# Results documentation

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## Table of contents

# 1 Introduction

## 1.1 Problem statement

The climate in Europe is changing: socio-economically, geopolitically and not least of all environmentally. Drinking water is one of the main necessity of life and its supply as a resource is crucial to the quality of life in Europe. Scenarios in which drinking water resources are threatened can be easily thought of, as effects of pollution, increase in demand and drought. A vital resource of drinking water supply in the Rhine-Meuse Delta is the use of fresh groundwater reservoirs in the dunes.

In anticipation of future scenarios and ensure the robustness of the drinking water supply in the dunes of The Hague (Meijendel-Berkheide), Dunea (the drinking water supplier) sought out to investigate the feasibility of the extraction of brackish groundwater as an additional resource. A state-of-the-art model has been created that can simulate groundwater flow in the dune area of the Hague.

The use of this model is prone to some impracticalities and uncertainties. The impracticalities are related to its limited application possibilities due to its large calculation times. The current model has an average calculation time of 1 hour per year of geohydrological simulation in the domain. To run a paleohydrological reconstruction with this model for a 1000 year run (not an uncommon timescale for a geohydrological model), this would require a calculation time of 41 days using powerful computation by Amazon Web Services. Another issue with the model is that is has only been calibrated on hydrualic head data obtained from groundwater monitoring, effectively overlooking the variable density flows that occurr in fresh-saline groundwatersystems. Therefore, it's use as a state-of-the-art model for fresh-saline groundwater interactions can be questioned since it has not been tested on fresh-saline groundwater interactions through variable density flow.

## 1.2 Scientific relevance

This location's geohydrology is particularly suitable for investigation because of rapidly changing conditions (on a geohydrological timescale) it has submitted to. A fresh-saline groundwater distribution naturally develops over a long timescale (>100y). In this area, upconing of saline groundwater occurred in the 1950s due to excessive exfiltration of groundwater for drinking water supply. Consequently, the recharge of fresh groundwater had to be restored and improved by means of engineering. Infiltration ponds and a pipeline to pump water from Meuse to the reservoir were installed to enhance infiltration.

Moreover, geohydrological and geochemical conditions in this area have been closely monitored and rigorously studied. An elaborate geochemical study has been conducted by (Stuyfzand, 1993). Here he presents a spatial distribution of the subsufrace in the study area, in which various groundwater regions are distinguished by salinity and origin. The latter's added value is the designation of a groundwater region whose origin is artificial infiltration, in other words a valuation of the shape and size of the water which infiltration artificially in the dune area since the 1950s. (see Figure 1)

