Pergamon

Phys. Chem. Earth (B), Vol. 26, No. 4, pp. 337–344, 2001

1464-1909/01/$ - see front matter

PII: S1464-1909(01)00016-8

Saltwater Intrusion in 3D Large-Scale Aquifers: A Dutch Case

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Received 19 November 1999; accepted 25 July 2000

Abstract. Saltwater intrusion in a three-dimensional large-scale coastal aquifer in the northern part of the province Noord-Holland, The Netherlands, is investigated. The computer code MOCDENS3D, which is the code MOC3D of Konikow et al. (1996) but adapted for differences in density, is used to model the displacement of fresh, brackish and saline groundwater in this hydrogeologic system. It appears that a severe salinisation already occurs. This process is initiated by the reclamation of the (low-lying) polders during the past centuries. Though seepage quantities decreases in many polder araes due to an increase in salinity, the salt load increases significantly.

1 Introduction

The Netherlands is a highly populated country of which some 8 million people are living in the coastal zone. Due to several natural and anthropogenic causes, Dutch coastal groundwater systems are threatened by intrusion of saline water as displayed in Fig. 1. The salinisation of the groundwater systems may affect water management sectors such as the domestic and industrial, flushing of watercourses in low-lying polders and agriculture in terms of salt damage. In this paper, the interest is focussed on the problem of salt water intrusion in one specific three-dimensional coastal groundwater system where a non-uniform density distribution occurs. The present and future distributions of fresh, brackish and saline groundwater will be investigated in the northern part of the province Noord-Holland, called *De Kop van Noord-Holland*. Changes in salinity, seepage and salt load are explained. First, the genesis of the low-lying part of the Netherlands is discussed. Then, the applied computer code is briefly described. The geometry of the considered hydrogeologic system is given, followed by the discussion of some numerical results. Finally, conclusions are drawn and some recommendations will be given.

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2 Genesis of the Netherlands: a man-made environment

The major part of the Netherlands consists of lagoon and deltaic areas of the rivers Rhine, Scheldt and Meuse, created by natural processes such as sea level rise, forming of sand-ridges, sea invasions and the forming of lakes in invaded land. Before the occupation by man, the area behind the dunes was drained by a system of broad slowly moving streams (Fig. 2). Flood water from the high river stages and from the sea could easily enter the area. Starting from approximately the third century BC, the inhabitants built dwelling mounds and drained flood plains, to keep their feet dry. From about 1100 AD, embankments along the main rivers were built and sluices were set up at the outlets of smaller streams to protect themselves and their livestock against drowning and their agricultural land against flooding. Gradually, smaller inlets were embanked resulting into a pattern of small impoldered areas surrounded by dikes, the so-called polders. Later on, the land subsided because it was drained more efficiently (Fig. 3). This especially occurred in peat areas of Holocene origin in the western and northern part of the country. Peat was dug in these areas because it was needed as fuel, and thus, lakes were created. Subsequently, with the improvement of windmills and the paddle wheel in the sixteenth century, water from the polders could be removed more easily. It became possible to reclaim larger and deeper lakes. Especially during the seventeenth century ('the Golden Age'), numerous lakes have been reclaimed in Noord-Holland. These so-called droogmakerijen partly originate from digging and drying peat for heating purposes. Later on, the use of steam followed by electrical and diesel engines finally lead to the reclamation of the deepest lakes. What has been left from a swampy flat area with some streams and lakes is now a pattern of small and large polders, each having its own embankment and a controlled phreatic water level (the so-called polder level) with a specific elevation. The reclamation of the lakes initiated changes in the groundwater system. In order to drain the polders, the phreatic water levels in these polders had to be lowered com-

