LAND SUBSIDENCE AND SEA LEVEL RISE THREATEN THE COASTAL AQUIFER OF ZUID-HOLLAND, THE NETHERLANDS

G.H.P. OUDE ESSINK[1,✉], V.E.A. POST[2], M.J.M. KUIJPER[1] and B. MINNEMA[1]

[1]Netherlands Institute of Applied Geoscience (TNO-NITG), Princetonlaan 6, 3584 CB Utrecht, The Netherlands
[2] Free University Amsterdam, Faculty of Earth and Life Sciences, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands
E-mails:g.oudeessink@nitg.tno.nl, vincent.post@falw.vu.nl,
m.kuijper@nitg.tno.nl and b.minnema@nitg.tno.nl

Abstract

Large parts of the Province Zuid-Holland, the Netherlands, are situated several metres below mean sea level. Saline groundwater from the North Sea and from deep marine fine-grained deposits intrudes the upper aquifers. Natural processes and anthropogenic events of land surface settling, that have been going on for nearly a millennium, cause the salinisation of the subsoil. In addition, future sea level rise and land subsidence are expected to jeopardise the groundwater system even more. Water managers are concerned about the future state of this dynamic groundwater system during the coming 200 years. A 3-dimensional model was constructed to quantify changes in the groundwater system. Large amounts of hydrogeological data from the national geodatabase REGIS are used to derive a calibrated model for variable-density groundwater flow and solute transport. The model predicts that past land subsidence and sea level rise will lead to an accelerated inflow of saline groundwater towards the coastal groundwater system in the next centuries. The groundwater system, especially the upper part, will contain more saline groundwater. The salt load to low-lying areas will increase, which will seriously affect surface water management in these lower parts of the Netherlands.

Keywords: Salt water intrusion, coastal aquifer, variable-density groundwater flow, sea level rise, land subsidence, three-dimensional model, The Netherlands

Introduction

The aim of the EU Water Framework Directive is that in 2015 the status of all groundwaters and surface waters must be good. Fresh groundwater bodies have to be monitored and assessed in the Province of Zuid-Holland (Figure 1). Trends in groundwater pollution have to be identified and reversed, if possible. This study is initiated by water managers of the Province of Zuid-Holland. The objective is to determine the

---

✉ Corresponding author

future distribution of fresh, brackish and saline groundwater in this coastal aquifer in the Dutch coastal zone. Salinisating and freshening processes are quantified. The effect of sea level rise and land subsidence on the regional groundwater system is assessed. A large-scale three-dimensional model was constructed to quantify the effect of future developments on this Dutch coastal aquifer under stress.

In this paper, the area of the Province of Zuid-Holland is briefly described and the development of the numerical model is presented, including the construction of the initial density distribution. Some numerical results on the impact of sea level rise and land subsidence in the dynamic groundwater system are presented. Finally, conclusions are drawn and recommendations are given.

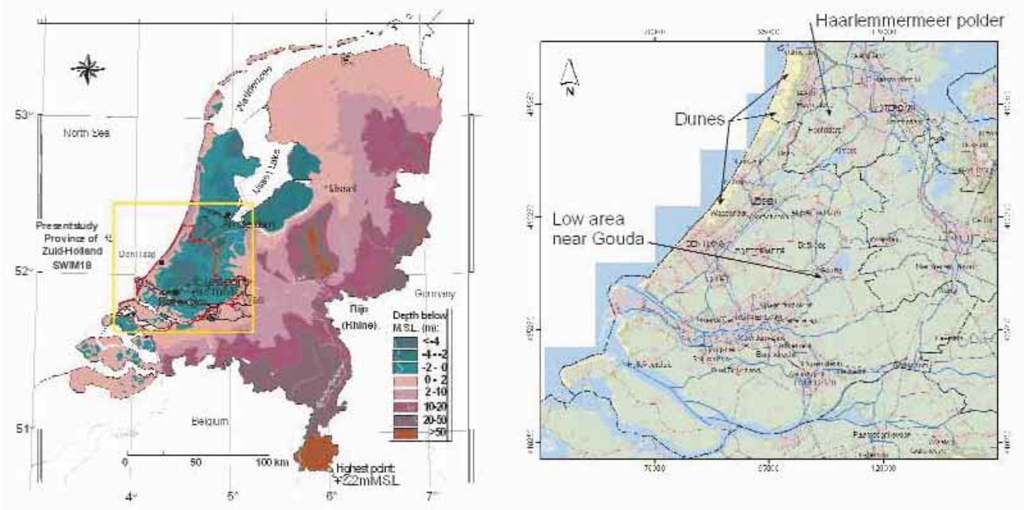

Figure 1. a) Map of the Netherlands: position of the Province of Zuid-Holland and ground surface of the Netherlands; b) Position of cities, roads and water canals in the Province.

