17th Salt water Intrusion meeting

Delft, May 6-10, 2002, The Netherlands

Salinisation of the Wieringermeerpolder, The Netherlands

Dr.ir. Gualbert Oude Essink
1. TNO-NITG (Netherlands Institute of Applied Geosciences)
Grondwater Department
Princetonlaan 6
3584 CB UTRECHT
The Netherlands
tel.: +31-(0)30-2564761
g.oudeessink@nitg.tno.nl

2. Free University of Amsterdam
Faculty of Earth Sciences
Hydrology and Hydrogeology Department
De Boelelaan 1085
1081 HV AMSTERDAM
The Netherlands
tel.: +31-(0)20-4447265
oudg@geo.vu.nl

Salinisation of the Wieringermeerpolder, The Netherlands

Gualbert H.P. Oude Essink
Netherlands Institute of Applied Geosciences (NITG), Schoemakerstraat 97, Postbus 6012, 2600 JA Delft, The Netherlands (g.oudeessink@nitg.tno.nl)
&
Free University (VU), Faculty of Earth and Life Science, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands (oudg@geo.vu.nl)

ABSTRACT

Salt water intrusion is investigated in the Wieringermeerpolder in the northern part of The Netherlands. This coastal aquifer system consists of Quaternary deposits. Ground surface of some parts of the polder is below –7 m mean sea level (M.S.L.). The saline estuary called the Waddenzee more or less borders the polder at the northern side. Saline and brackish groundwater is already present in the upper part of the hydrogeologic system. A strong saline seepage, up to several mm per day, occurs in the lowest part of the Wieringermeerpolder. A fresh surface water lake is planned in the area to improve surface water management, to reduce the effect of saline seepage on crops and ecological values. In this paper, the interest is only focussed on the design of the used model and its calibration, and on the assumed changes in seepage and salt load as a function of time. Two scenarios for the future are considered: an autonomous scenario (viz. stresses are constant in the hydrogeologic system) and a relative sea level rise scenario. A density dependent groundwater flow model has been developed in three-dimensions, making use of MOCDENS3D (Oude Essink, 1999). The dimension of the model is about 27 km by 23 km by 385 m depth, whereas over three hundred thousand elements are used to simulate the system. Numerical computations indicate that the system is in a transient situation from a salinity distribution point of view. The salinity in the top layers will increase substantially during the coming decades to centuries. In addition, a relative sea level rise of 0.75 meter per century even intensifies the salinisation, causing a dramatic increase in salt load at the surface, even within the coming 50 years.

INTRODUCTION

The Wieringermeerpolder is one of the largest polders in the Netherlands (figure 1). The polder itself has a surface area of approximately 200 km^2. The polder was reclaimed during the early 1930s. The lowest phreatic water levels in the Wieringermeerpolder itself can be found in the southeastern part of the polder, down to –7.2 m N.A.P.[1] (figure 2). The high-lying area Wieringen (ground surface up to +13 m M.S.L.) borders the Wieringermeerpolder at the northern site. It used to be an island in the estuary the Waddenzee. The IJsselmeer (formerly called the Zuiderzee) was brackish and in open connection with the North Sea till 1932. In that year, the tidal inlet was closed by a dam (the so-called Afsluitdijk) and as a consequence, the former Zuiderzee became a freshwater lake after some years, viz. the IJsselmeer. Because the phreatic groundwater level in the Wieringermeerpolder is very low and the system is close to the sea, saline and brackish groundwater flows towards the low-lying land. Right now, the upper layers of this coastal system are becoming more saline. In order to improve surface water management in the whole area, a consortium of institutes, e.g., the local water board Uitwaterende Sluizen and the Province of North-Holland, wants to investigate the effect of several technical measures. For instance, a border lake (east of the Amstel Lake area) is planned between the low-lying Wieringermeerpolder and the former island Wieringen. This border lake will affect density dependent groundwater flow in the area. For that purpose, a variable density groundwater flow model is constructed to see the effects of several geometries of the planned border lake on groundwater flow, seepage and salt load values, and, indirectly, on the production of agricultural crops and ecological values (Grontmij, 2001). Some results of this study about the groundwater flow model are shown in this paper.

First, a brief elaboration is given of the computer code MOCDENS3D that is used to simulate variable density groundwater flow. The model design of the groundwater system of the region around the Wieringermeerpolder is given next, based on subsoil parameters, model parameters and boundary conditions. Calibration of the model is discussed. The results of two future scenarios, viz. an autonomous scenario and a relative sea level rise scenario, are discussed. Finally, some conclusions are drawn.

COMPUTER CODE

MOCDENS3D (Oude Essink, 1998, 1999, 2001a, 2001b), which is the three-dimensional computer code MOC3D (Konikow *et al.*,1996) adapted for density differences, simulates the transient groundwater system as it occurs at the Wieringermeerpolder and its surroundings. The MODFLOW module solves the groundwater flow equation (McDonald and Harbaugh, 1988;

---

[1] N.A.P. stands for Normaal Amsterdams Peil. It roughly equals Mean Sea Level and is the reference level in The Netherlands.