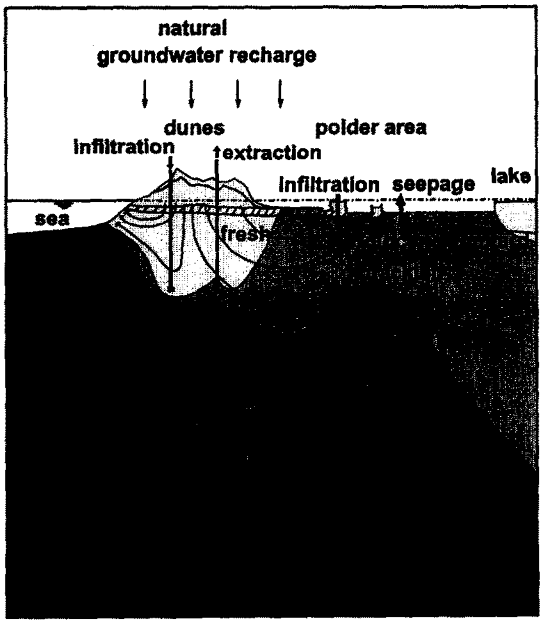

Fig. 1. A schematisation of the hydrogeological situation in the coastal western part of the Netherlands.

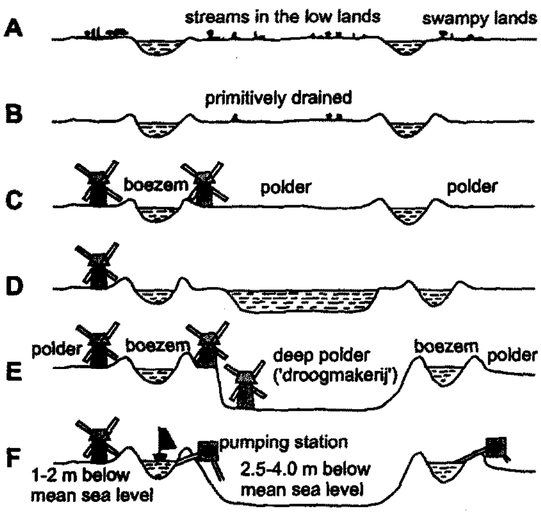

Fig. 2. Development of the Dutch polder region after Wesseling (1980). A. Before occupation of man; B. After damming of the streams at their mouths and their embankment, separation of 'boezem' and 'polder' by small dikes; C. Subsidence of the peaty polder soils and pumping of windmills; D. Digging out of some polders for peat making; E. After draining of the lake originating from peat making; F. Present situation.

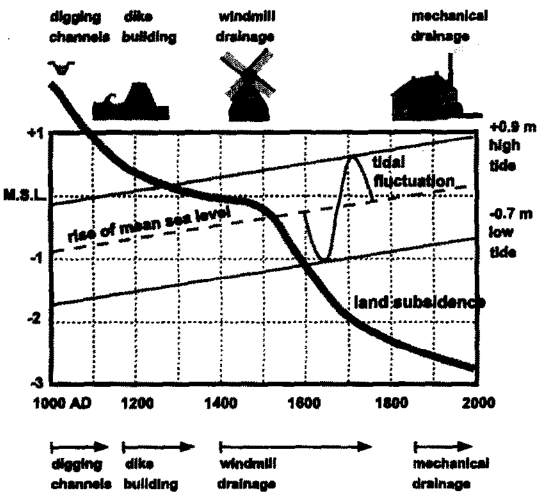

Fig. 3. Lowering of the grond surface in the Netherlands (schematic). Modified from Atlas van Nederland (1986).

pared to the original water level. As differences in phreatic water levels in adjacent areas have been created, groundwater was set in motion. Seepage in the polders was introduced because of a difference in phreatic water level in the polder and piezometric head in the aquifer. The seepage was accompanied by an intrusion of salt as, among others, regressions and transgressions of the sea in the western and northern part of the Netherlands created large zones of fresh, brackish and saline groundwater in the upper parts of the hydrogeologic system.