Description of the Province of Zuid-Holland

Some 3.3 million people live in the province, with Rotterdam and Den Haag as the two largest cities. The Province is situated in the coastal zone of the Rhine, Meuse and Schelde Delta. It is located in an area with a diversity of land types such as sea, dunes, rivers, polders, peat areas and lakes. Large groundwater extractions in the dune areas and in the eastern part of the province supply the drinking-water demand. Phreatic water levels in the dune areas can go up to more than 7 meters above mean sea level. At the inland side of the dune area, low-lying polder areas with controlled water levels occur. The lowest phreatic water levels in the province itself can be found northwest of the city Gouda, down to nearly -7 m N.A.P. (N.A.P. is our national reference level and is approximately equal to Mean Sea Level, M.S.L.). This area is a peaty area with a high rate of land subsidence. Just north of the province, the Haarlemmermeer polder is situated, with levels as low as -6.5 m N.A.P. In addition, the polder Groot-Mijdrecht is mentioned here. Though the surface area of this polder is not large, the phreatic water level is low (less than -6.5 m N.A.P.) and the Holocene aquitard on top of the groundwater system is very thin. As such, seepage from the top aquifer to the surface water system in this area is very large (more than 5 mm per day) and groundwater from a large region around it is flowing towards the polder at a rapid pace.

Model design

Subsoil set-up and geometry

The numerical model predicts the movement of variable-density groundwater and coupled solute transport. The subsoil of the groundwater system has been discretised with REGIS (TNO-NITG, 1998), which is an interactive and open geohydrological application system with data on distribution, depth, thickness and hydraulic properties of individual geological layers. In our model, nine aquifers and aquitards are considered (Figure 2). The effective porosity is set equal to 30%.

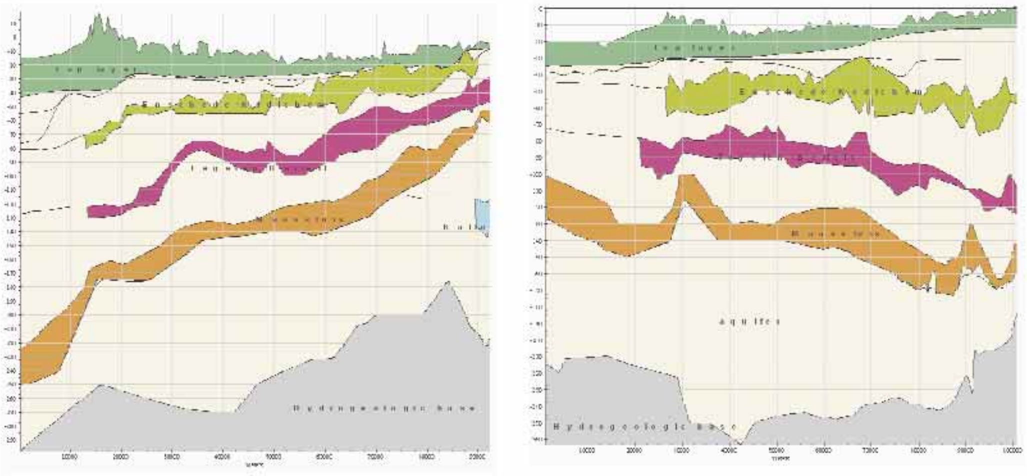

Figure 2. Two cross-sections through the model area: position and names of aquitards in the groundwater system, derived with CUS, Construction Underground Scheme (TNO-NITG, 2001).

Model set-up

The model for simulating solute transport in this variable-density groundwater system has an area of 100 by 92.5 km^2 and is maximum 300 m deep. The grid contains 370 rows, 400 columns and 40 layers. Four million cells of 250 by 250 meter are active in the model, due to the rugged coastline of the system and the irregular shape of the assumed impervious hydrogeologic base. In the vertical direction the thickness of the elements varies from 5 m for the upper twenty layers to 10 m for the deepest twenty layers. The head on top of the system is imposed through the so-called MODFLOW package 'General Head Boundary'. The applied conductances are such that the initial water levels in the polders units are the phreatic water level in the considered polders units (McDonald and Harbaugh, 1988). In the model, sea level rise and land subsidence are implemented by raising and lowering the water level in the top system in every cell in the top layer, every year, respectively. Each element initially contains eight particles, which gives in total

31.8 million particles to solve the advection term of the solute transport equation. The used computer code is based on MODFLOW and MOC3D (Konikow et al., 1996), and it takes into account variable-density groundwater flow: MOCDENS3D (Oude Essink, 1999, 2001).