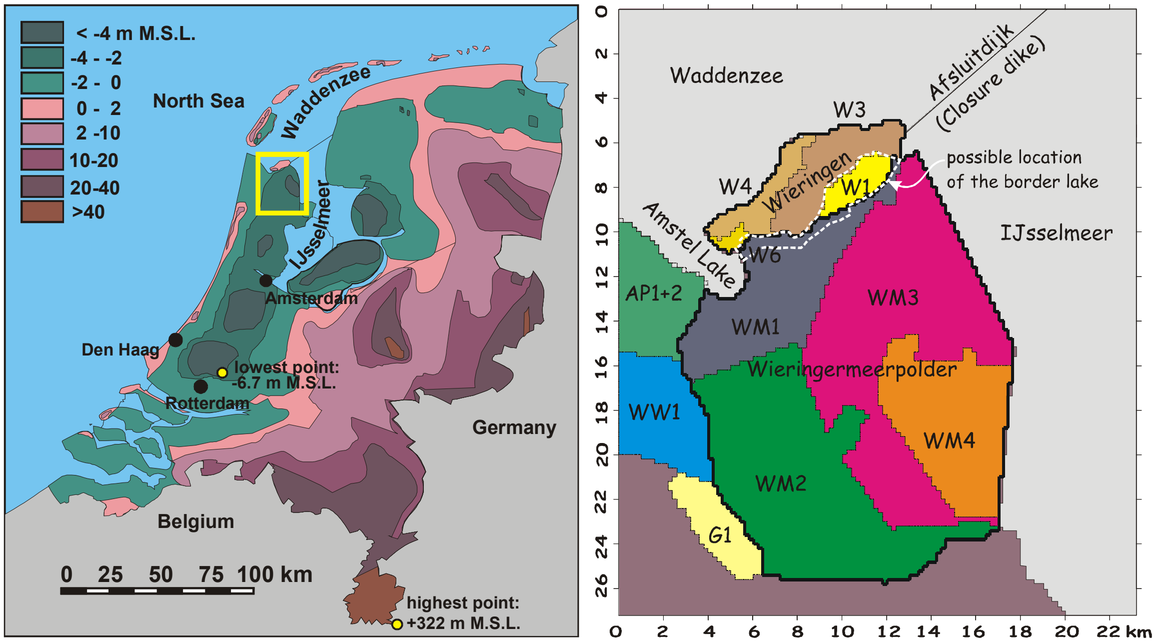

Figure 1: ***a.*** *map of The Netherlands: position of the Wieringermeerpolder and ground surface of the Netherlands;* ***b.*** *map of the Wieringermeerpolder, the former island Wieringen and its surroundings. WM1-WM4=polder units of the Wieringermeerpolder; W1-W4=polder units the former island Wieringen; AP1+2=Anna Paulowna polder; WW1=Wieringerwaard polder; and G1=Groetpolder. The possible location of the border lake is marked by the white dotted area.*

Harbaugh and McDonald, 1996). The MOC module, using the method of characteristics, solves the solute transport equation (Konikow and Bredehoeft, 1978; Konikow *et al.*, 1996).

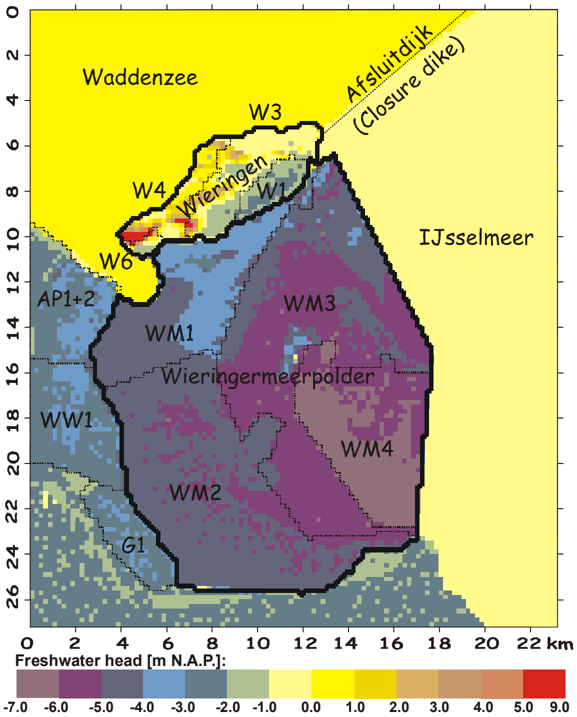

Figure 2: *Phreatic water level in the area.*

Advective transport solutes is modelled by the method of particle tracking. Dispersive transport is separately modelled by the finite difference method. A so-called freshwater head ϕ_f is introduced to take into account differences in density in the calculation of the head:

$$\phi_f = \frac{p}{\rho_f g} + z \qquad \textbf{(1)}$$

where ϕ_f is the freshwater head [L], ρ_f is the reference density, usually the density of fresh groundwater at reference chloride concentration C_0 [M L^{-3}], p is the pressure [M L^{-1} T^{-2}], and z is the elevation head [L]. A linear equation of state couples groundwater flow and solute transport:

$$\rho(C) = \rho_f [1 + \beta_C (C - C_0)] \qquad \textbf{(2)}$$

where $\rho(C)$ is the density of groundwater [M L^{-3}], C is the chloride concentration [M L^{-3}], and β_C is the volumetric concentration expansion gradient [L^3 M^{-1}].

MODEL DESIGN

The entire groundwater system consists of a 3D grid of 23.2 km by 27.2 km (~631 km^2) by 385 m depth and is divided into a number of elements. Each element is 200 m by 200 m in horizontal plane. In vertical direction the thickness of the elements varies from 2 m in the top of the system to 70 m for the lowest layers (figure 3). The grid contains 312153 active elements: n_x=116, n_y=136, n_z=22, where n_i denotes the number of elements in the i direction (some elements in the top system are not active). Each active element contains initially eight particles, which gives in total some 2.5 million particles to solve the advection term of the solute transport equation. 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^{-4} m. The above-mentioned chosen model parameters are based on numerical experience with this kind of modelling. Data has been retrieved from water board itself, ICW (1982) and the database of DINO (stands for Data and Information of the Dutch Subsurface, NITG-TNO). A large number of borehole measurements of the water board is used to determine the geological building up of the subsoil (Grontmij, 2001). The Graphical User Interface GMS is used to inter- and extrapolate the subsoil data and to convert the hydrogeologic system to the MODFLOW format. PMWIN is also used as a preprocessor whereas self-made packages were used as postprocessors. The molecular diffusion for porous media is taken equal to 10^{-9} m^2/s (though diffusion is of negligible importance).

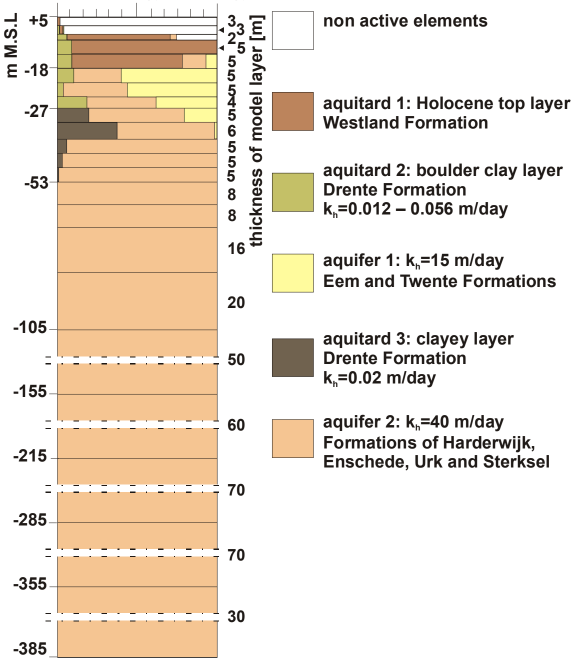

Figure 3: *Simplified subsoil composition of the bottom of the water board Uitwaterende Sluizen and hydraulic conductivity values. For each model layer, the percentage of the specific formation in question is also given.*