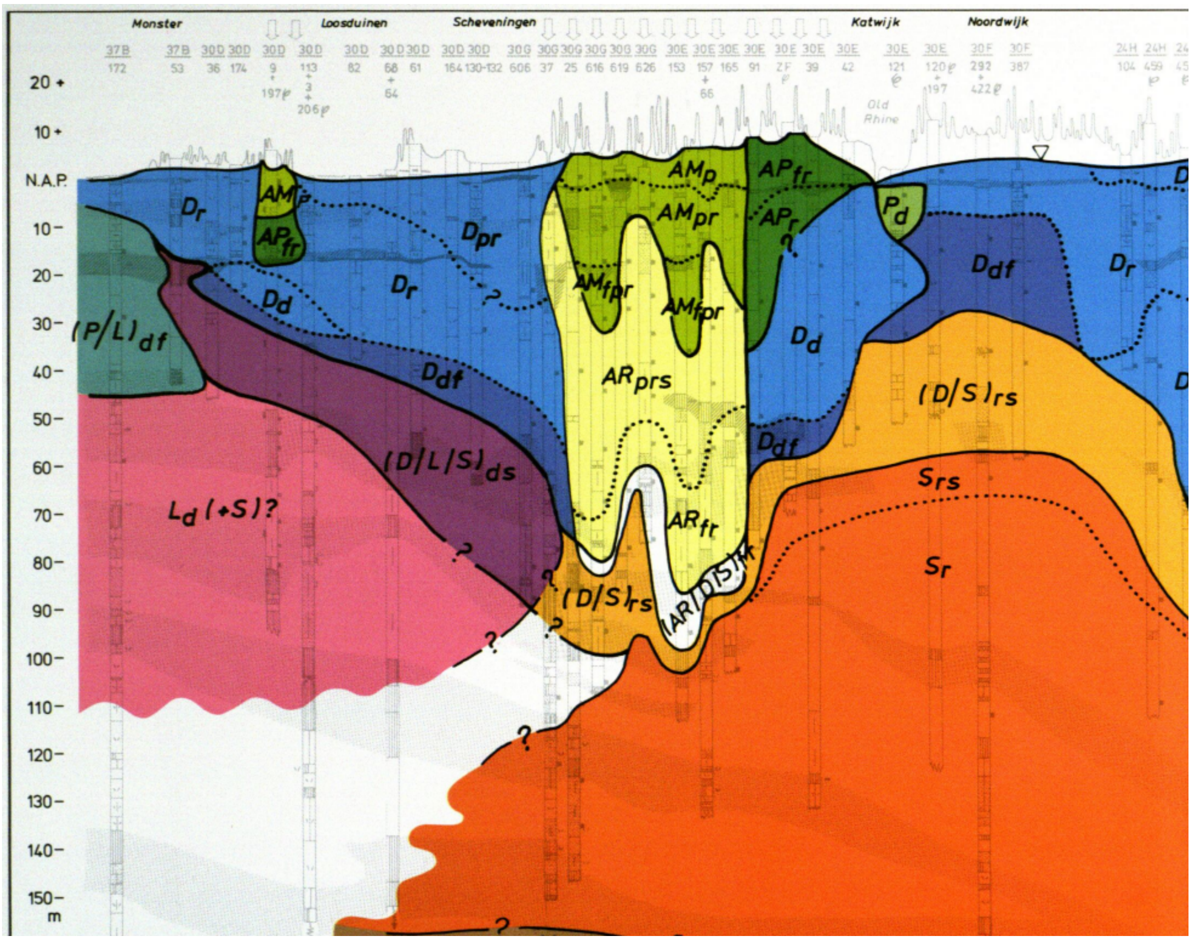



Figure 1: Cross section along coastline (Stuyfzand, 1993). Green corresponds to the artificial infiltration in the Hague dune area, blue:freshwater infiltrated through dunes, yellow:brackish grounwater, orange:saline groundwater

These conditions present an opportunity to study various features of drinking water resources in the dunes and of fresh-saline groundwater distributions and drinking water resources. Besides validation of the existing groundwater model, this research can shed light on the timescale over which a freshwater resource can develop, with human intervention. This question is particularly interesting to scenarios where the recharge of the fresh groundwater reservoir is limited for an amount of time.

### 1.3 Objective

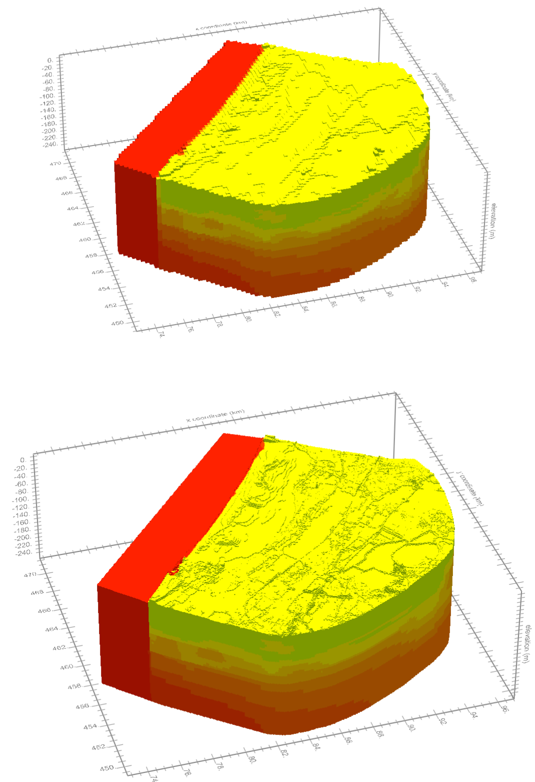
The goal is to assess the current knowledge of fresh-saline groundwater distributions by improving a state-of-the-art groundwater model for the Meijendel-Berkheijde drinking water reservoir, and to explore applications and improvements of fresh-saline groundwater modelling in this study area.

