# Groundwater flow paths in a glacially affected flat area in the Netherlands

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# Grundwasserfließwege in einem glacial geprägten Gebiet in den Niederlanden

## 1 Introduction

During Elsterian (0.5 million year BP), glaciers cut a few km wide and up to 250 m deep gullies in pre-glacial sediments in the northern part of the Netherlands (Bosch et al., 2009; Huuse & Lykee-Andersen, 2000; Smit & Bregman, 2012). At the end of this ice age, these gullies were filled by fluvioglacial sediments (lower part) and fine-grained glacio-lacustrine sediments (upper part). The elongated fluvioglacial sediments form significant aquifer systems, covered with clay from Saale glaciation. This hydrogeological setting makes the gullies favourable locations for drinking water abstraction. In 2002, well field Garyp was taken into operation because of too saline water in the old well fields Ritskebos and Noordelijke Puttenveld. However, this well field Garyp in the Province of Friesland in the Netherlands (53º10'37"N, 5º57'52"E, elevation 3 m – m.s.l.) was hampered by rapid salinization of the abstraction wells. Already within two years the extracted water became too saline for drinking water use. In order to reveal the source of the salinization, the origin, distribution and hydrogeological properties of the area was studied in detail. Furthermore, the origin and flow paths of brackish/salt water was investigated by using a detailed groundwater model.

In the Province of Friesland, groundwater levels are regulated through a dense network of ditches in polders, which are connected via weirs and pumping stations to a surface water storage network: the so called Friese Boezem. Figure 1 shows the hydraulic head pattern of the Province Friesland and surrounding area. Southeast of Garyp pumping station a relatively elevated area (Drents Plateau) with glacial till at shallow depth can be found. In Figure 1 it is clearly visible that groundwater flows from that plateau towards the north and west. Due to salinization, total water abstraction for two well fields Ritskebos and 'Noordelijke

### Zusammenfassung

Das Brunnenfeld Garyp entnimmt tiefes Grundwasser aus fluvioglazialen Sedimenten, welche von glazio-lakrustinen Tonen überdeckt sind. Die Trinkwasserentnahme wird durch rasche Versalzung der Entnahmebrunnen erschwert. Durch eine detaillierte Grundwassermodellierung wurden die Fließwege und die Interaktionen zwischen Oberflächen- und Grundwasser dokumentiert. Es wurde gezeigt, dass weder die Außerbetriebnahme einzelner Brunnen, noch eine reduzierte Fördermenge oder die Reduktion der Fördertiefe eine Verringerung des salinen Brackwasserzulaufs bewirken kann.

**Schlagwörter:** Grundwasserhydrologie, Interaktionen Oberflächen- und Grundwasser, MODFLOW, Versalzung.

### Summary

Well field Garyp is abstracting deep groundwater from fluvioglacial sediments, which are covered by glacio-lacustrine clay. This drinking water abstraction is hampered by rapid salinization of the abstraction wells. A detailed groundwater modelling study was done, to reveal the water pathways and the groundwater-surface water interaction. It was concluded that shutting down wells, nor reducing abstraction rates or reduction of well screen depth would result in significantly less abstracted water from brackish layers.

**Key words:** Groundwater hydrology, groundwater-surface water interaction, MODFLOW modeling, salinity.

Puttenveld' (both north of Garyp) had to be reduced from ~24 $10^6$ $m^3$ $year^{-1}$ in the 80's to 7 $10^6$ $m^3$ $year^{-1}$ in 2012. Well field 'Noordelijke Puttenveld' was closed completely and replaced by well field Garyp with a max abstraction 3 $10^6$ $m^3$ $year^{-1}$ in 2002 (LODDER & STEINWEG, 2013a; LODDER & STEINWEG, 2013b). The local water authority Wetterskip Fryslân supplies extra surface water to the area surrounding the well fields. This led to a reduction of the drawdown in the pumping cone, but had less influence effect on the salinization.

The salinity of groundwater in the aquifers and aquitards in this region depends predominantly on the condition at the time of sedimentation. During Early Pleistocene (2.6 – 1.4 M years BP) marine sediments (Maassluis complex) were deposited in the area, with brackish pore water (CUSTODIO, 2010). Overlying Pleistocene fluvial formations can be considered as fresh water aquifers. Even though the Maassluis complex often is considered as the hydrological base, because of the low vertical hydraulic conductivity, significant flow from this complex could be the cause of drinking water well salinization.