In the upper part of the system, several strata are present in the area, next to each other. Figure 3 shows the composition of the groundwater system into two permeable aquifers, intersected by three aquitards. For each subsystem, the interval of the used hydraulic conductivity k_x is given in figure 3. On top of the groundwater system, a Holocene aquitard is present. The vertical hydraulic resistance of this top layer depends on the thickness of the layer in question and varies from 50 to 7500 days. Below this Holocene aquitard, low-permeable layers of clayey and boulder clay composite as well as the first aquifer (k_x is 15 m/day) can be found. The hydraulic conductivity of the boulder clay aquitard also depends on its thickness, which varies in the area. For the clayey aquitard, present in the model between –27 m to –53 m N.A.P., a constant hydraulic conductivity k_x of 0.02 m/day is assumed. At the deeper part of the groundwater system (in the model everywhere present from –53 m N.A.P. to the bottom at –385 m N.A.P.), the subsurface consists of good permeable Pleistocene strata (the so-called Formations of Harderwijk, Enschede, Urk and Sterksel). The hydraulic conductivity k_x of this thick lower second aquifer is 40 m/d, which is based on several pumping tests in the area. The anisotropy ratio k_z/k_x is assumed to be 0.25 for all layers. The effective porosity n_e is a bit low: 25%. The longitudinal dispersivity α_L is set equal to 2 m, while the ratio of transversal to longitudinal dispersivity is 0.1. On the applied time scale, the specific storativity S_s [L^{-1}] to model transient groundwater flow can be set to zero.

The bottom of the system at –385 m N.A.P. is a no-flow boundary. At the top of the system, surface water management in the Wieringermeerpolder is rather complex. The inflow of fresh water in the polder system for infiltration and irrigation of agricultural land and bulb farms is separated from the outflow system of water, because saline seepage would deteriorate water quality. The so-called DRAIN, RIVER and RECHARGE packages of the MODFLOW module are applied in the model to represent interaction with the surface water system. They are present at the top of the land surface and they are uniformly spread over the area. The DRAIN water levels in the polder area differ from +12.2 m N.A.P. at the southwestern part of polder unit W4 of the high-lying Wieringen to –7.0 m N.A.P. at the southern part of polder unit WM4. The DRAIN conductances vary from 420 to 1140 m2/day and they depend on the drainage resistance and the area surface of a model element. Note that a drain in an element only drains water from the groundwater system when the computed water head is higher than the DRAIN water level; when the computed water head is lower the drain does not work. The RIVER water levels are from +11.0 m to –6.6 m N.A.P., with river conductances from 75 to 700 m2/day. This conductance value depends on distance between and width of channels/ditches, and on hydraulic conductivity and thickness of the bottom of the channel/ditch. Small seasonal fluctuations in water level are neglected. The RECHARGE package of MODFLOW is also used at the land surface, varying from 0.63 to 0.87 mm/day. The top system at the Waddenzee and the IJsselmeer are modelled in MODFLOW by using fixed heads. In the Waddenzee, the strong tidal surface water fluctuations suggests a fixed head which is somewhat higher than 'averaged' mean sea level in surface water systems with enough water depth. The reason is that at low tide, the piezometric head in the phreatic aquifer of the tidal foreland outside the land cannot follow the relatively rapid tidal surface water fluctuation. The head will be retarded which results in a higher low tide level of the sea, and thus in a higher averaged mean sea level. For the Waddenzee, the fixed head varies from 0.1 to 0.4 m N.A.P., depending on the position of bottom of the innersea and the amplitude of the tide. It is constant in time for the autonomous case, which will be described later. In the IJsselmeer, the fixed head on top of the system is equal to –0.3 m N.A.P. At the northern (Waddenzee) and eastern (IJsselmeer) vertical sea boundary sides of the model, hydrostatic conditions occur. At the western and southern vertical land boundary sides of the model, polders are present. The so-called GENERAL HEAD BOUNDARY package is used here. The conductance of the general head boundary for each land boundary side element depends on the thickness of the element. Its value is such that polders outside the modelled area are taken into account.

At the initial situation (2000 AD), the hydrogeologic system already contains a lot of saline, brackish and fresh groundwater (figure 4). On the average, the salinity increases with depth. The volumetric concentration expansion gradient β_C is 1.34 x 10^{-6} l/mg Cl$^-$. At the Waddenzee, the chloride concentration at these great depths is quite high, though saline groundwater in these lower layers does not exceed 16000 mg Cl$^-$/l. The corresponding density of that saline groundwater equals 1021.4 kg/m^3.

