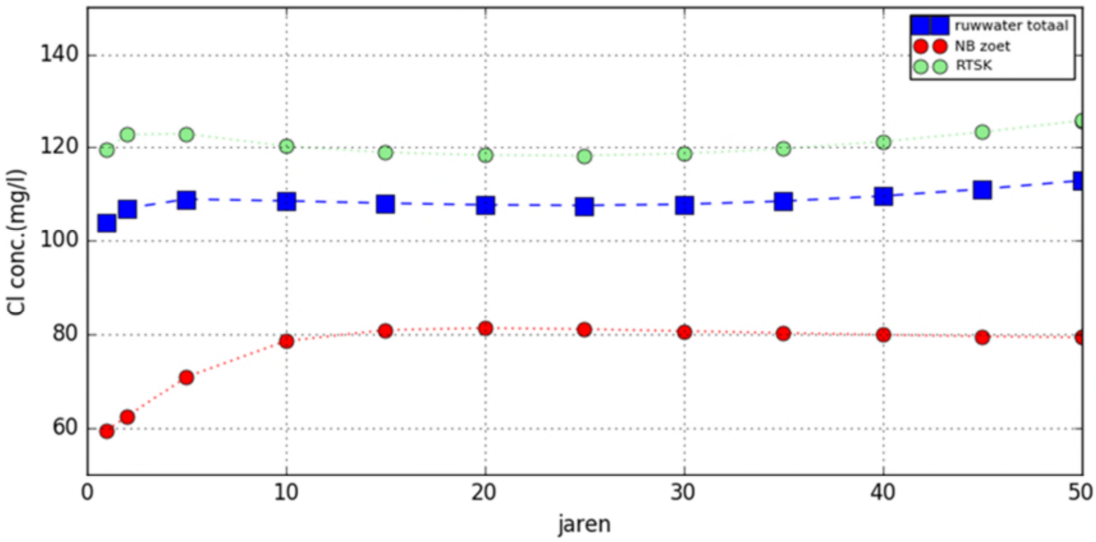



**Figure 5-2 Chloride concentrations in scenario D. 2Mm3/y combined Freshkeeper and brackish water reverse osmosis (BWRO). Concentrations in Noardburgum are stable at approx. 80 mg/L. Concentrations at Ritskebos gradually increase only after 40 years, ten years later than in scenario C. This is because a smaller volume of brackish water is reinjected in scenarion D (but with a higher salinity).**

**E. +2Mm3/y production RTSKB**. This scenario shows a very stable chloride concentration at 120mg/L, and in terms of salinity may be considered the secure scenario. However, water well clogging (particle clogging) is a severe risk at Ritskebos, which is now under control by lowering production hours for each of the wells to an average of about 9 to 10 hours per day only. Increasing production at Ritskebos thus implies construction of additional water wells, for which there is not may space available at the well field.

**F. 1 Mm3/y Freshkeeper NB, +1 Mm3/y RTSKB**. This scenario results in stable chloride concentrations at the Noardburgum well field and the Ritskebos well field, though for the latter concentrations slowly, but gradually increase after 40 years of production. This again is because of reinjected brackish water reaches to the Ritskebos well field via the glacial gully.

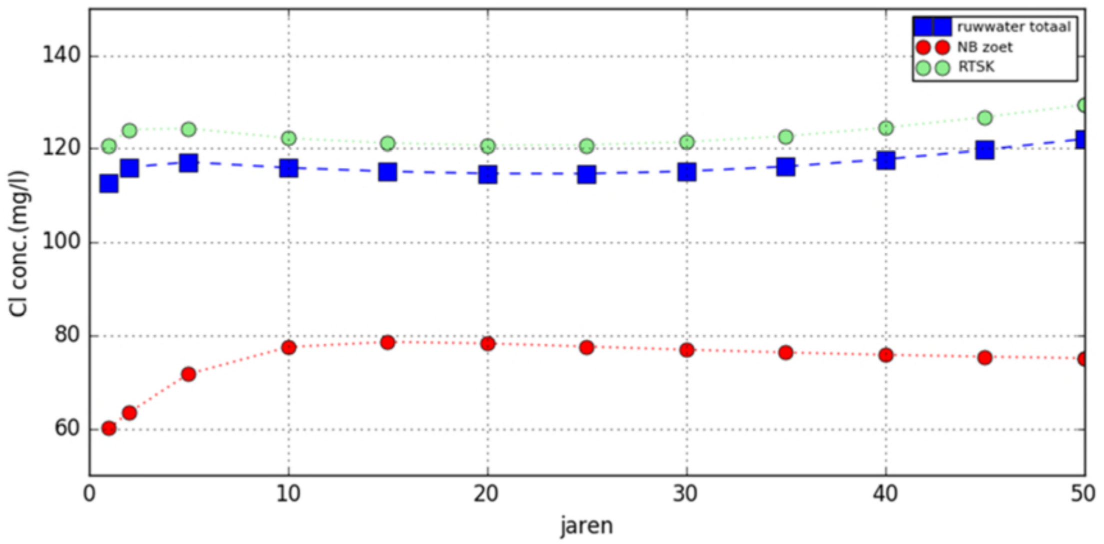



Figure 5-3 Chloride concentrations in scenario F. 1 Mm3/y Freshkeeper NB, +1 Mm3/y RTSKB.

Table 5-3 summarizes the results of the model scenario analysis of scenarios C – F. All scenarios meet Vitens sustainability criteria, i.e. chloride concentration of the mixed production water (Ritskebos + Noardburgum) does not exceed 150 mg/L in the next 50 years.