## 2 Method

To validate the model and to simulate scenarios and reconstructions, the model's practicality must be increased. This can be done by constructing a new model (Metamodel, MM) which has a lower calculation time, while still accurate to the original model's (OM) outputs. This metamodel's output can be calibrated to the OM's output by running parralel simulations and investigating the discrepancies between the obtained hydraulic head distributions and water balances (cell budgets), which can be quantified by a mean error. The spatial distribution of this error is of importance since the main area of interest is in the dunes itself, the rest of the domain functions as boundary condition to the flow of groundwater inside the study area.

A parallel simulation of the OM and MM are compared, based on the available data from an earlier simulation by the OM. This simulation had a certain starting head and starting concentration, along with a simulation time of 39 years (and a set of secondary boundary conditions). The starting concentration can be seen in figure 2.

After the metamodel's output is sufficiently accurate to the OM, it can be used to run further simulations and investigate the fresh-saline behaviour. This will be done by investigating the fresh-saline interface, it's development depth over time and finally, by recreating the origin distributions as presented by (Stuyfzand, 1993). If the model shows similar groundwater distribtions, this can hint at the soundness of the current understanding of the fresh-saline groundwater interactions. The geochemical analysis of (Stuyfzand, 1993) will be reconstructed with the use of "species" inside the concentration dimension in the MM. Various freshwater origins can be represented, by applying a species to a specific boundary condition. Artificial Infiltration through the infiltration ponds can be distinguished from other freshwater infiltrations in this way, to represent the geochemical tracers that Stuyfzand used to trace back the origin of groundwater in the subsurface.



Starting [Cl$^-$] of the parallel 39y simulations. Red : Saline groundwater, Yellow : Fresh groundwater

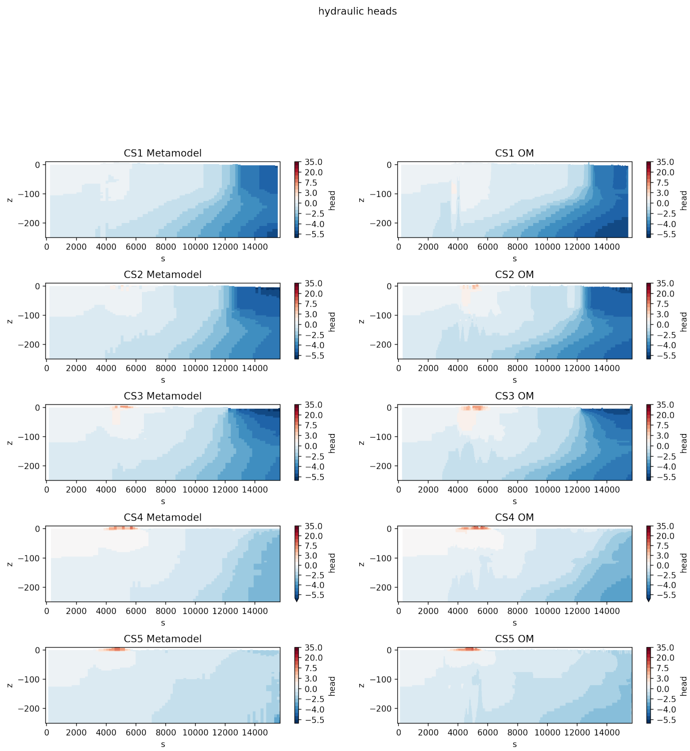



Figure 2: Cross sections of MM and original model. Errors: (entire domain: 0.029m),(study area: -0.056m)

# 3 Results

## 3.1 1. Hydraulic heads

### 3.1.1 Cross sections of distribution

## 3.2 Observations

- Looking at the cross sections, the main features of the hydraulic head gradient in the OM seem to be represented by the MM's output
- The model has a lower accuracy in the study area than in the entire domain. It's average error in the study area is about -5.6cm.

## 3.3 2. Budgets

### 3.3.1 Plots

### 3.3.2 Observations

- Plots: The shape of the coastline can be seen in the plots for drn and riv errors