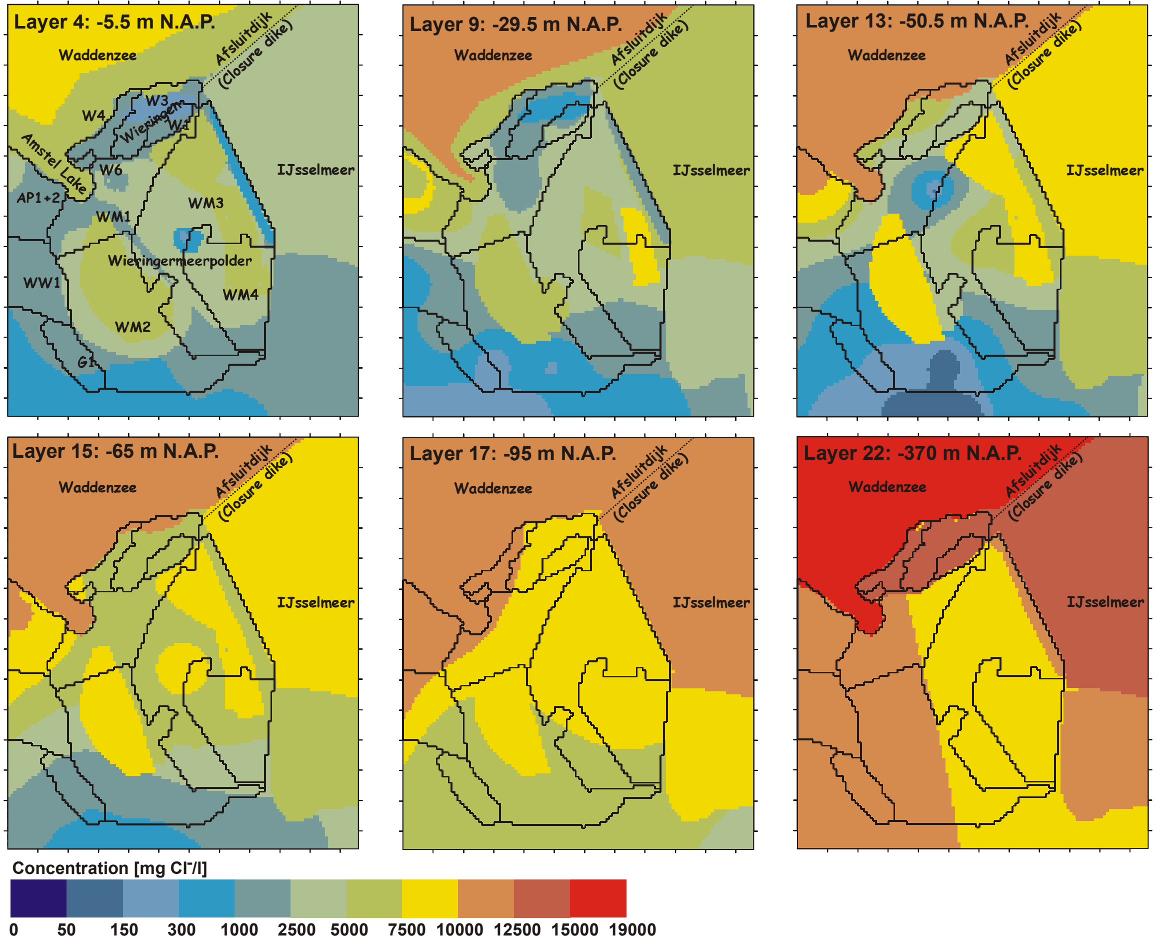

Figure 4: *Initial chloride distribution at six levels in the subsoil. The concentrations increases with depth.*

CALIBRATION

Calibration was focused on freshwater heads and chloride concentrations in the hydrogeologic system, as well as on seepage values and to some extent salt load values in all mentioned polder units. The maximum and minimum measured heads in the modelled area are +1.83 m N.A.P. in the southeastern corner of the model and –4.98 m N.A.P. at the center of the Wieringermeerpolder, respectively. The model is mainly calibrated by comparing only 95 available measured and computed freshwater heads (figure 5). Note that the measured freshwater heads are corrected for density differences. The mean absolute error between measured and computed freshwater heads is 0.37 m and the standard deviation 0.47 m. Though this value looks small, the difference between measured and computed head is sometimes quite large, partly due to the complexity of the top system and partly due to an inaccurate initial density distribution. The latter reason is as follows: the 3D density matrix, with values in over three hundred thousand elements, is based on a GMS inter-and extrapolation with only 95 measurements of chloride concentration (a linear relation between chloride concentration and density is assumed). As such, errors in this matrix are easily created. Those errors directly affect the computed freshwater heads and velocity field. For instance, it is very likely that quite a few density inversions between saline and fresh groundwater, which in reality do exist in the system (e.g. in aquitards), are not inserted in the 3D density matrix, as 95 chloride concentration measurements are not enough to detect these density inversions. Nevertheless, the mean absolute error seems to be rather limited, knowing that no automated parameter estimation has been used yet. Figure 6 shows the calibrated phreatic water levels in the area at the top four model layers.

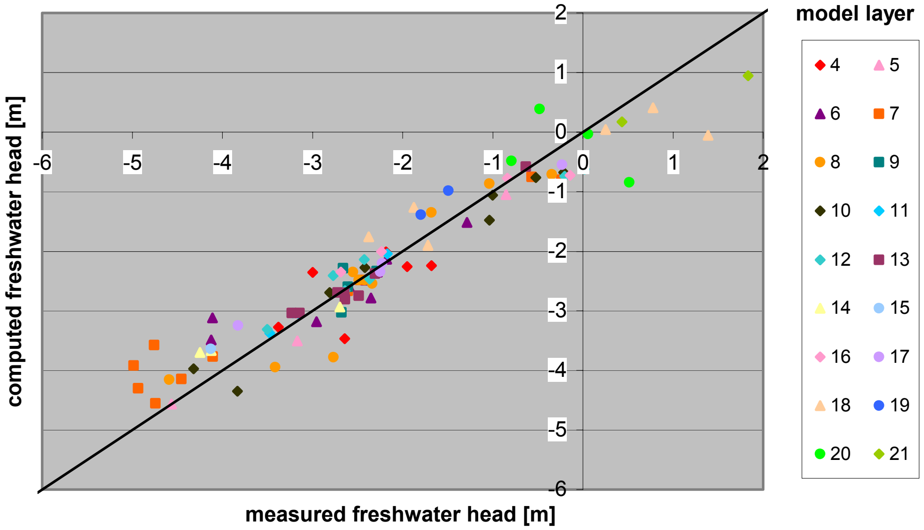

Figure 5: Measured versus computed freshwater heads [m] In the first three model layers, no measured heads are present.

Based on the computed heads and the used hydraulic conductivities in the system, seepage values are deduced for each element. The seepage values of the fourth model layer at –8 m N.A.P. is considered from now on. The seepage values for each polder unit are given in figure 7a (values per model element) and in table 1 (summarised per unit). Computed seepage values in the low-lying polder units can be quite high (up to some -10.1 mm/day in the polder unit WM3 of the Wieringermeerpolder, see figure 7a). The accuracy for the estimated seepage values per polder unit is deduced from several studies (Grontmij, 2001; ICW, 1982). These studies indicate that the values are not really consistent (table 1). On top of that, the lack of detailed and exact information of the resistance of the Holocene top layer is very likely causing a number of misfits. Sometimes, the computed seepage values are rather inaccurate and questionable, even more than head values. Obviously, the hydraulic resistance of the Holocene aquitard directly influences seepage and salt load values of the polder units, and the hydraulic resistance is difficult to determine. Furthermore, the size of the element could possibly be too coarse to fully take into account the so-called dike seepage between the high lying IJsselmeer and the adjacent low-lying polder units WM3 and WM4. Relative errors in the polder units WW1, G1 and AP1+2 can occur easily as the absolute seepage values are low.

The salt load is obviously high too, with values up to more than 205,000 kg/ha/year in an element of polder unit WM3 (see figure 7b and table 1).

The mean absolute error between measured and computed chloride concentrations of the 95 measurements points is 610 mg Cl^-/l and the standard deviation 1057 mg Cl^-/l (see figure 8). In the original model, the 3D concentration matrix was constructed with GMS by inter- and extrapolation of the 95 known chloride measurements. Before calibration, the 95 computed chloride concentration obviously perfectly fitted the measured values. However, after analysing the initial 3D concentration matrix, quite a few inversions of saline and brackish groundwater were found in the hydrogeologic system, even in good permeable aquifers, which is very unlikely to occur. The reason for this (partly numerical) phenomenon is the inter- and extrapolation of the 3D density and concentration matrix. Errors in assigning a concentration and thus density to an element can very easily occur, especially in the lower layers where chloride measurements are scarce, e.g. only eight measurements for the bottom four layers. By analysing the numerical velocity field in cross-sections, it could be deduced whether or not some saline-brackish inversions are likely or not. See figure 11, at t=2000 AD and its caption to clarify some details. In addition, during the calibration process, the chloride concentrations at specific places in the upper layers were changed sometimes to improve calibration of especially salt load values in the different polder units. As a consequence of the abovementioned reasons, (sometimes rather significant) discrepancies between measured and computed values do exist.