3 Numerical computer code

MOCDENS3D (Oude Essink, 1998, 1999), which is the three-dimensional computer code MOC3D (Konikow et al., 1996) but adapted for density differences, is used to simulate the transient groundwater system as it occurs in De Kop van Noord-Holland. The groundwater flow equation is solved by the MODFLOW module (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996). The advection-dispersion equation which simulates the solute transport is solved by the MOC module using the method of characteristics (Konikow and Bredehoeft, 1978; Konikow et al., 1996). Advective transport of solutes is modelled by means of the method of particle tracking and dispersive transport by means of the finite difference method. A so-called fictive freshwater head ϕ_f is introduced to take into account differences in density in the calculation of the head:

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

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 $[ML^{-3}]$, p is the pressure $[ML^{-1}T^{-2}]$, and z is the elevation head $[L]$. The vertical specific discharge is defined as follows:

$$q_z = -\frac{\kappa_z \rho_f g}{\mu}\left(\frac{\partial \phi_f}{\partial z} - \frac{\rho - \rho_f}{\rho_f}\right) \qquad (2)$$

As in normal hydrogeologic systems small viscosity differences can be neglected if density differences are considered (Verruijt, 1980; Bear and Verruijt, 1987), equation 2 can then be written as:

$$q_z = -k_z\left(\frac{\partial \phi_f}{\partial z} - \frac{\rho - \rho_f}{\rho_f}\right) \qquad (3)$$

where k_z=$\kappa_z \rho_f g/\mu$ is the hydraulic conductivity for fresh water and $(\rho - \rho_f)/\rho_f$ is the so-called buoyancy term. A linear equation of state couples groundwater flow and solute transport:

$$\rho(C) = \rho_f[1 + \beta_C(C - C_0)] \qquad (4)$$

where $\rho(C)$ is the density of groundwater $[ML^{-3}]$, C is the chloride concentration $[ML^{-3}]$, and β_C is the volumetric concentration expansion gradient $[L^3M^{-1}]$. MOCDENS3D takes into account hydrodynamic dispersion. For a conservative solute as chloride, the molecular diffusion for porous media is taken equal to 10^{-9} m^2/s.

4 Geometry of the groundwater system

The entire groundwater system is covered by a grid with a surface of about 65.00 × 51.25 km^2 (see Fig. 4). The sizes of each element are Δx =1250 m, Δy =1250 m and Δz =10 m. The grid contains 61828 elements: n_x=41 × n_y=52 × n_z=29, where n_i denotes the number of elements in the i direction. Due to the rugged coastline of the groundwater system, only 64.6 % of the elements (39933 out of the total 61828) are considered as active elements. Each active element contains 27 particles to solve the advection term of the solute transport equation. As such, 1078191 particles are initially used. The flow time step Δt to recalculate the groundwater flow equation equals 1 year. The convergence criterion for the groundwater flow equation is equal to 10^{-5} m of head difference. The total simulation time is 1000 years. The groundwater system consists of good permeable aquifers of Quaternary deposits, intersected by loamy aquitards and overlain by a Holocene aquitard of clayey and peat composite. As such, the hydraulic conductivity varies in the system, see Fig. 4. A hydrogeologic base is assumed at -290 m N.A.P. The anisotropy factor k_z/k_x (the ratio vertical and horizontal hydraulic conductivity) equals 0.4. The effective porosity n_e is 0.35. The longitudinal dispersivity α_L is equal to 2 m, while the ratio transversal to longitudinal dispersivity α_T/α_L is 0.2. The volumetric concentration expansion gradient β_C is 1.34 × 10^{-6} $l/mg\ Cl^-$. The specific storativity S_s $[L^{-1}]$ can be set to zero on the applied time scale. The bottom of the system is a no-flux boundary whereas hydrostatic conditions occur at the four sides. At the top of the system, the water level at the sea is constant in time (-0.15 m N.A.P.). A large number of low-lying polder areas is present in this system with an area of approximately 2000 km^2. Fig. 5 illustrates the phreatic water level in the polders which varies from -0.1 m to -6.2 m N.A.P. and stays constant in time. N.A.P. (Normaal Amsterdams Peil) roughly equals Mean Sea Level (M.S.L.) and is the reference level in the Netherlands. As such, relatively small fluctuations in the phreatic water level (polder level) are neglected over the applied time scale. At the initial situation (1990 AD), the hydrogeologic system contains saline, brackish as well as fresh groundwater. Fig. 6 gives the chloride concentration in six layers. The salinity increases with depth. In the sand-dune area, a constant natural groundwater recharge of 1 mm/d is used. In the three sand-dune areas 5.2 million m^3/yr groundwater is extracted from the second aquifer at -25 m N.A.P. In addition, 5.4 million m^3/yr groundwater is pumped at -35 m N.A.P. distributed over especially the eastern and southern part of the polder area, whereas a very large industrial groundwater extraction is taking place at southwestern corner of the model (22.5 million m^3/yr between -115 and -135 m N.A.P.).