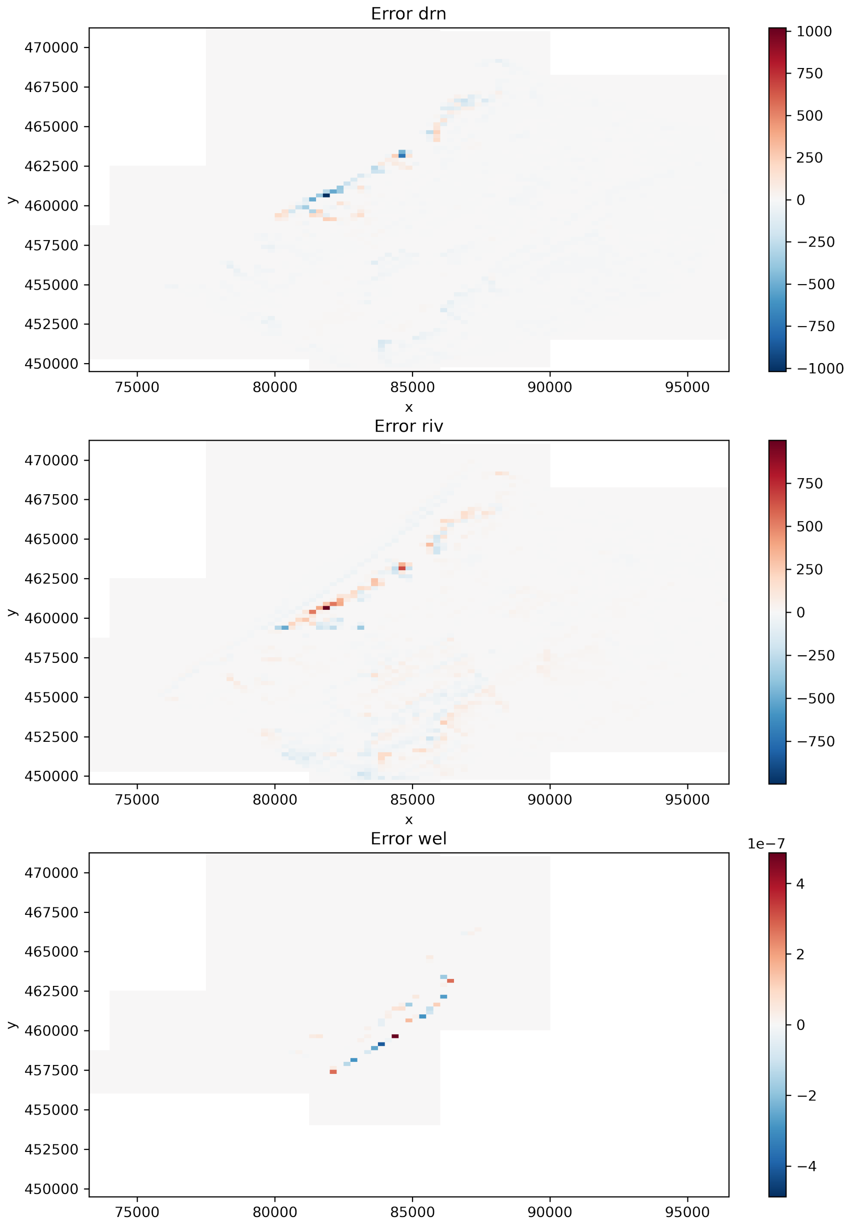



Figure 3: Budget errors: (river:1.80m$^3$ entire domain), (drain: -2.56m$^3$ entire domain), (budget well error = -1.58e-10m$^3$ entire domain)