The flow time step Δt to recalculate the groundwater flow equation is one year. The convergence criterion for the groundwater flow equation (freshwater head) is equal to 10^{-3} m. The above-mentioned chosen model parameters are based on quite a few numerical accuracy tests. The total simulation time is 200 years.

Compared with the modelling of a part of the regional area in the previous 17th SWIM at Delft in 2002 (Oude Essink and Schaars, 2003), the following improvements of the current model have been derived: 1) the most accurate Dutch 3D subsurface schematization available is used (REGIS, TNO-NITG, 1998); 2) more (5772 instead of 1632) chloride concentration measurements are used to determine the initial density distribution; 3) a new calibration technique for freshwater heads has been used in which no limitations in the choice of the model parameters are imposed and in which measurements are allowed to optimize the model parameters (Valstar et al., 2004), and 4) a better prognosis for land subsidence during the coming 200 years. Moreover, the area is bigger: 100 x 92.5 km^2. PMWIN Pro (Chiang and Kinzelbach, 2003) is used as a pre-processor whereas TECPLOT and 'homemade' packages were used as post-processor.

Initial density distribution

An accurate density distribution is essential to derive a reliable estimation of the future distribution of fresh, brackish or saline groundwater. Unfortunately, it is not possible to just let the system set its own initial density distribution, e.g. for the year 2000 AD, by simulating the current stress situation for a very long time. The reason is that the system is at present not yet in equilibrium. The best thing would be to go back in time (e.g. thousands of years) and to simulate all relevant hydrogeological events in the past. However, this exercise is beyond the scope of this research.

As such, the modelling will start with an estimated initial density distribution at 2000 AD. This initial three-dimensional density distribution is constructed with the most recent chloride measurements in the so-called DINO database (TNO-NITG) in the area, applying the interpolation technique of Hardy (1971). The most recent 5772 chloride concentration measurements in the Province are used over the period 1867-2001 (Figure 3a). The years 1903 and 1913 attract attention by the intensive measurement campaign in the dunes. Half of the used chloride concentration measurements are from before 1960. Though these data are 'old', they still increase the reliability of the initial density distribution. At great depth, measurements are scarce (Figure 3b).

A linear equation of state couples groundwater flow and solute transport: $\rho(C)= \rho_f[1+\beta_C(C-C_0)]$, where $\rho(C)$ is groundwater density [M L^{-3}], C is the chloride concentration [M L^{-3}], and β_C is the volumetric concentration expansion gradient [L^3 M^{-1}]. The volumetric concentration expansion gradient β_C in the equation is 1.34×10^{-6} L/mg Cl^-. Saline groundwater in the lower layers does not exceed 18630 mg Cl^-/L. The corresponding density of that saline groundwater equals 1025 kg/m^3. The molecular diffusion D_m for porous media is taken equal to 10^{-9} m^2/s.

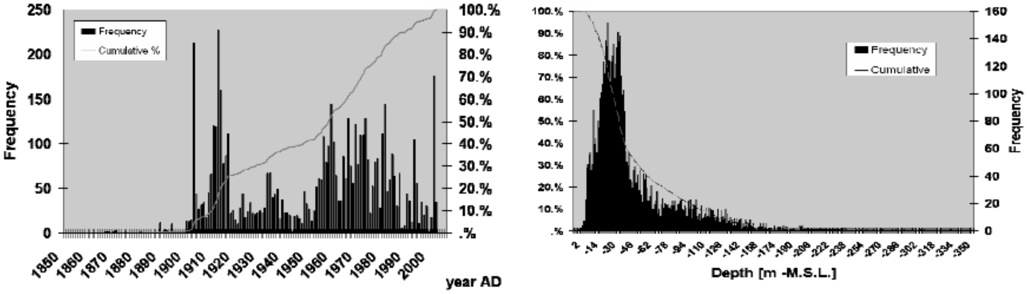

Figure 3. Histograms of chloride measurements. Left: frequency and percentage of measurements as a function of year of measurement; right: number of measurements per depth and percentage as a function of the depth. As can be deduced, measurements at greater depths are scarce (only 10% of measurements lies deeper than -100 m N.A.P.), so that the initial density distribution is less accurate there.