**Table 5-3 Simulated chloride concentration (mg/L) in abstracted water at Noardburgum and Ritskebos, and in the production water after 50 years of operation..**

| | C. $2Mm^3/y$ Freshkeeper production NB | D. 2Mm3/y combined Freshkeeper and BWRO | E. +2Mm3/y production RTSKB | F. 1 Mm3/y Freshkeeper NB, +1 Mm3/y RTSKB |
|---|---|---|---|---|
| Noardburgum | 84 | 80 | n.a. | 78 |
| Ritskebos | 136 | 126 | 125 | 130 |
| Production water | 122 | 112 | 125 | 121 |

**Sensitivity analysis**

The initial chloride distribution in the model remains an uncertain factor in the model simulations and thus in the scenario analysis. The robustness of the model and the results were therefore tested with a worst case estimations of the initial chloride concentration for scenario C ($2Mm^3/y$ Freshkeeper production NB) and the reference scenario. From these scenario runs it is concluded that the chloride concentrations of the abstracted water will be higher, but that the trends stay the same. Chloride concentrations of the abstracted water at Noardburgum will increase to 100 mg/L (instead of 80 mg/L), yet concentrations at Ritskebos increase to almost 300 mg/L within 5 years, after which they stabilize at about 200 mg/L. This almost immediate and steep rise in chloride concentrations in not related to the Freshkeeper application and reinjection at Noardburgum: the same pattern was simulated in the reference scenario. Given the chloride concentrations in the production water at Ritskebos in the past 15 years, these seem unlikely scenarios.

# 6 Conclusion

A regional scale groundwater model was developed and validated for the Noardburgum and Ritskebos well field: **Noardburgum FloPy 2017** model. The model uses the SEAWAT code because of its ability to simulate three-dimensional variable density groundwater flow coupled with multi-species solute transport. This allows for accurate description of the groundwater flow movement taking into account the density differences between fresh and saline water (buoyancy effects and upconing).

The **Noardburgum FloPy 2017** model was validated using the data on water levels at the Noardburgum and Ritskebos well fields and their surroundings, using observations from the Noardburgum (SUBSOL) reference pilot, and by using historic data on chloride concentrations in both well fields. It was concluded that the model is sufficiently plausible for all three validation tests.

Several scenario runs, all aiming to increase total production from the current 7 million $m^3$/y to 9 million $m^3$/y, were performed with the model, and evaluated against the sustainability criterion set by Vitens: chloride concentration of the mixed production water (Ritskebos + Noardburgum) should not exceed 150 mg/L in the next 50 years. From the analysis it is concluded that reopening of the Noardburgum well field is possible only by applying the Freshkeeper concept, either with or without subsequent desalination and reuse of the abstracted brackish water. Another sustainable option to increase the total production at Ritskebos (+ 2 million $m^3$/y), yet this increases the risk of water well clogging at this site.

The (initial) chloride distributions remain an uncertain factor in the model. Even though an additional monitoring campaign was performed prior to the model development, we have a limited view on chloride distributions, simply at greater distance from the well field observation wells and thus data remains scarce. The robustness of the model and the scenario analysis were therefor tested with a worst-case estimation of the initial chloride concentrations. This analysis added to our confidence in the model, as simulated chloride concentrations at Ritskebos were considerately higher than those observed in the past 15 years (under similar operation).

Following the scenario analysis described in this report, Vitens has decided to increase the freshwater production from the Noardburgum well field to 1 million $m^3$/y by 2018. This means the Freshkeeper concept will be applied full-scale (multiple wells) within the timeframe of SUBSOL. Also, production at Ritskebos will be increased with an additional 1 million $m^3$/y. Furthermore, Vitens is investigating options to safeguard water supply at other salinity-threatened well fields by Freshkeeper-alike concepts.

# 7 Literature


Bakker, M., V. Post, C.D. Langevin, J.D. Hughes, J.T. White, J.J. Starn, and M.N. Fienen. 2016 Scripting MODFLOW Model Development Using Python and FloPy. *Groundwater*, pages 1–7, doi: 10.1111/gwat.12413.

Berendrecht, W.L. , J.J.J.C. Snepvangers, B.Minnema, and P.T.M. Vermeulen. 2007. Mipwa: A methodology for interactive planning for water management. In: MODSIM07 International Congress on Modelling and Simulation "Land,Water and EnvironmentalManagement : Integrated Systems for Sustainability", Christchurch, 10-13 *December 2007*, pages 330–334.Modelling and Simulation Society of Australia and New Zealand.

COGroWa, 1977. Onderzoek naar de invloed van de wateronttrekking door het pompstation Tietjerksteradeel (Noordbergem en Ritskebos) op de stijghoogte van het grondwater. Rapport GW-279.

De Graaf, C., Niemeijer, A. and Zaadnoordijk, W.J., 2007. Verziltingsprognose pompstation Noardburgum. Royal Haskoning, Groningen.

F.C. Dufour. 1998 Grondwater in Nederland. Onzichtbaar water waarop wij lopen. TNO, Delft.

J. Ehlers, K.D. Meyer, and H.J. Stephan. 1984. The pre-weichselian glaciations of North-West Europe. *QuaternaryScience Reviews*, 3(1):1 – 40. doi: 10.1016/0277-3791(84)90003-9.

Geul, K.R.A., 2016. Modelling the ‘smart well’ in Noardburgum, an uncertainty and confidence analysis of the sustainability of the smart well. MSc thesis, Delft University of Technology.

Guo, W. and Langevin, C.D., 2002, User’s guide to SEAWAT: A computer program for simulation of threedimensional variable-density ground-water flow: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 6, Chap. A7.

IWACO, 1994. Grondwatermodelstudie Noordbergum. Report, IWACO, Rotterdam.

IWACO, 1997. Modelonderzoek verzilting Noordbergum. Report 2234230, IWACO, Rotterdam.

IWACO, 1986. Nader onderzoek verzilting pompstation ‘Storm’ te Noordbergum. Report 1214. IWACO, Rotterdam.

Langevin, C.D. and W. Guo, 2006.. MODFLOW/MT3DMS–Based Simulation of Variable-Density GroundWater Flow and Transport. *GroundWater*, 44(3):339–351, 2006. doi: 10.1111/j.1745-6584.2005.00156.x.