Note that no numerical 'Peclet' problems (viz. over- and undershooting of respectively maximum and minimum inserted concentration values) occurred during the simulations of groundwater flow and solute transport because of the chosen numerical technique of the method of characteristics (Oude Essink and Boekelman, 1996).

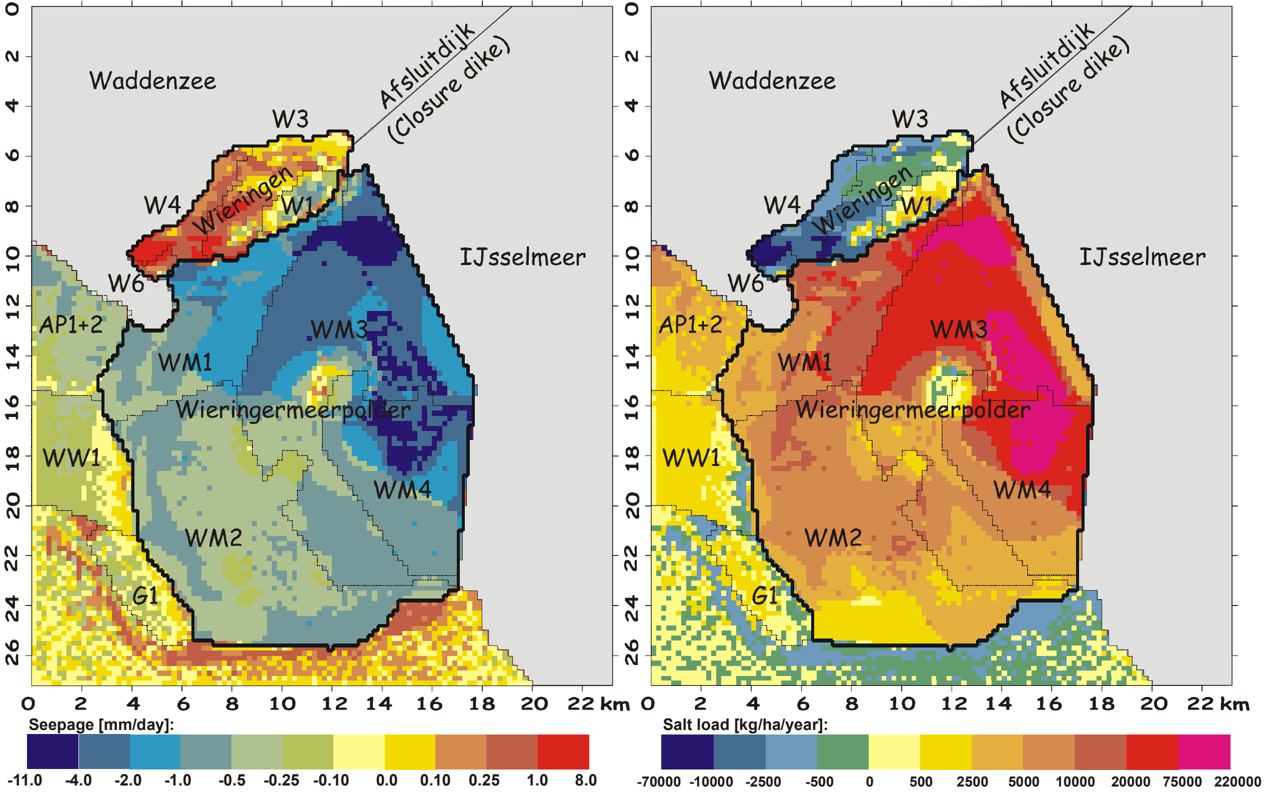

Figure 7: *Seepage (in mm/day) and salt load (in kg/ha/year) at –10 m N.A.P. for the present situation (2000 AD).*