Scenarios of sea level rise and land subsidence

Different scenarios of future global mean sea level rise are generated by the IPCC (2001). A rise of 0.47 m between 1990-2100 with an uncertainty range from 0.09 to 0.88 m is expected to be the most likely scenario. In this study, a scenario of 0.5 m per century is used. Land subsidence is considered due to groundwater recovery, compaction and shrinkage of clay, and especially the oxidation of peat that differs from place to place (Figure 4). These last processes are not implemented in the modelling itself, but they affect the land subsidence. During this time span, the following changes are not taken into account: 1) changes in groundwater recharge in dunes due to climate change or infiltration area reduction, 2) changes in land use, and 3) changes in shoreline position due to new coastal defence systems.

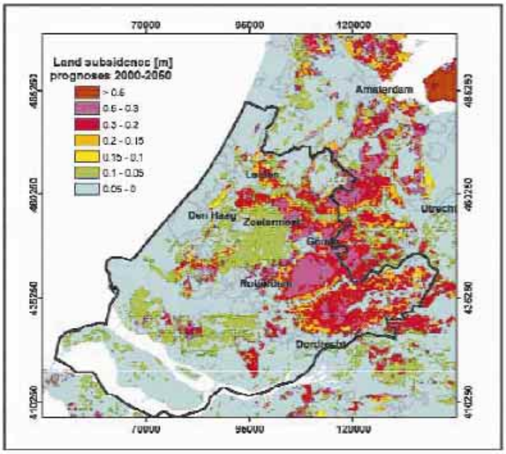

Figure 4. Land subsidence in 2050 relative to 2000 (prognosis).

Discussion

Several topics will be discussed in this paragraph about the consequences of autonomous development, sea level rise and land subsidence on the groundwater system and the distribution of fresh, brackish and saline groundwater.

Present volume freshwater body

The chloride concentrations are the highest in the western part of the area (Figure 5). The deep polders show an increased chloride concentration, relative to their surroundings. On the average, chloride concentrations increase with depth, and vary locally near large groundwater extractions. Based on the initial chloride distribution, the present freshwater volume in the Province of Zuid-Holland equals nearly 27 billion m^3 fresh groundwater (<150 Cl$^-$ mg/L). The largest part of this body is located in the eastern part of the province. The percentages of fresh, brackish (<1000 Cl$^-$ mg/L) and saline groundwater (>1000 Cl$^-$ mg/L) in the province are 36%:14%:50%, respectively.

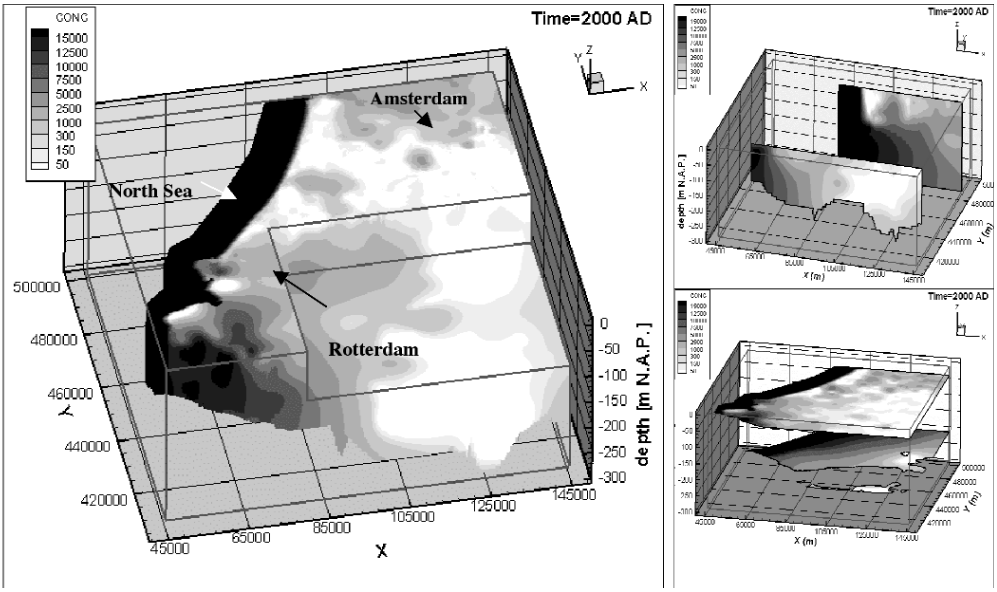

Figure 5. Initial chloride distribution [mg/L Cl$^-$] at 2000 AD, based on Hardy's interpolation technique.