Langevin, C.D., D.T. Thorne Jr, A.M. Dausman, M.C. Sukop, and W. Guo. *SEAWAT Version 4: a computer program for*

Margat, J., S. Foster, and A. Droubi. 2006. Concept and importance of non-renewable resources. *Non-renewable*groundwater resources: A guidebook on socially-sustainable management for water-policy makers, 10:13–24.

MILFAC, 1996. Diepinfiltratie Noordbergum.

Olsthoorn, T.N., 2012. *CIE4420 Fresh and salt water*. Delft University of Technology.

Royal Haskoning. 2004. Triwaco User’sManual, Triwaco 3.x. Report, Royal Haskoning

Rus, J.S., 1997. Modelonderzoek verzilting Noordbergum. Report, IWACO, Groningen.

Stuurman R., and G.H.P. Oude Essink, 2007. Naar een uniforme landelijke inrichting van het KRW grondwatermeetnet Zoet-Zout. Report TNO, Delft.

TNO, 1987. Grondwaterkaart van Nederland Harlingen/ Leeuwarden 2D, 5D, 5oost, 6west.

Van der Gun, 1979. Schatting van de elastische bergingscoëfficiënt van zandige watervoerende pakketten. Dienst Grondwaterverkenning TNO, Jaarverslag 1979, p.p. 51-61;

Van der Linde, S.J., 2014. Effect of a fresh keeper at Noardburgum on the regional hydrology, KWR2015.031, KWR Watercycle Research Institute, Nieuwegein, the Netherlands;

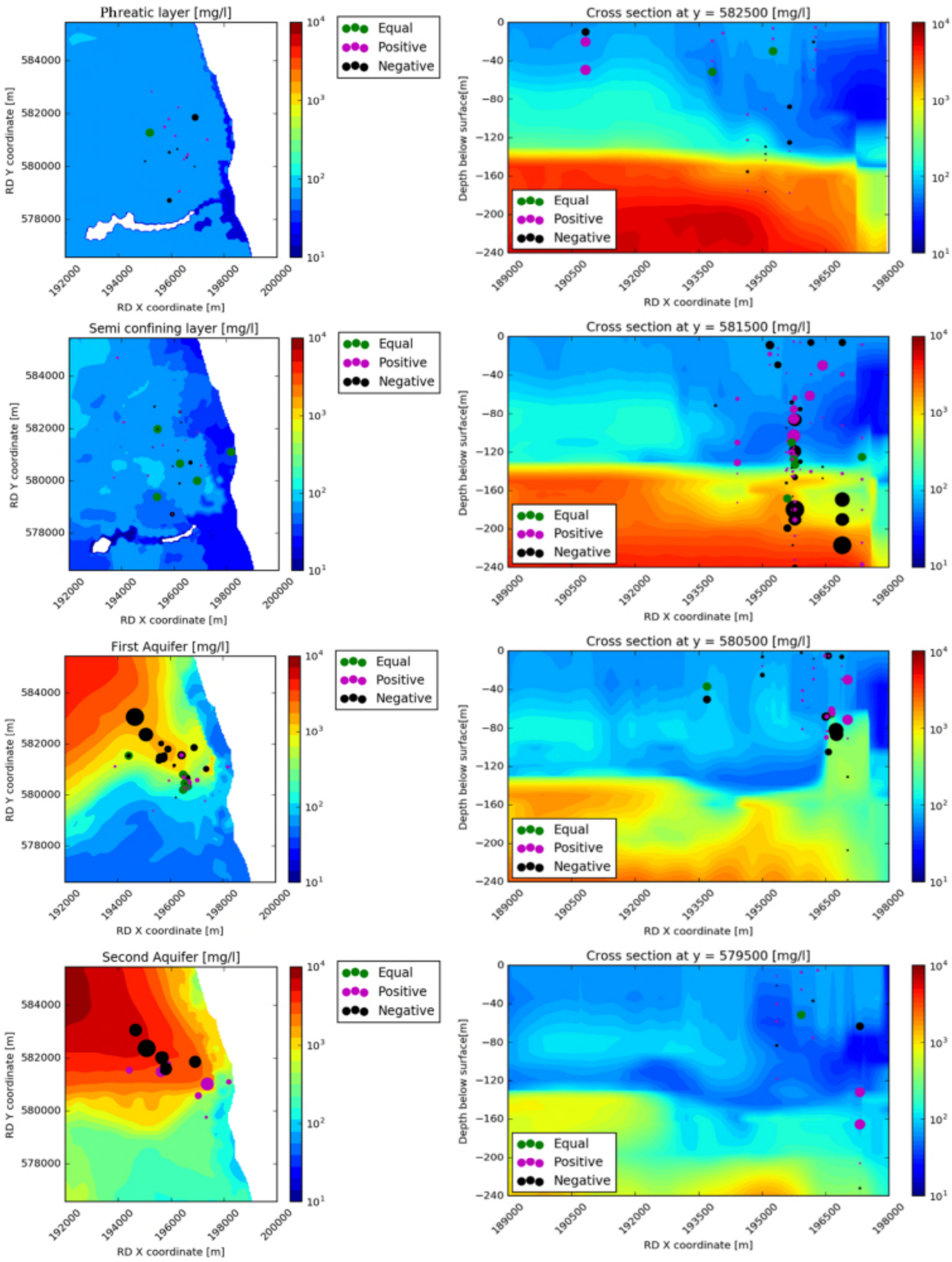
Van der Valk, M.J.H., 2011. A fresh-keeper for Noard Burgum, the future for a salinated well field?, MSc thesis, Delft University of Technology.

Wetterskip Fryslan, 2015. Ontwerp- Watergebiedsplan Tusken 1e en Swemmer. Wetterskip Fryslan.

C. Zheng and P.P.Wang. MT3DMS: a modular three-dimensional multispecies transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems; documentation *and user's guide*. University of Alabama, Alabama, 1999.