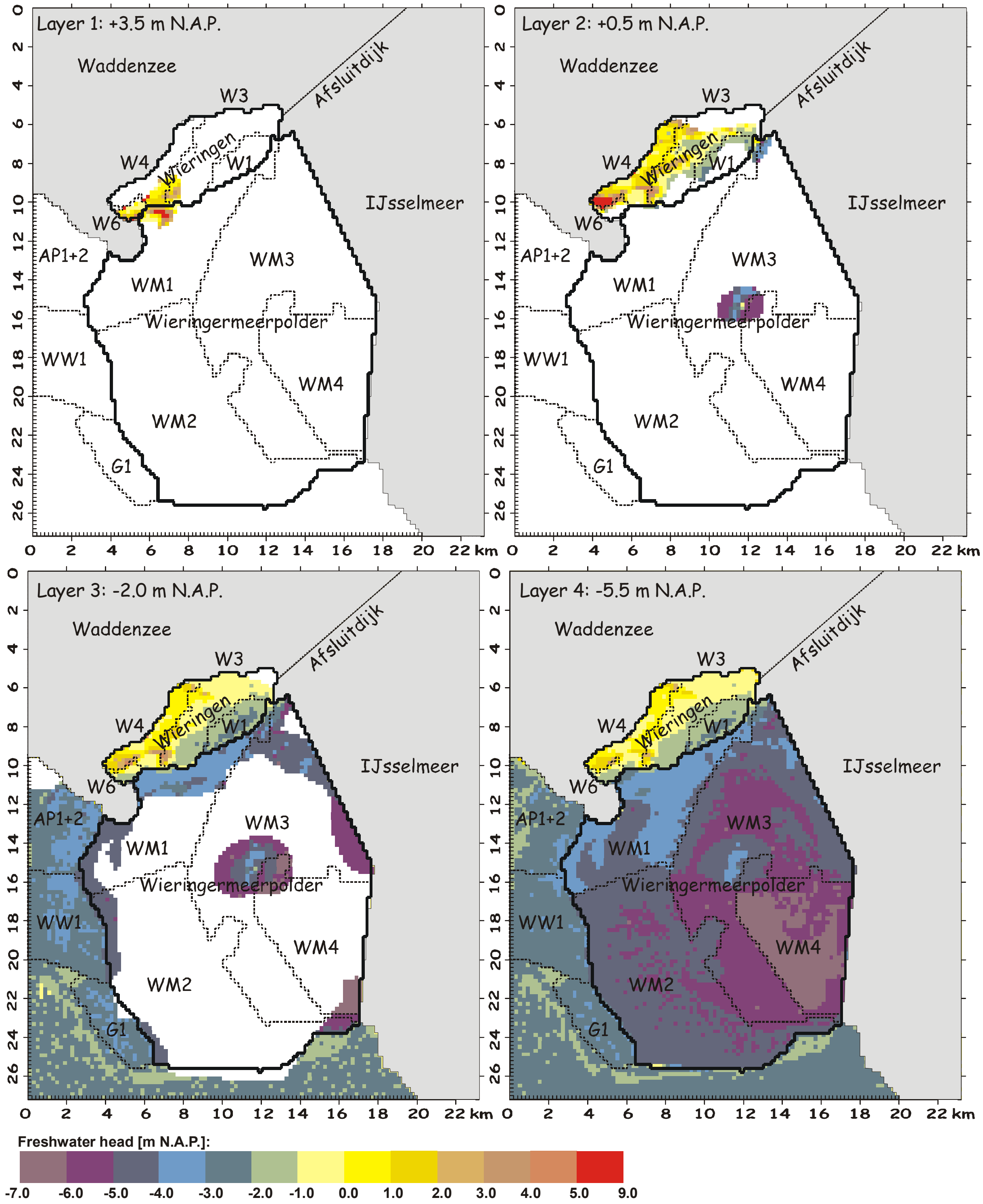

Figure 6: *Calculated phreatic water levels in the area in the top four model layers at 2000 AD. Due to the difference in ground surface elevation, especially between the Wieringermeer polder and the former island Wieringen, the top three layers contain a significant number of inactive elements (in white).*

Polder unit	estimated seepage, including accuracy (mm/day)		computed seepage (mm/day)	estimated average chloride conc. (mg Cl^-/l)	estimated average salt load (ton Cl^-/yr)	computed salt load (ton Cl^-/yr)	(kg Cl^-/ha/yr)
Wieringermeerpolder (19950 ha)	1.45	+/- 0.05	1.43		481776	459153	23015
WM 1+2	1.00	+/- 0.1	0.71	4500	156933	83423	8737
WM 3+4	1.90	+/- 0.1	2.12	4500	324843	375730	36121
WM 1 (3180 ha)	0.75	+/- 0.5	1.17			45755	14388
WM 2 (6368 ha)	1.25	+/- 0.5	0.48			37668	5915
WM 3 (7102 ha)	1.70	+/- 0.1	2.20			263483	37100
WM 4 (3300 ha)	2.35	+/- 0.2	1.92			112248	34015
WW1: Wieringerwaard (2530 ha)	0.15	+/- 0.1	0.17	5000	6931	1713	677
G1: Groet (884 ha)	0.40	+/- 0.2	0.16	800	1033	629	712
AP1+2: Anna Paulona polder (1850 ha)	0.35	+/- 0.25	0.36	5000	11825	5587	3020
Wieringen							
W1: Waard Nieuwland (463 ha)	1.50	+/- 1.5	0.25	1000	2537	309	667
W3: Hyppolytushoef (703 ha)	0.20	+/- 0.05	0.01	1200	616	67	95
W4: Hoelm (565 ha)	0	+/- 0.2	0.00	1600	0	0	0
W6: Haukes (109 ha)	0	+/- 0.2	0.02	2200	0	14	128

Table 1: *Seepage (in mm/day), and salt load (in ton/year) at –8 m N.A.P. for the present situation (2000 AD): estimated values (Grontmij, 2001) versus computed values. Estimated salt load values are based on average chloride oncentrations of seepage water in the specific polder unit.*

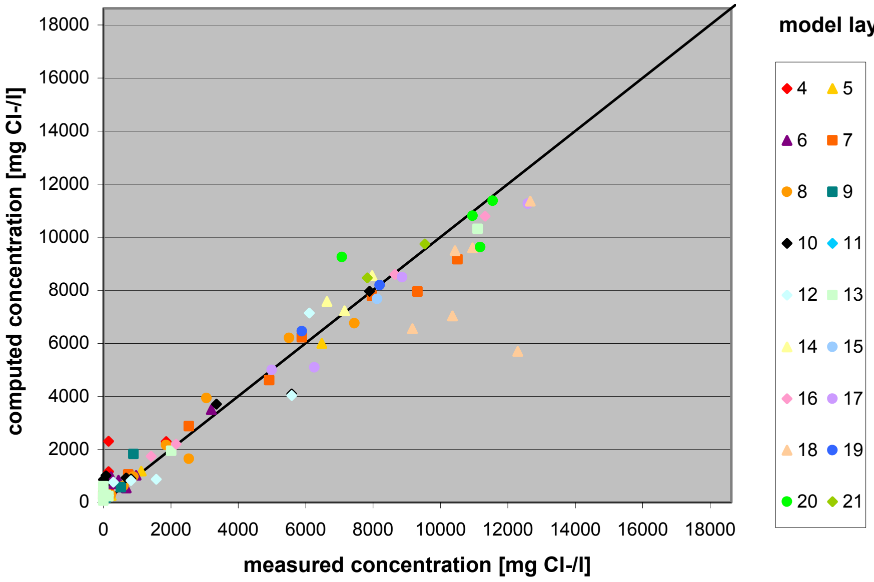

Figure 8: *Measured versus computed chloride concentrations [mg Cl^-/l].*

FUTURE SCENARIOS

Two scenarios have been composed to assess future developments in this area:

1. The autonomous scenario.
   This case serves as a reference to quantify the effect of the autonomous salinisation of the groundwater system due to past human activities. The most important past human activity is the land reclamation of the 1930s causing a large drastic drawdown of phreatic water levels in the entire area. The effect of this (anthropogenic) activity will probably still be noticed in the system from a density distribution point of view.
2. The sea level rise scenario.
   It is very likely that climate change causes a rise in mean sea level. As exact figures are not known yet, a maximum impact scenario is simulated here. According to the Intergovernmental Panel of Climate Change (IPCC, 2001), a sea level rise of 0.48 m is to be expected for the year 2100 (relative to 1990), with an uncertainty range from 0.09 to 0.88 m. This rate is 2 to 4 times the rate experienced over the last century. Based on these figures, a relative sea level rise of 75 cm per century has been implemented, in

steps of 0.0075 m per each time step of one year, for 2000 AD on at both the Waddenzee ánd the Lake IJsselmeer. The option of only a relative sea level rise in the Waddenzee gives less prominent results. Land subsidence caused by oxidation of peat, compaction and shrinkage of clay, and groundwater recovery are implemented in the scenario by means of a relative sea level rise. Changes in natural groundwater recharge are neglected.

The total simulation time is 200 years.