## 3.4 3. Groundwater salinity

### 3.4.1 Cross sections [Cl-]

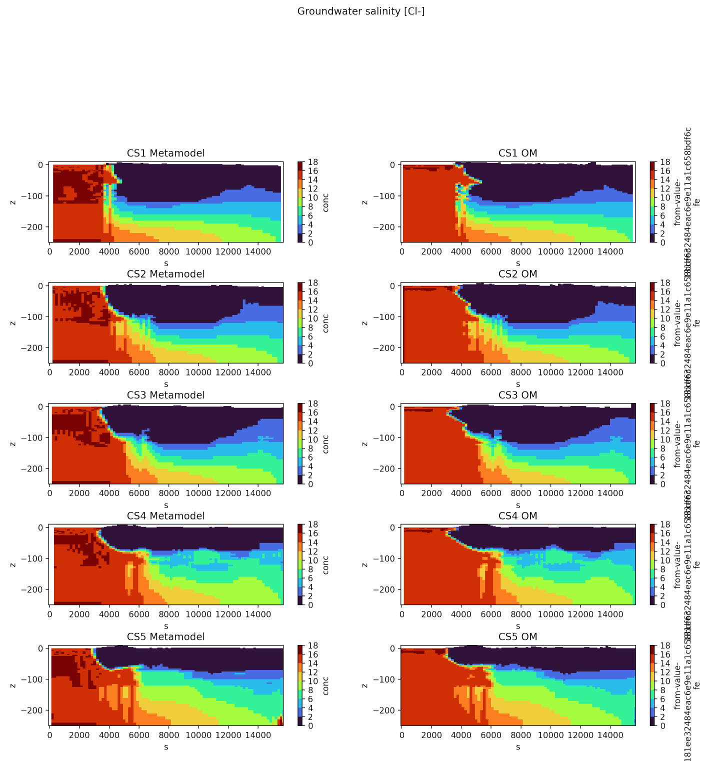



Figure 4: MM cross sections. Errors: (-0.08 [g/l] entire domain), (-0.48 [g/l]) study area)