# Appendix I Regional comparison measured and modelled chloride concentration

Difference between modelled chloride concentration and measured chloride concentration, displayed on a contour plot of the initial chloride distribution created for 2016. The size of the dots indicates the difference. The Left figures are a top view of the different layers, note that this is scaled to the Noardburgum area and no the entire model. The figures on the Right are a cross sectional view through the different layers to give more perspective of the measurements over the depth of the aquifer.



# Appendix II Model results

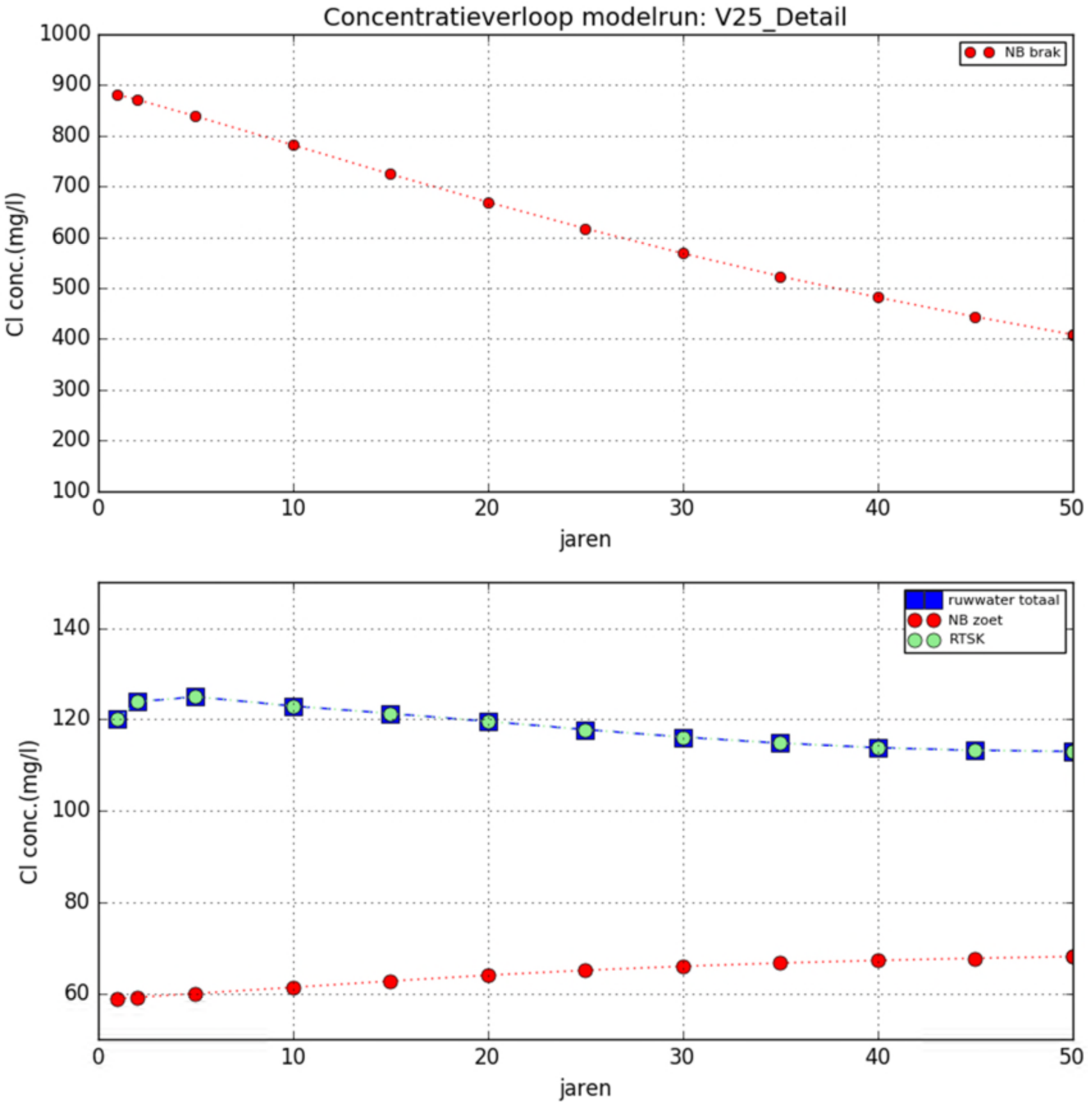
Legend upper figure:
● mean calculated chloride concentration at the brackish water filter at Noardburgum

Legend lower figure:
■ mean calculated chloride concentration of the raw water of the well fields together
● mean calculated chloride concentration at well field Ritskebos
● mean calculated chloride concentration at the fresh water filters at Noardburgum.