Zone of influence and land subsidence

Figure 6 shows the influence of sea level rise and land subsidence on the head between 2000 and 2100 at a depth of -12.5 m N.A.P. In the first kilometres from the coastline, in the dune area, the effect of the sea level rise is noticeably. Consequently, the infiltration of the natural groundwater recharge to the aquifers decreases. The rise in freshwater head attenuates in landward direction. The effect is hardly perceptible anymore at a distance of 10 km from the coastline. Land subsidence has a regional character. At the location of the peat areas, the head lowers.

Salt water intrusion

In the entire province the seepage from the top aquifer to the surface water system increases on average some twenty percent in 200 years. Salt load increases much more, some eighty percent in 200 years, due to an increase of seepage but mainly due to higher concentrations in the top of the groundwater system. Based on the seepage and salt load figures (Figure 7), it can be deduced that local geometrical and

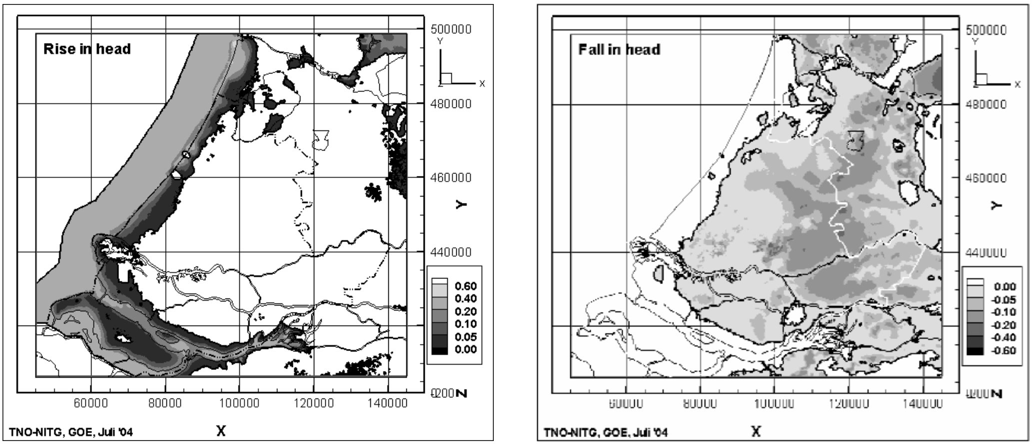

Figure 6. Influence of sea level rise and land subsidence: difference in head [m] at a depth of -12.5 m M.S.L. in 2100 relative to 2000 (modelled).

hydrological circumstances highly determine salinisation and freshening processes, which occur next to each other in the groundwater system. On one hand, a deep polder close to the sea, like the Haarlemmermeerpolder, attracts much more saline and brackish groundwater. On the other hand, in subsiding peaty areas infiltration of surface water from the high-lying (not subsiding) rivers enlarge the freshwater resources locally. In some cases, brackish groundwater is even pushed back by infiltrating fresh surface water from a river or a lake, and the upconing phenomenon will eventually vanish, as Van Dam suggested already in 1976. Simulation of chloride concentration and salt load in the polder Groot-Mijdrecht seems to support this theory.