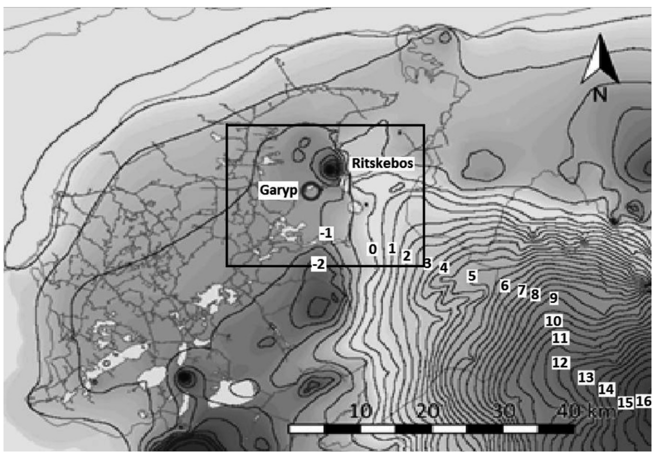


Figure 1: Hydraulic head pattern of the Province Friesland and surrounding area. Garyp well field is indicated with a circle, the deep pumping cone NE of Garyp represents the larger Ritskebos well field. The black rectangle indicates Fig. 2, isohypses are shown with an 0.5 m interval, the open water of the Friese Boezem with light grey lines (after NHI, 2013)

Abbildung 1: Wasserspiegellagen des Umlandes der Provinz Friesland. Das Brunnenfeld Garyp ist durch einen Kreis gekennzeichnet. Der Pumptrichter nordöstlich von Garyp zeigt das größere Ritskebos Brunnenfeld. Die schwarze Rechtecksumgrenzung zeigt den Ausschnitt aus Abb. 2. Die Grundwasserisolinien weisen eine Auflösung von 0.5 m auf

The objective of this paper is to show that embedding a detailed hydrogeological schematization in a large model can help to get a better insight in not only horizontal flow to drinking water abstractions, but also help to improve knowledge on vertical water movement and groundwater-surface water interactions.

## 2 Model setup

MODFLOW (NGUYEN et al., 2005), with the GMS graphical user interface, was used to develop a groundwater model with a 25x25 m grid and 13 model layers, covering the Netherlands, called MIPWA (Methodology for Interactive Planning for Water Management; BERENDRECHT et al., 2007). This Dutch widely accepted model is currently still under construction, but ready and available for the northern part of the Netherlands. All sources and sinks of water (canals, ditches, lakes, drains, wells) are embedded in this model. To limit calculation time needed for this study, the MIPWA model was clipped to an area of approximately 20x20 km, called NOORDBURGUM model. See Figure 2 for the model boundaries. To model the hydrological situation at Garyp well field in detail, a new detailed model for the gully was developed by analysing existing boreholes in the area, i.e. the GARYP model (Figure 3), with also a 25x25 m grid. This local GARYP model was embedded in the regional NOORDBURGUM model, as shown in Figure 4. This improved NOORDBURGUM model was used to analyse groundwater-surface water interactions. The isohypses in Figure 4 represent average groundwater levels. Variation in surface water level and related phreatic groundwater level is limited in these flat polders.

The dense local surface water system around Garyp was implemented using data from the local water authority, combined with NOORDBURGUM (MIPWA) data on drain conductance, implemented as diffuse drainage.

## 3 Results

Firstly the difference between the GARYP and NOORDBURGUM/MIPWA schematization was studied. The most significant difference is that the clay at -200m is represented as a series of rather thin clay layers in GARYP (max 33 model layers) and as one clay layer of >10 m in NOORDBURGUM model (max 13 model layers). This absence of a relatively thick aquitard causes less resistance for ground-