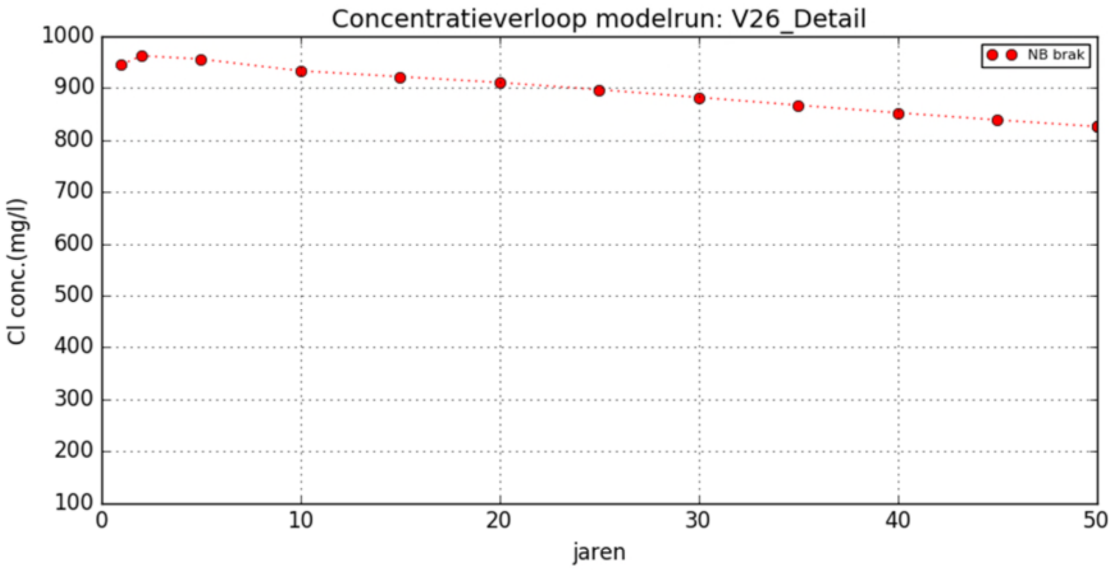
| | Noardburgum | | | RTSKB | Total |
|---|---|---|---|---|---|
| | Freshwater [Mm$^3$/y] | Brackish [Mm$^3$/y] | Injection [Mm$^3$/y] | Freshwater [Mm$^3$/y] | Freshwater [Mm$^3$/y] |
| A. Reference scenario** | 0 | 0 | 0 | 7 | 7 |
| B. 2Mm$^3$/y (standard) production NB | 2 | 0 | 0 | 7 | 9 |
| C. 2Mm$^3$/y Freshkeeper production NB** | 2 | 0.4 | 0.4 | 7 | 9 |
| D. 2Mm$^3$/y combined Freshkeeper and brackish water reverse osmosis (BWRO) | 2 | 0.4 | 0.2 | 7 | 9 |
| E. +2Mm$^3$/y production RTSKB | 0 | 0 | 0 | 9 | 9 |
| F. 1 Mm$^3$/y Freshkeeper NB, +1 Mm$^3$/y RTSKB | 1 | 0.2 | 0.2 | 8 | 9 |

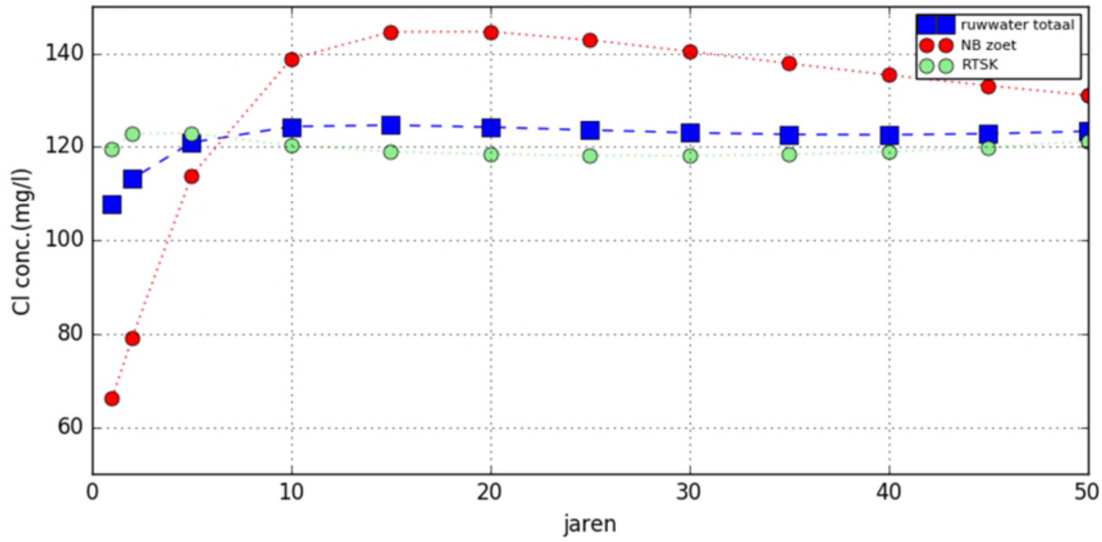
*NB = well field Noardburgum, RTSKB = well field Ritskebos. Well field Ritskebos has only wells with one filter. ** these scenarios were also been modelled with the worst-case initial chloride concentration.