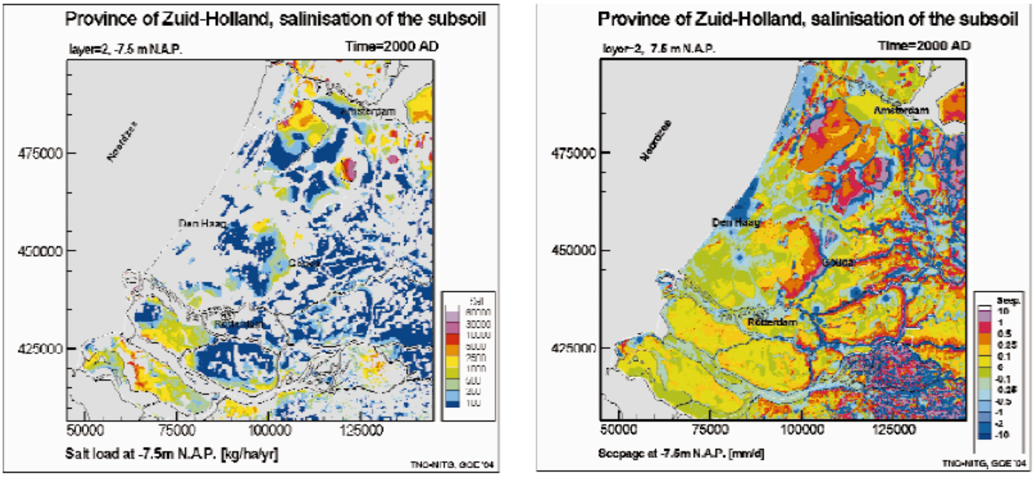

Figure 7. Seepage [mm/d] and salt load [kg/ha/yr] in the Province of Zuid-Holland. Infiltration of surface water in river canals and lakes are discretised (gray lines) in the model (cells of 250 x 250 m). Seepage is huge in the peaty area west of Gouda, as well as in the cluster of low-lying polders in south-west of Amsterdam.

Conclusions

A 3D state-of-the-art hydrogeological model has been constructed for the subsurface of the Province of Zuid-Holland. Questions asked within the EU Water Framework Directive can be answered. Freshwater resources are diminishing due to autonomous developments, sea level rise and land subsidence. On average, more saline water from the North Sea enters the coastal aquifer of the province, about thirty percent in 200 years in the model. However, the model suggests an enormous increase in salt load (plus eighty percent in 200 years) which will definitely change the present ideas of water management in this area of the Netherlands from a hydrological and socio-economical point of view.

Recommendations

This regional model can answer regional questions within the EU Water Framework Directive. However, local scale models are essential to improve the conceptual understanding of local phenomena, like the dynamics of small freshwater lenses at agricultural plots. Complex coupling with surface water models is necessary to translate the changes in the groundwater system to surface water issues like droughts, floods, safety and water quality, e.g. how will dryer summers and wetter winters effect our water management.

References

CHIANG, W.H. and W. KINZELBACH (2003). *Processing Modelflow Pro, 3D groundwater flow and transport modeling, version 7*. WebTech360.

HARDY, R.L. (1971). Multiquadric equations of topography and other irregular surfaces. J. *Geophysical Research*, 76: 1905-1915.

IPCC, Climate Change (2001). *The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Houghton, J.T.; Y. Ding; D.J. Griggs; M. Noguer; P.J. van der Linden; X. Dai; K. Maskell and C.A. Johnson (Eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881 p.

KONIKOW, L.F.; D.J. GOODE and G.Z. HORNBERGER. (1996). A three-dimensional method-of-characteristics solute-transport model (MOC3D). *U.S.G.S. Water-Resources Investigations Report 96-4267*, 87 p.

McDONALD, M.G. and A.W. HARBAUGH (1988). A modular three-dimensional finite-difference ground-water flow model. *U.S.G.S. Techniques of Water-Resources Investigations*, Book 6, Chapter A1, 586 p.

OUDE ESSINK, G.H.P. (2001). Salt water intrusion in a three-dimensional groundwater system in The Netherlands: a numerical study. *Transport in Porous Media*, 43(1): 137-158.

Oude Essink, G.H.P. (1999). Simulating 3D density dependent groundwater flow: the adapted MOC3D. In: *Proc. 15th Salt Water Intrusion Meeting*, May 1998, Ghent, Belgium, 69-79.

OUDE ESSINK, G.H.P. and SCHAARS, F. (2003). Impact of climate change on the groundwater system of the water board of Rijnland, The Netherlands. *Proc. 17th Salt Water Intrusion Meeting,* May 2002, Delft, The Netherlands: 379-392.

TNO-NITG (1998). *REGIS, Regional Geohydrological Information System*. Database TNO-NITG, Delft. (Internal).

TNO-NITG (2001). *CUS, Construction Underground Schemes, version 1.02.* TNO-NITG, Delft. (Internal).

VALSTAR, J.R.; MCLAUGHLIN, D.B.; TE STROET, C.B.M. and VAN GEER, F.C. (2004). A representer-based inverse method for groundwater flow and transport applications, *Water Resources Research*, 40, W05116.

VAN DAM, J.C. (1976). Partial depletion of saline groundwater by seepage. *Journal of Hydrology* 29: 315-339.