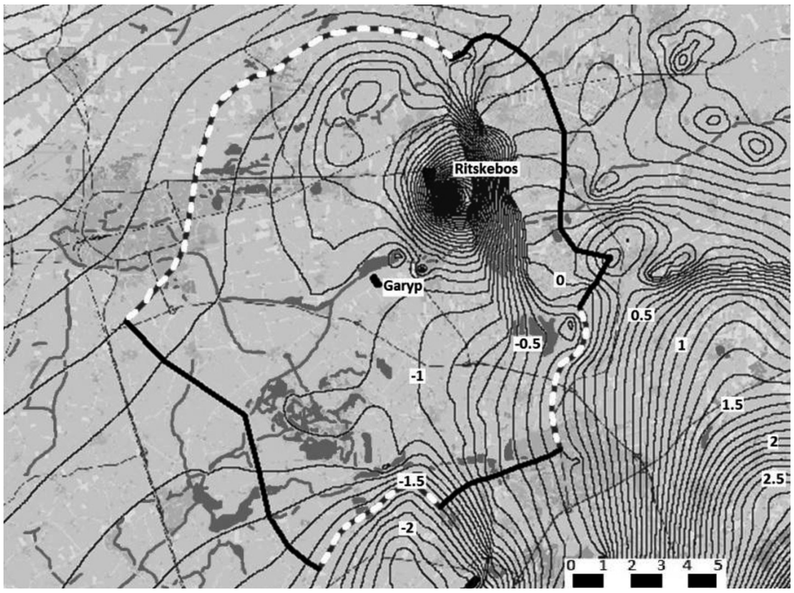


Figure 2: Detail of isohypses around Garyp, including boundaries of the NOORDBURGUM (after MENKVELD, 2013)

Abbildung 2: Detailansicht der Grundwasserisolinien um Garyp (nach Menkveld, 2013)

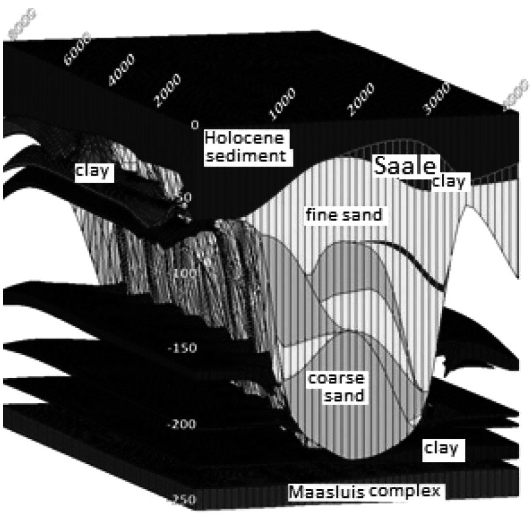


Figure 3: Pseudo 3D visualisation of the hydrogeological settings in the Garyp well field. The main aquitards are shown adjacent to the gully. Numbers indicate distance and depth (m) (after MENKVELD, 2013)

Abbildung 3: 3D-Visualisierung des hydrogeologischen Untergrunds des Garyp Brunnenfeldes. Die Grundwasserstauer nahe der GW-Senke werden gezeigt. Die Zahlen beschreiben die Lagekoordinaten in Meter (nach Menkveld, 2013)

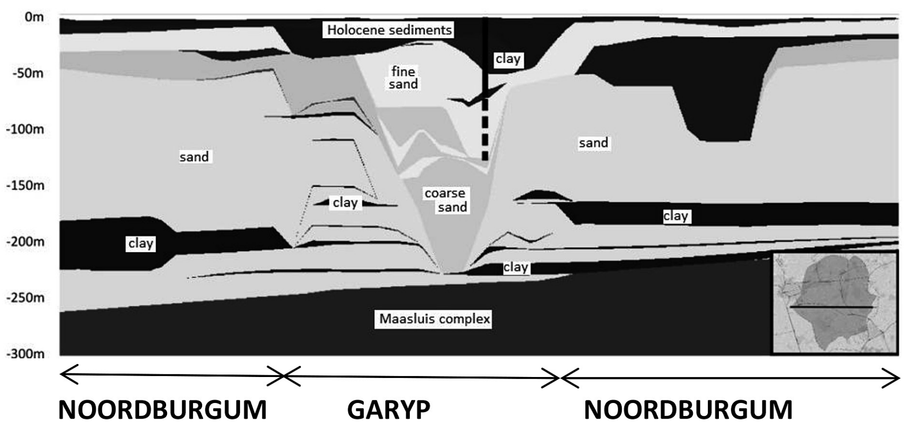


Figure 4: Cross section through the combined NOORDBURGUM and GARYP model. Garyp well field filter screen is indicated by a vertical line and dashed line, respectively. The location of the cross section is shown in the lower right corner (after MENKVELD, 2013)

Abbildung 4: Querschnitt durch die Modelldomäne NOORDBURGUM und GARYP. Die Filterschicht des Garyp Feldes ist durch eine vertikale, strichlierte Linie wiedergegeben. Die Lage des Querschnitts ist in der Überblicksdarstellung (im Bild rechts unten) gezeigt (after Menkveld, 2013)

