Hydrological history of Amsterdam Water Supply Dunes simulated with a 2D cross-section model

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ABSTRACT

To allow sufficiently reliable inference of feasibility of future seasonal storage of fresh water in the aquifers below the Amsterdam Water Supply Dunes (AWD), the entire hydrological history of the drinking water production in the Amsterdam Water Supply Dunes since 1853 has been simulated with a 2D cross-section groundwater model. The 2D model was extracted from the existing 3D groundwater model and its calibration was exclusively based on that of its parent 3D model. As the 2D model yielded semi-quantative insights until then unavailable with the 3D model, additional calibration and validation was started, in turn yielding information on the sensitivity of the present-day situation for early historical hydrological situations.

INTRODUCTION

In the course of modeling of seasonal storage of fresh water in fresh or saline aquifers below the Amsterdam Water Supply Dunes (AWD; location see Figure 1), it proved unavoidable to model the entire history of the drinking water supply abstraction since the mid-19th century including the dynamics of the fresh groundwater lens (Nienhuis and Olsthoorn, 2012, 2013). Even though that history was only modeled in a 2D cross-section, it yielded already an unintended but welcome byproduct, viz. an improved and comprehensive insight in the large-scale behavior of the fresh water lens. The overall hydrological history was already qualitatively known and had even partly been simulated and –to some extent- validated with a transient 3D-groundwater model (Kamps et al, 2006). Recent simulations of the hydrological history yielded for the first time semi-quantitative indications on relative contributions to, and effects on, the fresh groundwater lens by various historical events and on the validity of our groundwater models as regards the fresh/saline groundwater distribution under and around the AWD.

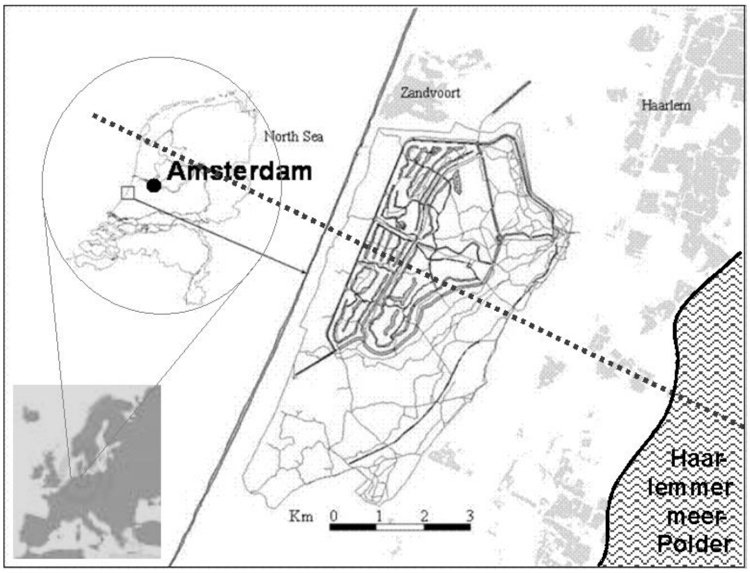

Figure 1. Location of Amsterdam Water Supply Dunes

MODEL BUILD-UP

The 2D-cross-section model was extracted from the 3D AMWADU groundwater model (Kamps, 2006). The cross-section lies perpendicular to the coast, parallel to the predominant groundwater flow direction, and extends from 3 km into the North Sea to 12 km inland (Figure 1). The movements of the fresh/saline groundwater interface (FSI) in AMWADU is based on the SWI package. As that SWI version doesn't allow the FSI to move through aquitards, nor allows generation of brackish water, the 2D cross-section model has been based on Seawat. Mflab (Olsthoorn, 2010) was used for all model manipulations.

Initially the model assumed fully saline aquifers in the entire coastal area, with only a shallow (~5 m thickness) fresh groundwater layer under the historical lake Haarlemmermeer in the East. To obtain an acceptable starting position of the fresh/saline interface under the AWD, we modeled a theoretical build-up of the freshwater lens out of precipitation starting in 1500 AD. The modeled period 1500-1850 proved sufficient (in the model) to obtain a freshwater lens in dynamic equilibrium with precipitation and other boundary conditions. From 1850 on the hydrological history was entered in the model as far as we could reconstruct it from historical data and -information.

Preliminary calibration and verification

AMWADU has extensively been calibrated as far as possible within technical and practical limitations. Historical movements of the FSI have been validated for the period 1904-2004 (Kamps et al, 2006). AMWADU's calibration was inherited as a start for the 2D cross-sectional model. We only verified the 2D-model in terms of the depth of the FSI under the AWD. It was concluded that the FSI position was simulated about 10 % too shallow (see also Nienhuis et al, 2012). At the time, this state of the calibration was found acceptable for the original purpose of the 2D model, i.e., a pre-feasibility study of future seasonal fresh water storage in and under the freshwater lens. For that purpose a much more important requirement was that the simulated FSI at the start of the simulated seasonal storage was in point equilibrium with past stresses, to mitigate model artefacts caused by the model seeking equilibrium from possible incorrectly entered starting positions of the FSI. It would be virtually impossible to distinguish such artefacts from the simulated effects of seasonal storage we were after.