DISCUSSION

Numerical computations indicate that, even for the autonomous scenario, especially the low-lying parts of the Wieringermeerpolder have to cope with higher salinities in the top system (figure 9). For the year 2050 AD the changes will be for the autonomous scenario (figure 10): a 8% decrease of the seepage but a 36% increase of the salt load, relative to the present situation for the entire Wieringermeerpolder. For the coming 200 years, the total seepage in the entire Wieringermeerpolder decreases somewhat for the autonomous scenario due to an increase in salinity, as groundwater flow and solute transport are coupled. The autonomous development dominates the salinisation process during the coming 50 years from a salt load point of view (figure 10b). For the sea level rise scenario, the values are: a 3% seepage decrease and a 43% salt load increase for the year 2050 AD. The more or less instantaneous lowering of the phreatic water level in the Wieringermeer area in the early 1930s of several meters still has its affect on present groundwater flow and solute transport: the system is not in a steady state situation (figure 9, 10b and 11). Though a relative rise level rise accelerates the increase in salt load in the coming two centuries, it seems to be of secondary importance. Relative small changes on the surface, e.g., the implementation of the border lake, will not affect regional groundwater flow in a substantial way. It should be noted that the estimated initial density and chloride concentration distributions cause numerical errors. These errors will smooth out in time, but they can be relevant during the first decades of the simulation.

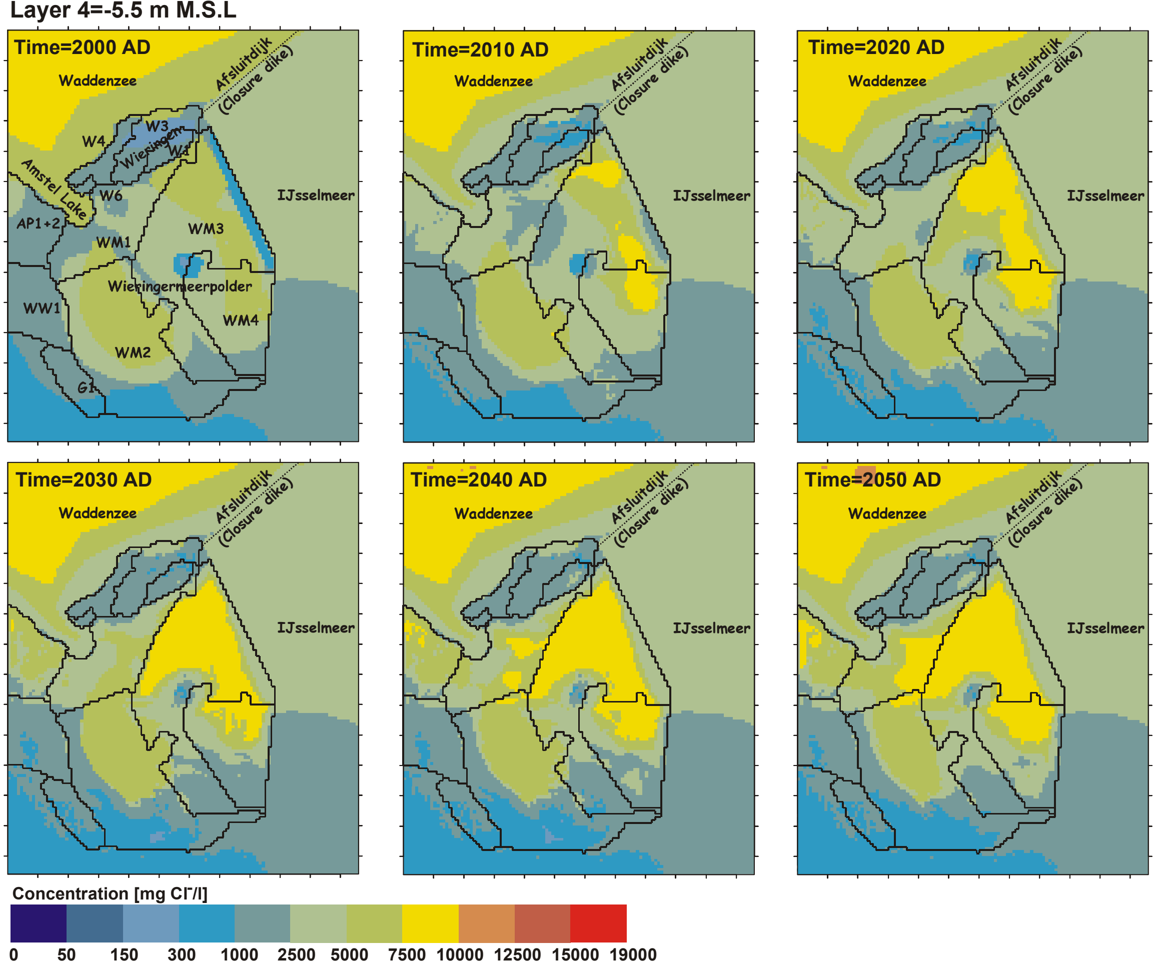

Figure 9: *Chloride concentration at –5.5 m N.A.P. on six moments in time up to 2050 AD for the autonomous scenario.*

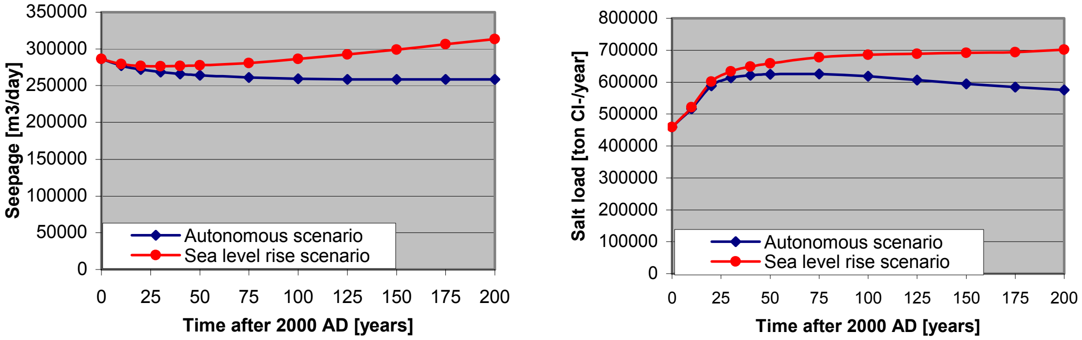

***Figure 10:** a. seepage (in m^3/day) and **b.** salt load (in ton Cl$^-$/year) through the fourth model layer at –8 m N.A.P., summarised for the entire Wieringermeerpolder (WM1 up to WM4), as a function of 200 years for both future scenarios*