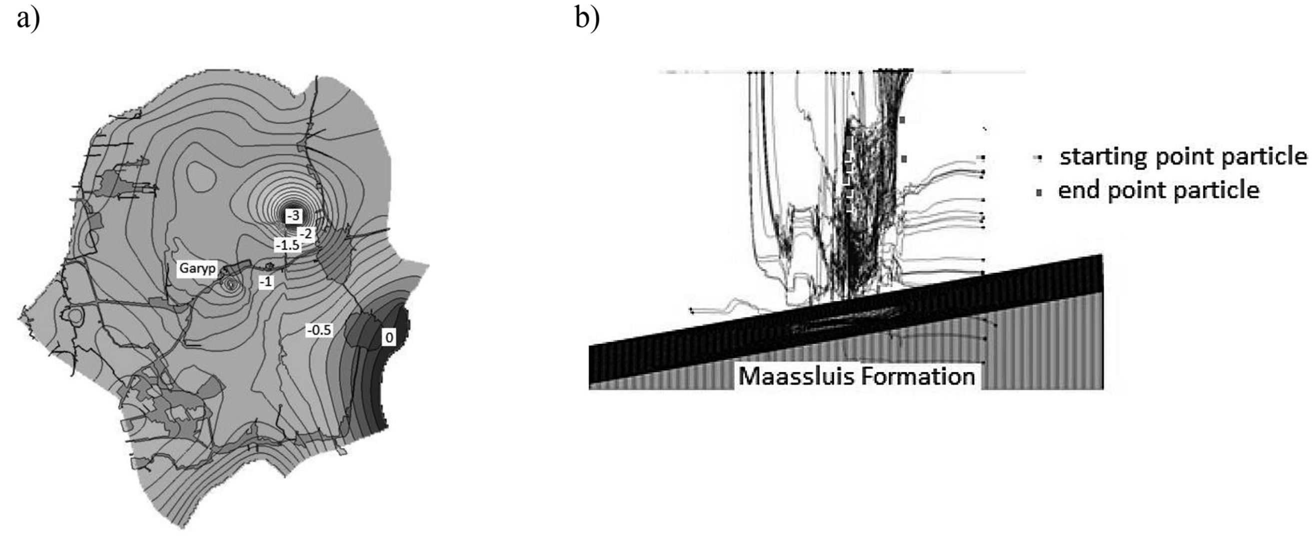


Figure 5: a) steady state modelled isohypses calculated by using combined GARYP/NOORDBURGUM model, and b) some flow routes in an east-west cross section plane

Abbildung 5: a) Stationär modellierte Grundwasserisolinien mittels kombiniertem GARYP/NOORDBURGUM Model. b) Fließwege im Ost-West-Querschnitt

water abstraction from deep (saline) aquifers, i.e. Maassluis complex. The modelled steady state groundwater heads (Figure 5a) mimic the measured hydraulic head pattern around Garyp (Figure 2). In Figure 5b a cross section plane is given. The hydrogeological setup follows the cross section as indicated in Figure 5. The upper aquifers are made transparent. Some particles start at the eastern boundary, some from the surface water system (Friese Boezem) and also some from the deeper saline Maassluis complex (Figure 3). This indicates that indeed part of the abstracted drinking water is coming from Maassluis Formation.

Three possible scenarios were proposed which could immediately be implemented at the Garyp well field:

1) shutting down two of in total six wells (leaving the wells in the outer corners of the well field in operation, and reducing the extraction rate from 3 $10^6$ $m^3$ $year^{-1}$ to 2 $10^6$ $m^3$ $year^{-1}$),
2) reducing overall extraction rate in Garyp from 3 $10^6$ $m^3$ $year^{-1}$ to 2 $10^6$ $m^3$ $year^{-1}$, by reducing the extraction in all six wells, and
3) reducing well screen length from 80–130 m-msl to 80–100 m-msl, with the intention to increase the vertical distance between well screen and Maassluis complex.

Figure 6 shows the flow routes for water particles for all three scenarios. It was concluded that there were some differences in flow routes and in the relative contribution of the source but that in all scenarios a significant amount of water was still abstracted from the saline Maassluis complex. It was also found that glacial till from another glaciation (Saale clay, see Figure 3) acts as the main aquitard in the system. As a result, limited amounts of water can be abstracted from the upper layers. Given the abstraction rate, inevitably water will be abstracted from the brackish layers.