### 3.4.2 Depth of fresh-saline interface

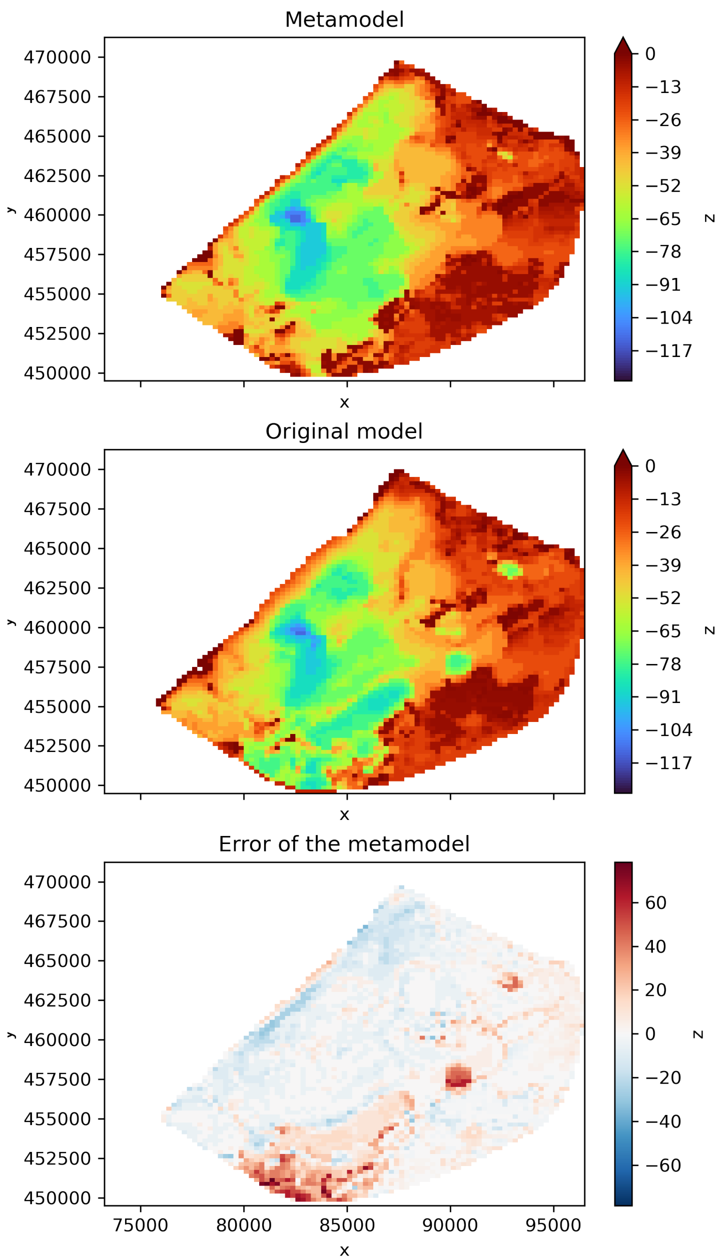
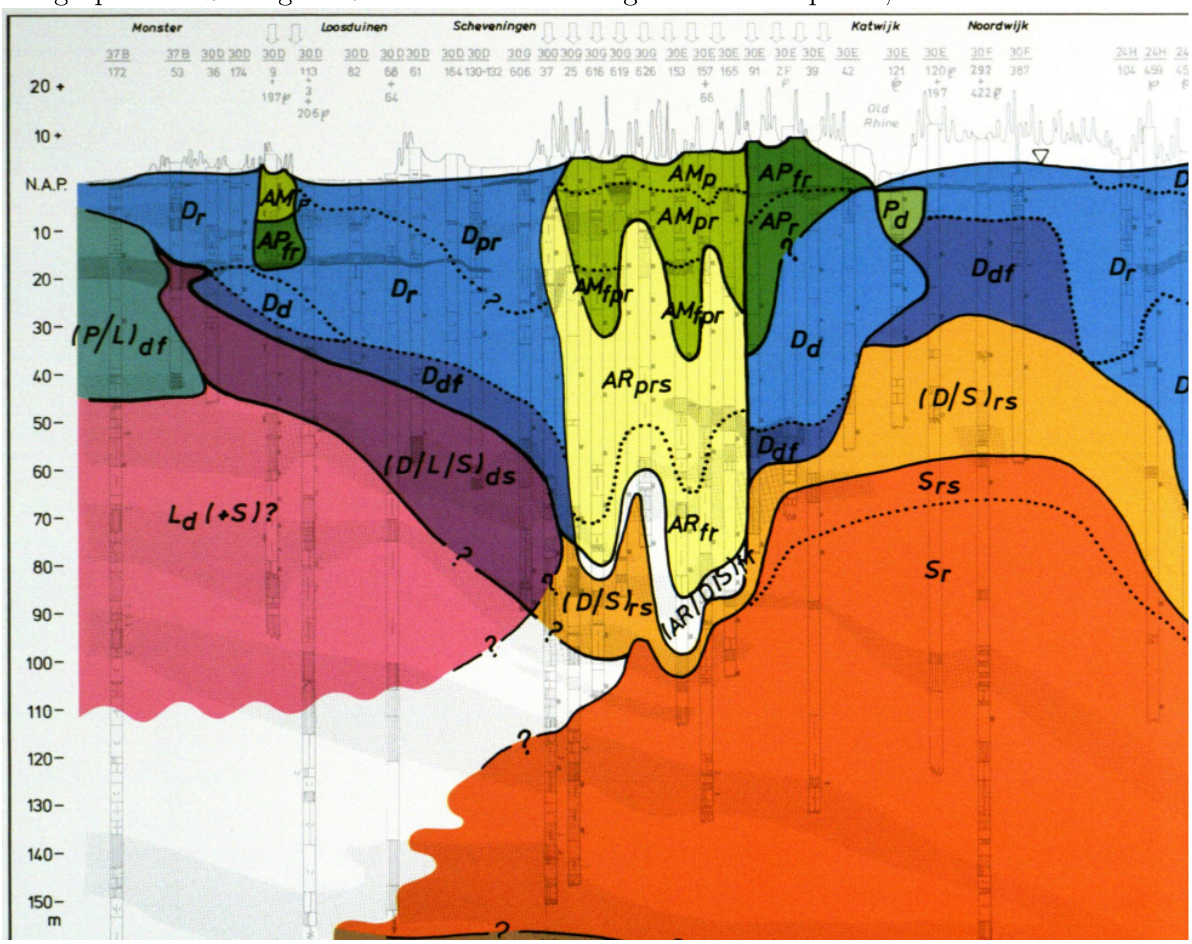
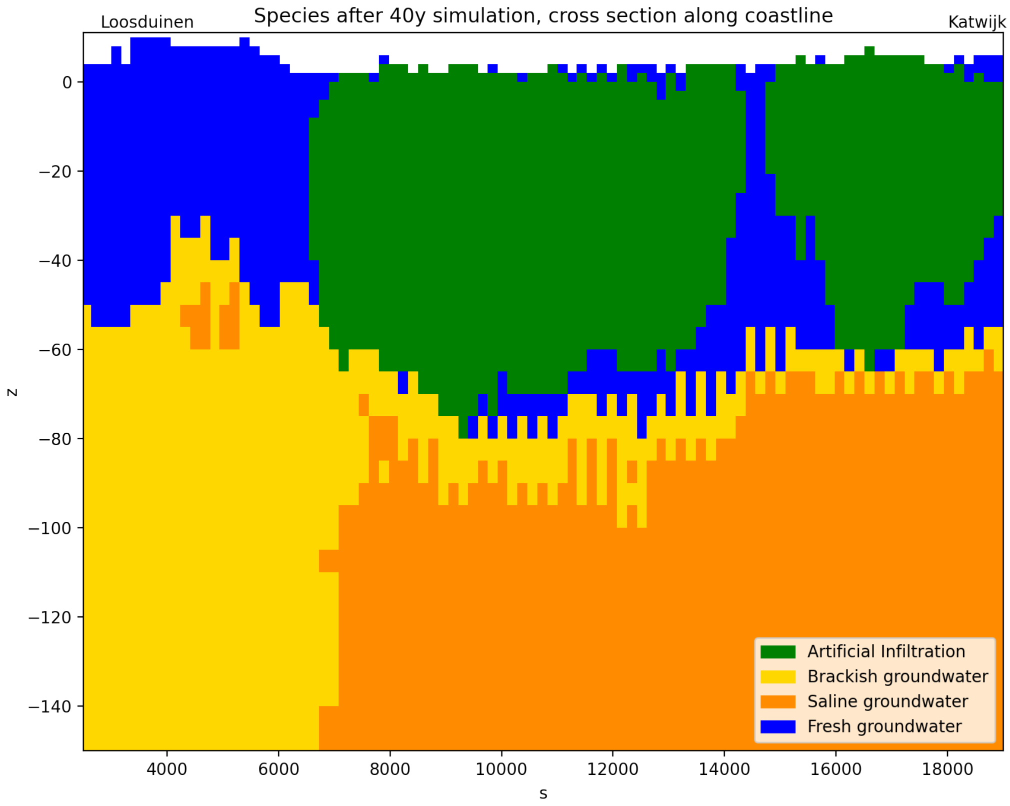