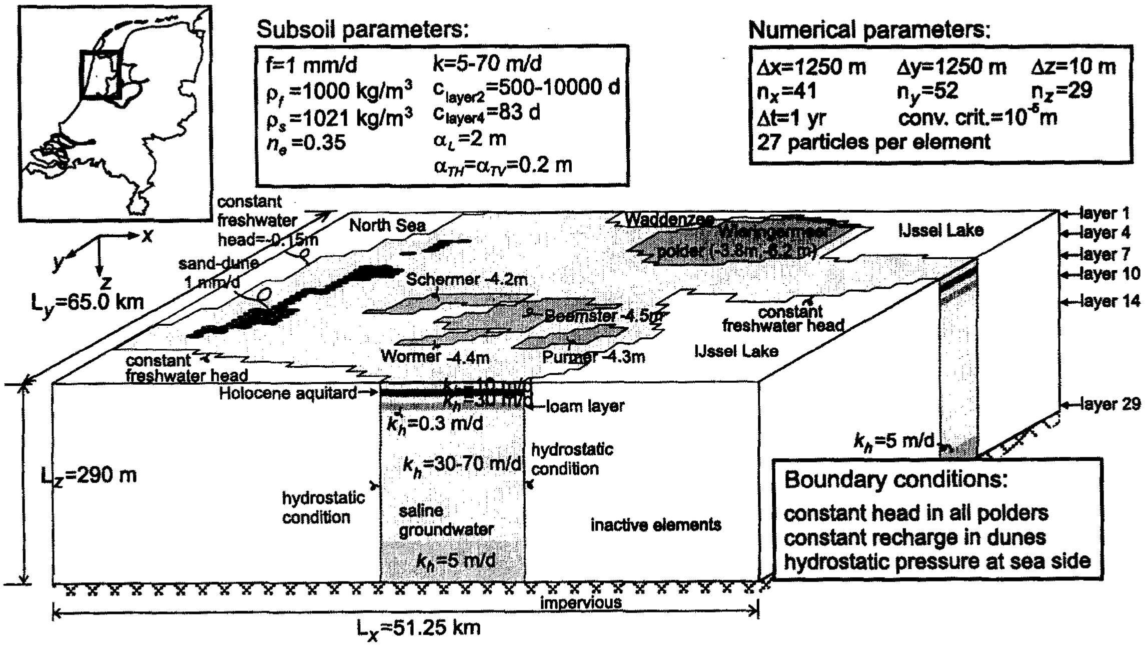

Fig. 4. The geometry of the groundwater system in De Kop van Noord-Holland.