## A. Reference scenario

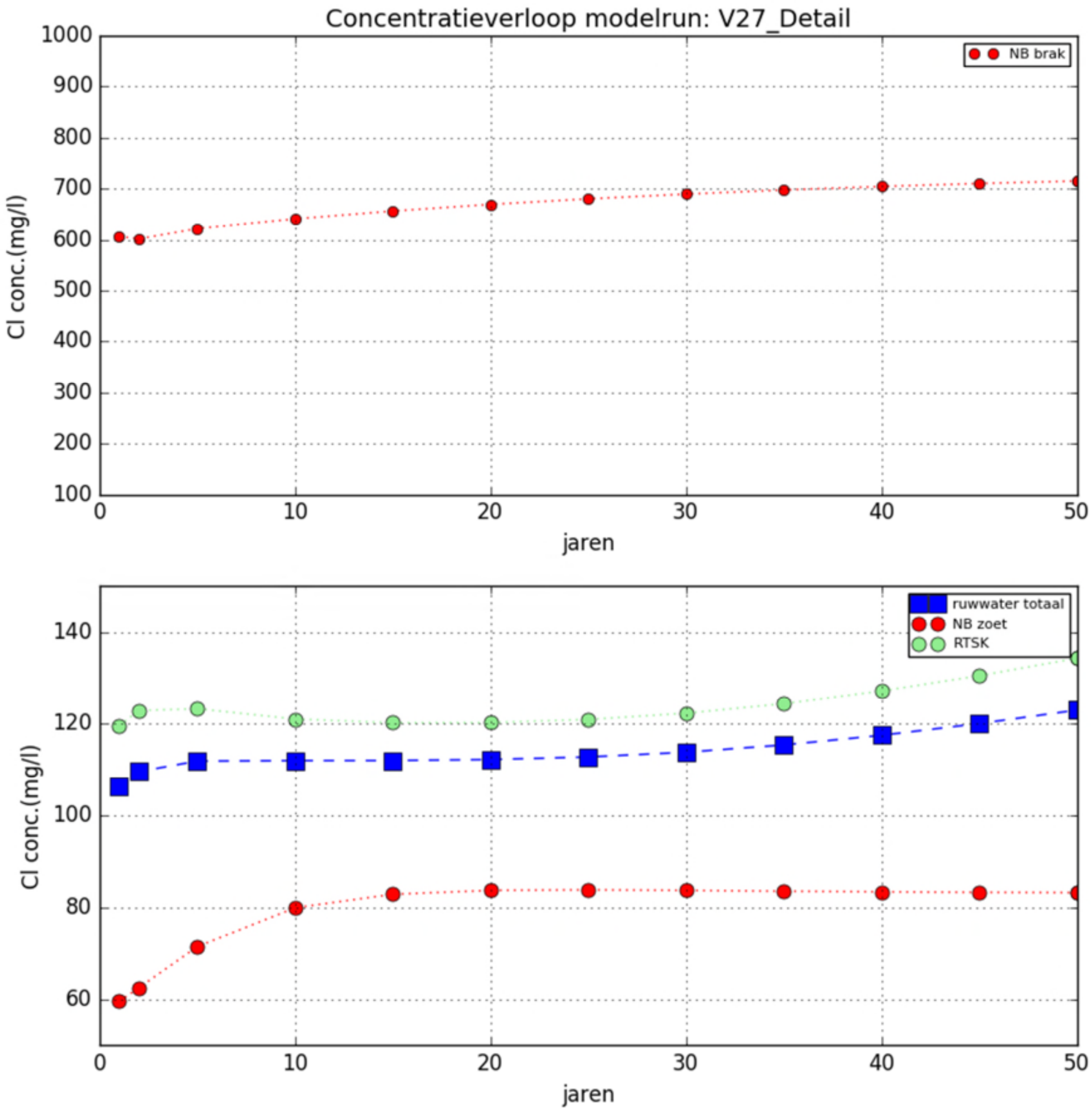


## B. 2Mm3/y (standard) production NB