Figure 5: Depth of fresh-saline interface. Errors: (1.73m entire domain), (-7.09m study area)

### 3.4.3 Cross section along coastline

In his geochemical analysis, (Stuyfzand, 1993) provided a series of cross sections through the dune area of the Netherlands. In figure 5, a part of this cross section can be seen. With the use of species, the effect of geochemical tracers can be simulated in iMOD-WQ using species. See figure 6 for the calculated groundwater species, or tracer distribution.




Species after 40y simulation, cross section along coastline
Loosduinen
Katwijk
0
−20
−40
−60
−80
−100
−120
−140
z
4000
6000
8000
10000
12000
14000
16000
18000
s
Artificial Infiltration
Brackish groundwater
Saline groundwater
Fresh groundwater

### 3.4.4 Observations

Table 1: Overview of the errors of the MM when running a parralel simulaiton with the existing OM runs.

| Sanity Check | Study Area | Total Area | Unit |
|---|---|---|---|
| Heads | -0.056 | 0.0289 | m |
| budgets: river | | -2.60 | $m^3$ |
| budgets: drain | | 1.80 | $m^3$ |
| Depth f/s | -7.09 | 1.73 | m |
| [$Cl^-$] | -0.08232 | -0.48 | [g/l] |

- Cross sections: The main features are represented by the output of the MM. The intrusion of salt water is represented in the MM, the shape of the freshwater is also reproduced by the MM.
- Depth interface plots: near the coastline in the study area, it can be seen that the depth of the fresh-saline interface is deeper in the MM than in the OM
- Species/tracers: The depth of artificial infiltration of the MM reaches a depth of 80m after a simulation time of 39 years. In Stuyfzand's analysis, the artificial recharge reaches a depth of 90m.

## 4 Discussion

- Currently, the heads calculated by the MM inside the study area are about 6cm lower than the OM and the error of depth of the fresh-saline interface (1.73m entire domain, -7.09m SA). This may be due to the error in hydraulic heads

Further steps to take:

- The species plot gives insight in the velocity of artificial infiltration. To further investigate the timescale for the infiltration to reach a steady state, plots will be made on which the depth of the fresh-saline interface is plotted vs time. This may hint at the actual timescale of a freshwater reservoir to form/recharge. These plots will also give insight in the accuracy of the MM with the OM, a crucial step to test the state of the art knowledge.
- Reconstruction of saltwater upconing in the 1950s by setting the starting groundwater salinity in the dune area to fully saline and investigate the obtained distribution after a 40y simulation (1950 up to 1990).
- Sensitivity analysis of the MM to conductivity in the dune area. This may give a range of acceptable intercell conductances and provide insight in the OM's sensityvity to conductances.

- Change type of numerical solver from VDF (Variable Density Flow) to MoC (Method of Characteristics), describe the results