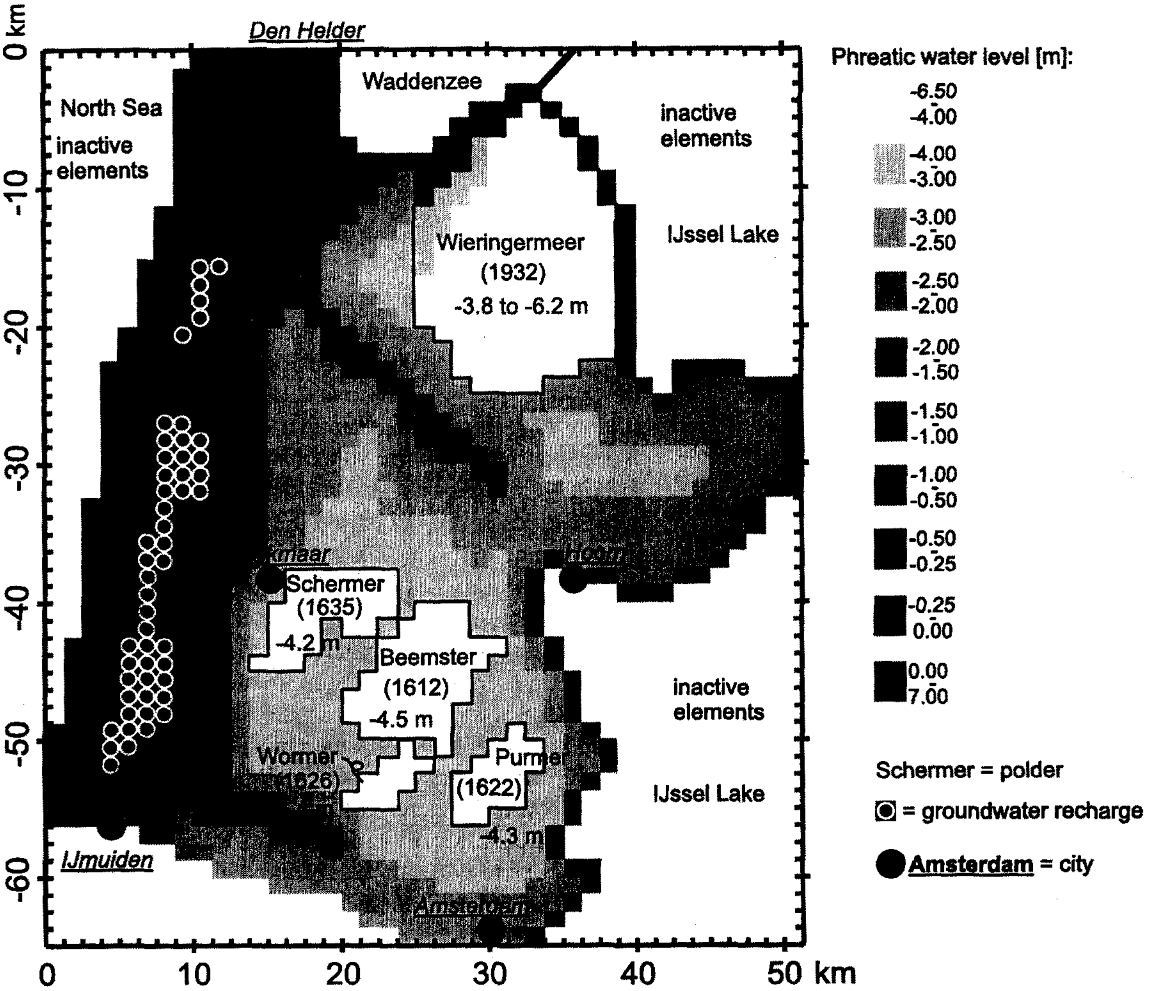

Fig. 5. Present phreatic water level in the top layer (1990 AD). Between brackets the date of reclamation. The following five polders have a very low phreatic groundwater level: Wieringermeer, Schermer, Beemster, Wormer, and Purmer. The recharge in the sand-dune area is equal to 1 mm/d.