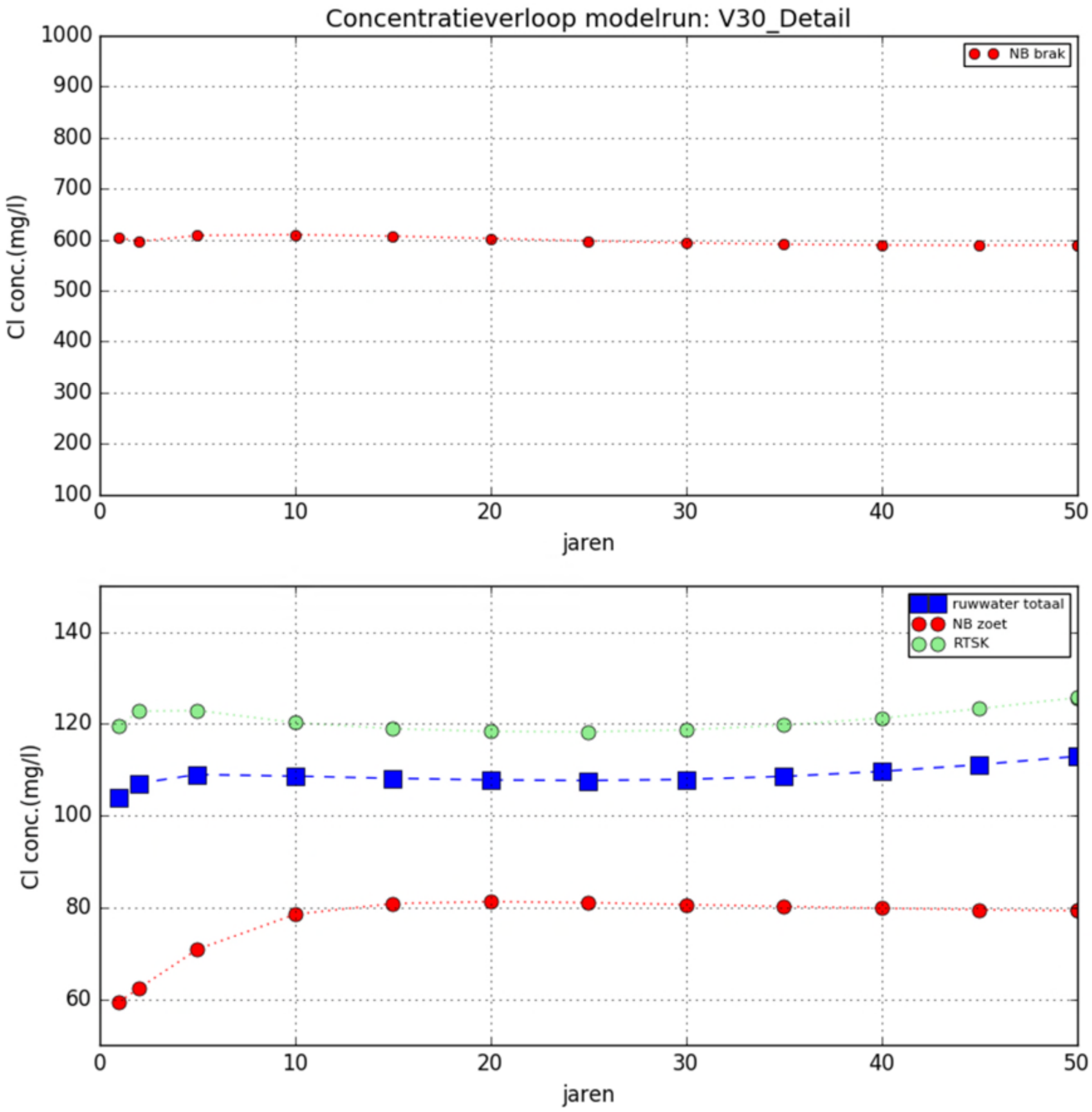


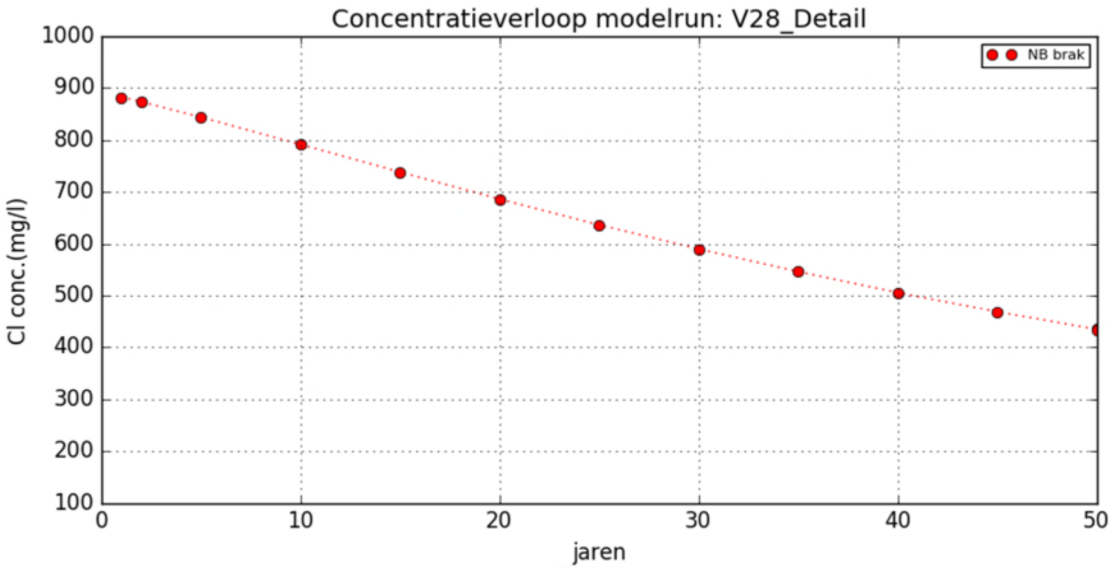
## C. 2Mm3/y Freshkeeper production NB**