Additional results

The simulations clearly show the rise of the FSI under the AWD due to overexploitation of the freshwater lens in the first half of the 20th century by wells tapping the deeper aquifers, and the recuperation of the freshwater lens after the start of infiltration of prepurified Rhine water around 1957. The 2D model allowed for the first time semi-quantative insights in hydrological phenomena that couldn't be inferred from the existing 3D model. Examples are that (1) the reclaimed lake Haarlemmermeer, where in 1850 the hydraulic potential was lowered by more than 6 meters, induced a large-scale groundwater flow system transporting saline North Sea water, beneath the freshwater lens system under the AWD, to the present-day Haarlemmermeerpolder, and (2) this saline groundwater flow system has significantly dragged the freshwater lens in eastward direction. The 2D model simulations show that because of this drag, the future equilibrium position of the FSI near the coast is significantly shallower than in 1850, hitherto rendering full recuperation of the local freshwater lens thickness to historical values unattainable. Reclamation of lake Haarlemmermeer in 1850 proved to be the dominating factor influencing groundwater flow and distribution of fresh and saline groundwater in a wide area, much more than the drinking water supply in the AWD itself, and this situation will continue a long time into the future.

CONTINUED SIMULATION STEPS

The abovementioned insights motivated further simulation steps aimed at getting a better quantitative understanding of the groundwater systems in and around the AWD.

A first attempt to calibrate the 2D model is based on comparing the simulated historical positions and movements of the FSI with historical positions inferred from chloride- and GEM-cable ("geohm cable") measurements (Kamps, 2011). Starting from the very late 19th century some scarce quantitative data are available. The data intensity grew slowly until the 1950's. From the period since 1960 a fair amount of quantitative data is available.

Based on Delsman et al (2013) the historical FSI under former lake Haarlemmermeer (before 1850) was assumed to lie at about 50-60 m below datum level. To that end the build-up of the freshwater lens from scratch was replaced by a theoretical FSI position in 1500 AD, with the FSI at the sea bottom some 200 m from the water line, from there gradually descending under the AWD to about 60 m depth, and extending horizontally at that depth to theeast of the 2D model cross-section.

RESULTS

Initial calibrations runs show that the FSI position in the first half of the 20th century is not very well simulated in the AWD. However, simulated and measured FSI positions match better starting from the 1960s onward (Figure 2). With a thicker initial fresh part of the aquifer under lake Haarlemmermeer the simulated freshwater lens under the AWD reaches greater depths.

Because the fresh groundwater initially input under former lake Haarlemmermeer in the east is hydraulically connected with the North Sea, the fresh groundwater is pushed up in the period 1500-1850. Higher potentials in lake Haarlemmermeer can be used to mitigate this effect but we have yet insufficient data to support this.

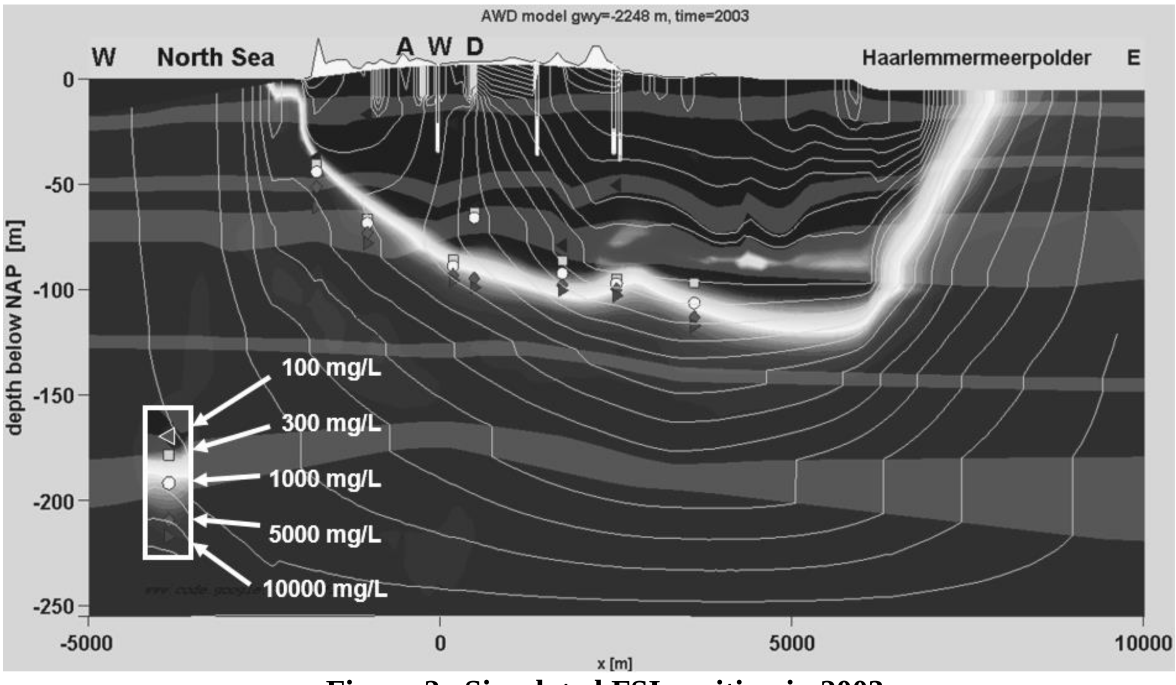

Figure 2. Simulated FSI position in 2003

DISCUSSION AND CONCLUSIONS

The strong influence of assumed FSI positions from before 1850 on the simulated present-day situation implies that the model results should be interpreted with due caution. This is not unexpected, given the long response time of the freshwater lens to changing external stresses; the response time is probably much longer than the 160+ years since 1850. On the one hand this sensitivity suggests that some imaginable historical hydrological situations are more probable than others; on the other hand there are insufficient data to validate the early hydrological history.

In spite of the great uncertainties about theexact paleo-hydrological conditions, the simulated FSI position at the end of the simulated period is reasonably in accordance with the salinity distribution inferred from chloride and GEM-cable measurements.

It seems the best we can do is concentrate on the movements and positions of the FSI in fairly recent decades, taking advantage of the fact that the earlier in history a hydrological stress occurred, the less influence it has on the current and future hydrological situations.

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