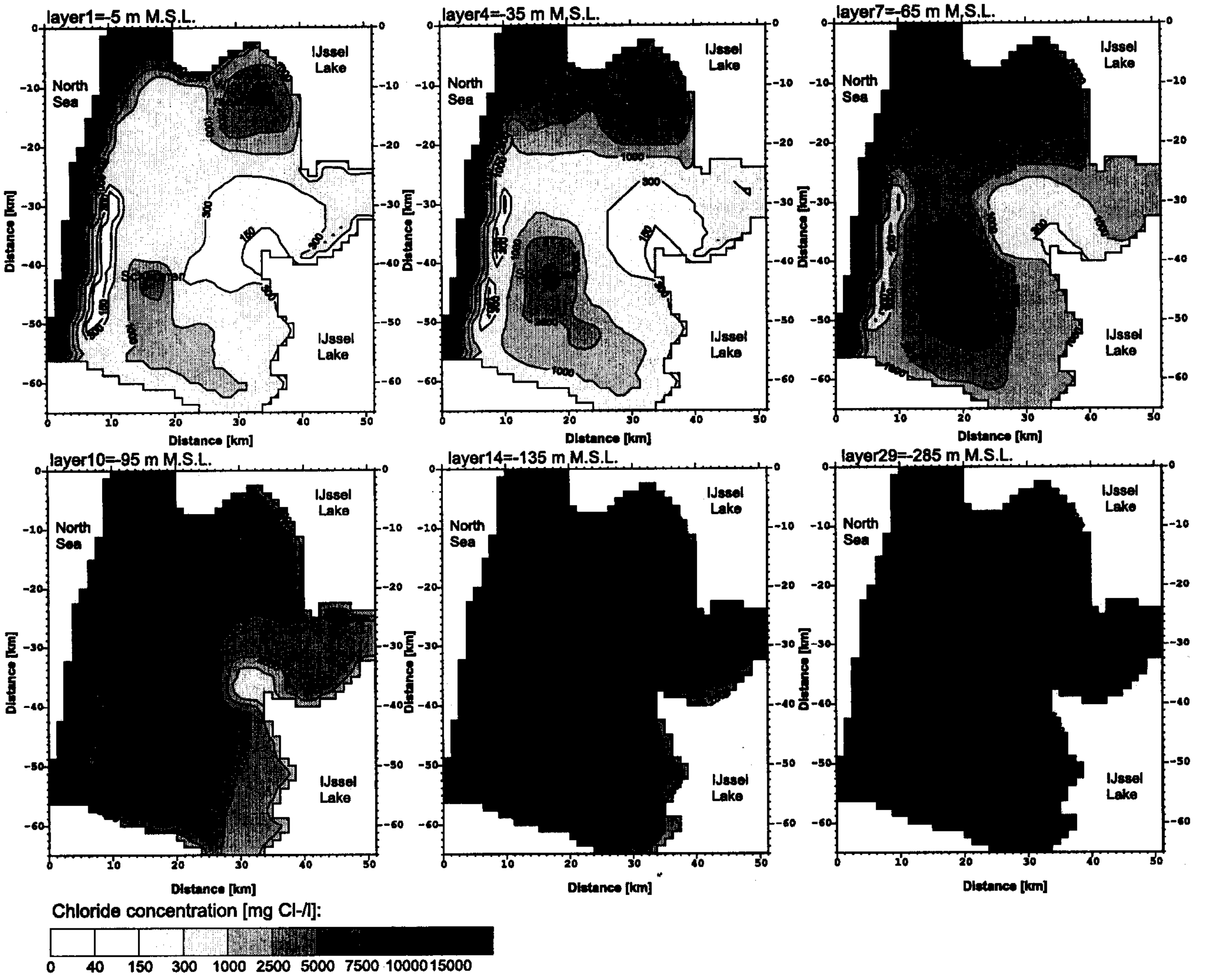

Fig. 6. Initial chloride concentration in the hydrogeologic system at the beginning of the simulation (1990 AD) at six layers: -5 m, -35 m, -65 m, -95 m, -135 m and -285 m N.A.P.