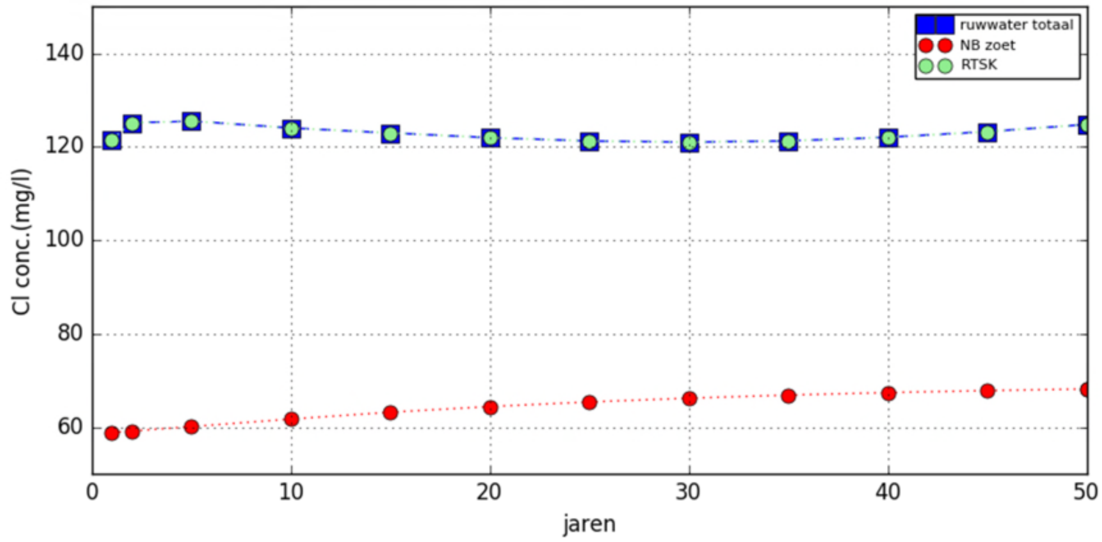


## D. 2Mm3/y combined Freshkeeper and brackish water reverse osmosis (BWRO)

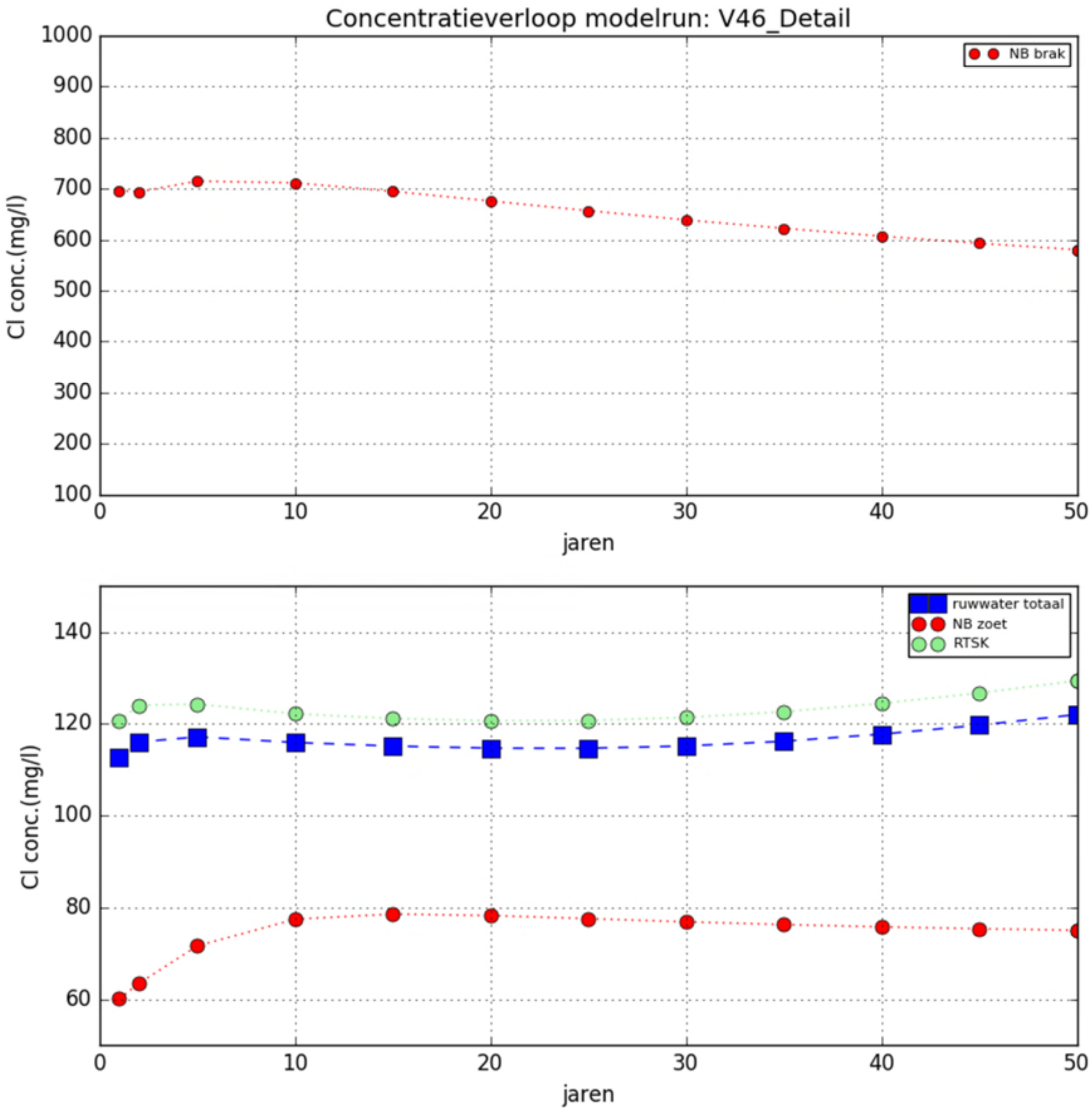


## E. +2Mm3/y production RTSKB



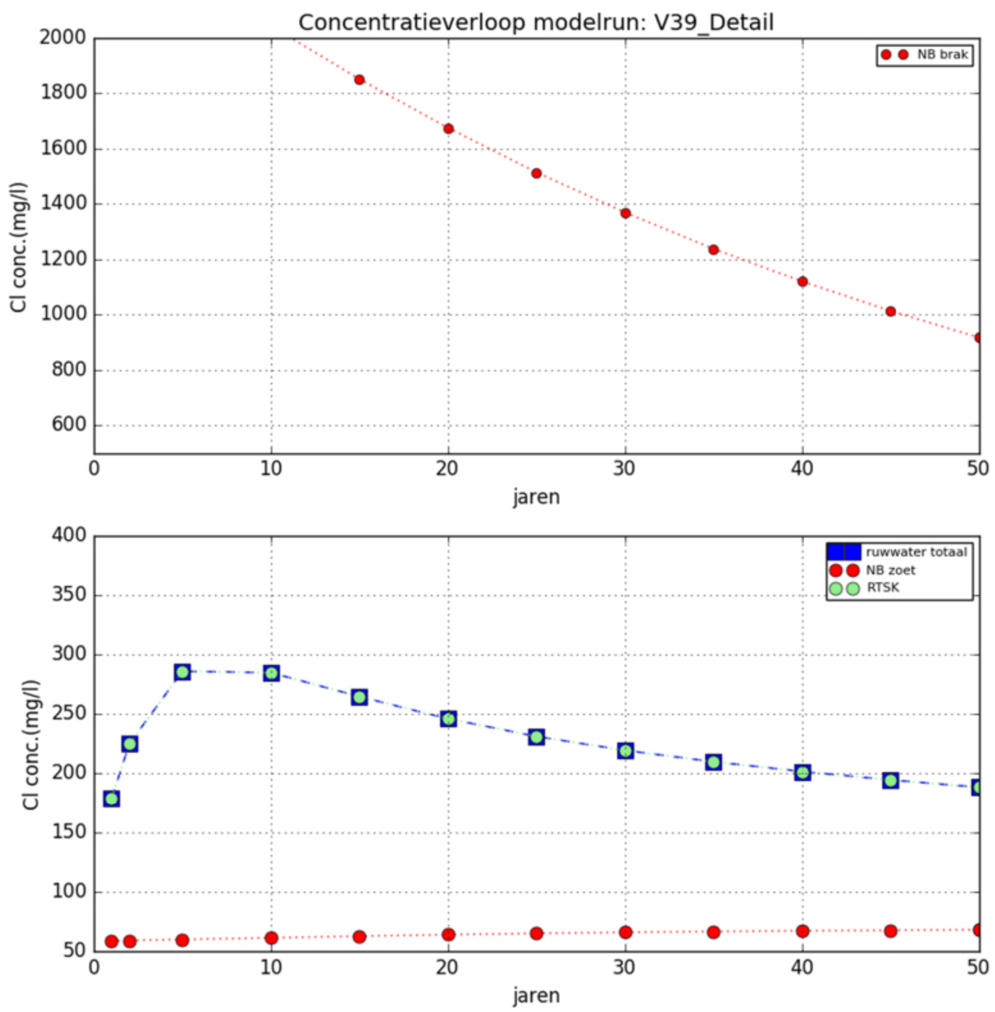
## F. 1 Mm3/y Freshkeeper NB, +1 Mm3/y RTSKB



# Appendix III Model result, adjusted initial chloride concentration to worst-case scenario

| Legend upper figure: | Legend lower figure: |
|---|---|
| ● mean calculated chloride concentration at the brackish water filter at Noardburgum | ■ mean calculated chloride concentration of the raw water of the well fields together<br>● mean calculated chloride concentration at well field Ritskebos<br>● mean calculated chloride concentration at the fresh water filters at Noardburgum |

**A. Reference scenario****



## C. 2Mm3/y Freshkeeper production NB**