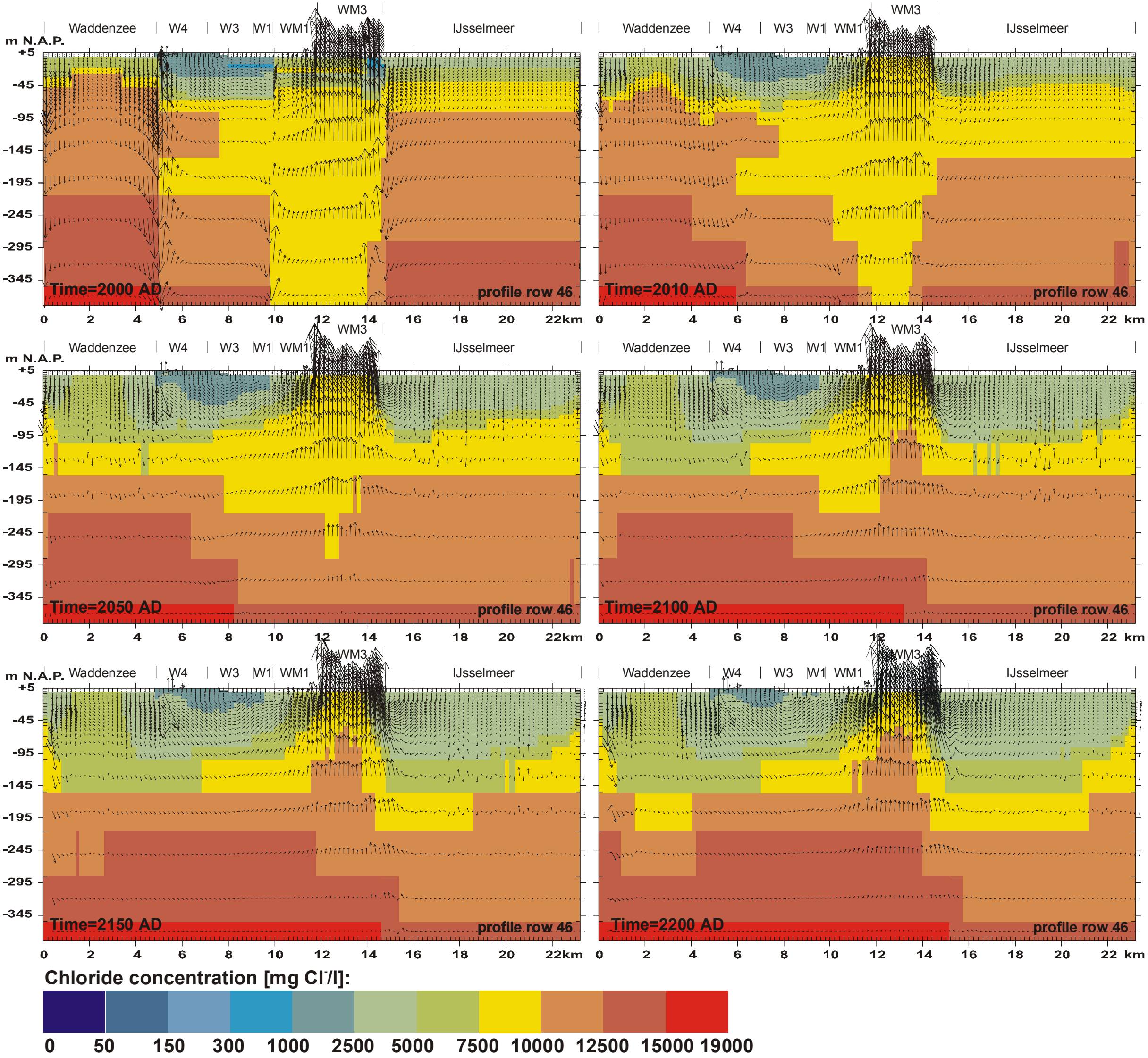

***Figure 11:** Chloride concentration in the profile of model row 46 for the sea level rise scenario case for the year 2000, 2010, 2050, 2100, 2150 and 2200 AD. The lengths of the arrow correspond with the displacement of groundwater during a time step of 5 years. Notice that at t=2000 AD, an inversion of saline and brackish groundwater occurs. The distribution of initial chloride concentration (which sets the density) is abrupt at some places, especially in the lower part of the system, and vertical velocities fluctuate. As can be seen, these numerical velocity fluctuations smooth out in time rather rapidly. Note that quite a few apparently numerical inversions have been removed from the entire hydrogeologic system manually.*

CONCLUSIONS

The model of the variable density groundwater flow system of the region of the Wieringermeer polder shows that the drastic lowering of the phreatic water level in the polder itself more or less started the salinisation process in the area. A relative sea level rise will accelerate the process, but this phenomenon is at least during the coming 50 years of secondary importance. The computer code MOCDENS3D can be used to simulate density dependent groundwater flow in three dimensions at this area with the sizes ~630 km^2 by 385 m thick. The interest has been focussed on calibration of the model with freshwater heads, chloride concentration, relatively well-known seepage values and even some salt load values. Nevertheless, the reliability of the whole model, and its predictive capacity to assess the future salinisation in this groundwater flow system stands with the number of accurate measurements of especially concentrations (chloride or Total Dissolved Solids).

REFERENCES

GRONTMIJ. (2001). Geohydrologisch Onderzoek Wieringerrandmeer, Grontmij Noord-Holland, in opdracht van Hoogheemraadschap Uitwaterende Sluizen namens de stuurgroep ‘Water Bindt’.

HARBAUGH, A.W. and M.G. MCDONALD. (1996). User's documentation for the U.S.G.S. modular finite-difference ground-water flow model; U.S.G.S. Open-File Report 96-485, 56 p.

ICW, Institute for Land and Water Management Research (1982). Wageningen. Quantity and quality of ground- and surface water in Noord-Holland north of the IJ. (in Dutch). Werkgroep Noord-Holland, ICW Regional Studies 16, 166 p.

IPCC, Intergovernmetal Panel on Climate Change (2001). Climate Change 2001: The Scientific Basis; http://www.ipcc.ch/.

KONIKOW, L.F. and J.D. BREDEHOEFT. (1978). Computer model of two-dimensional solute transport and dispersion in ground water; U.S.G.S. Tech. of Water-Resources Investigations, Book 7, Chapter C2, 90 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. (1998). MOC3D adapted to simulate 3D density-dependent groundwater flow; *Proc. MODFLOW'98 Conf., Golden, Colorado, USA, 291-303.*

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

OUDE ESSINK, G.H.P. (2001a). Density dependent groundwater flow at the island of Texel, The Netherlands; *Proc. 16th Salt Water Intrusion Meeting, June 2000, Miedzyzdroje-Wolin Island, Poland, 47-54.*

OUDE ESSINK, G.H.P. (2001b). 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. and R.H. BOEKELMAN. (1996). Problems with large-scale modelling of salt water intrusion in 3D; *Proc. 14th Salt Water Intrusion Meeting, Malmö, Sweden, June 1996, 16-31.*