## 4 Conclusions

By incorporating a detailed schematisation of the erosion gully (GARYP model) in a clip (NOORDBURGUM model) of MIPWA, it could be calculated that part of the abstracted water at Garyp well field is originating from Maassluis Formation. It also could be calculated that all scenarios which can be implemented immediately at the well field do not have significant effect on the flow routes and will not lead to a reduced salinity of the abstracted water.

## References

Berendrecht, W. L., Snepvangers, J. J. J. C., Minnema, B. & Vermeulen, P. T. M. (2007): MIPWA: A methodology for interactive planning for water management. In:

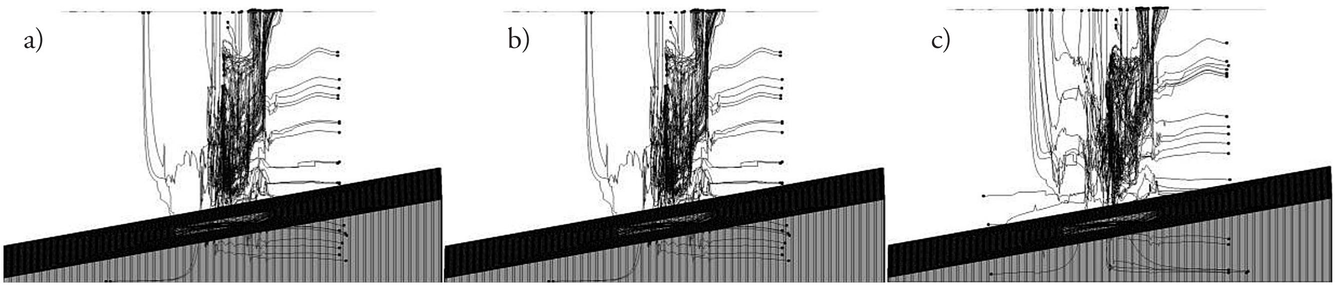


Figure 6: Flow routes in an east-west cross section for scenario a) shutting down wells, b) reducing overall extraction rate and c) reducing well screen depth

Abbildung 6: Fließwege im Ost-West-Querschnitt für die Szenarien a) Außerbetriebnahme von Brunnen, b) reduzierte Gesamtfördermenge und c) die Reduktion der Fördertiefe

Oxley and Kulsari (eds): MODSIM 2007 International Congress on modelling and simulation. Modeling and simulation society of Australia and New Zealand, Dec 2007, pp 74–80.

Bosch, J. H. A., Bakker, M. A. J., Gunnink, J. L. & Paap, B. F. (2009): Airborne electromagnetic measurements as basis for a 3D geological model of an Elsterian incision, Zeitschrift der Deutschen Geselschaft Für Geowissenschaften, 160, 249–258.

Custodio, E. (2010): Coastal aquifers of Europe: an overview. Hydrogeology Journal, 18, 269–280.

Lodder, A. & Steinweg, C. (2013a): Gebiedsdossier Noardburgum Ritskebos; Grondwaterbeschermingsgebieden in Fryslân. Royal Haskoning DHV (in Dutch), 74 pp.

Lodder, A. & Steinweg, C. (2013b): Gebiedsdossier Garyp; Grondwaterbeschermingsgebieden in Fryslân, Royal Haskoning DHV (in Dutch), 72 pp.

Huuse, M. & Lykke-Andersen, H. (2000): Overdeepened Quaternary valleys in the eastern Danish North Sea: morphology and origin. Quaternary Science reviews, 19, 1233–1253.

Menkveld, S. H. (2013): Salinization of Garyp well field, Friesland; hydrogeological investigation using GMS-MODFLOW to model the groundwater flow patterns and investigate measures to create sustainable drinking water extraction. MSc thesis, Wageningen, The Netherlands, 90 pp.

Nguyen, C. D., Araki, H., Yamanishi, H. & Koga, K. (2005): Simulation of groundwater flow and environmental effects resulting from pumping, Environmental geology, 47, 361–374.

NHI (2013): Grondwatermodeldatabank (in Dutch), gmdb.nhi.nu.

Smit, F. W. H. & Bregman, E. P. H. (2012): Buried glacial valleys as drinking water reservoirs: an assessment on function and risks in their role as drinking water reservoirs in the ice-marginal landscape of northern Europe, ENCORE project record, Province of Drenthe, Netherlands and Ärhus University, Denmark.

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