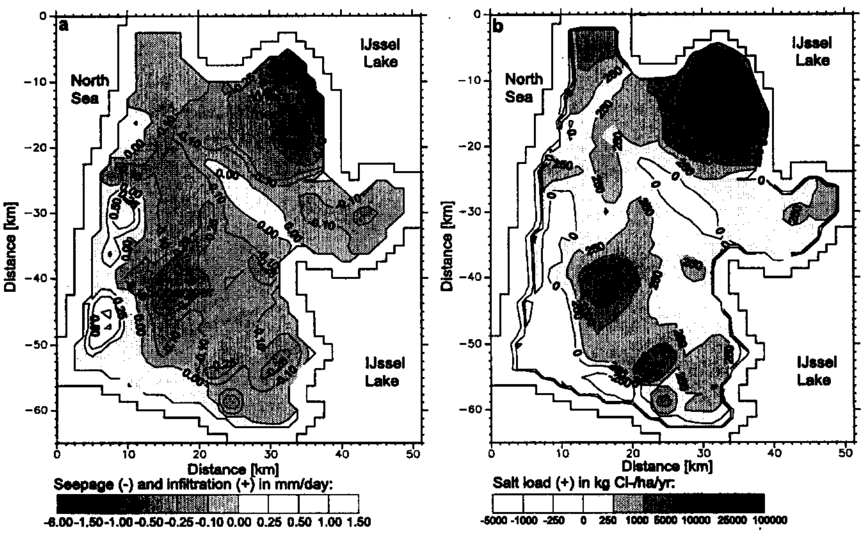

Fig. 7. Seepage in mm/day (a) and salt load in kg Cl^-/ha/yr (b) through the top layer at -20 m N.A.P. in the hydrogeologic system.

5 Discussion

The groundwater system was satisfactorily calibrated with freshwater distributions at different levels, with seepage and salt load quantities through the top aquitard in five polders (viz. Wieringermeer, Schermer, Beemster, Wormer and Purmer), and with recharge figures in the sand-dune areas. Major calibration steps with different subsoil parameters were needed to calibrate the system satisfactory. Anisotropy, hydraulic conductivity (30-70 m/d), hydraulic resistance (83-10000 days), phreatic water levels, boundary conditions, but especially the initial chloride concentration, were changed to improve the fit between simulation and measurements. The low-lying polders cause a low freshwater head in the center of the hydrogeologic system, inducing an inflow of groundwater from the North Sea and the IJssel Lake. Seepage occurs especially in the low-lying polders (Fig. 7a). In the northeastern part of the Wieringermeer polder, the seepage quantity can be as high as 5.6 mm/d, mainly caused by the low hydraulic resistance in that area. Fig. 7b shows the salt load in the hydrogeologic system through the bottom of the top aquitard at -20 m N.A.P. Note that at least 80 % of the total salt load in the Kop van Noord-Holland comes from the Wieringermeer polder.

Now, the system has been simulated for the next 1000 years. During this time, boundary conditions remain the same. Fig. 8 shows the change in chloride concentration in the top layer at -5 m N.A.P. at six moments in time: 1990 AD, 2090 AD, 2240 AD, 2490 AD, 2740 AD and 2990 AD. As can be seen, the chloride concentration increases significantly, especially in the low-lying polders Wieringermeer and Schermer. In conclusion, this implies that the system is not yet in a steady state situation. The salinity in the hydrogeologic system increases, especially the next centuries (Fig. 9). The polders induce the salt water intrusion into the hydrogeologic system because of their low phreatic water levels. The groundwater system was seriously set into motion at the moment the deep polders Schemer, Beemster, Wormer and Purmer were reclaimed during the beginning of the seventeenth century. With an average velocity in the range of at least 10 to 20 m per year saline groundwater enters the system.

Now, the interest is focussed on the five selected polders Wieringermeer, Schermer, Beemster, Wormer and Purmer. Fig. 10a shows the change in seepage through the bottom of the Holocene aquitard. The seepage quantity is enormous in the Wieringermeer polder due to its short distance to the IJssel Lake with its high lake level, but especially due to the low hydraulic resistance of the Holocene aquitard (500 to 4000 days). It is remarkable that seepage quantities decrease significantly for all polders. This is because of the increase in salinity in the hydrogeologic system. As salinity increases, the freshwater head, with takes into account density differences, is adjusted to lower values. Whereas the phreatic water levels in the polders remain the same, the seepage quantity decreases accordingly. On the other hand, the salt load is the resultant of seepage times salinity. As salinity increases substantial, the salt load increases accordingly. Fig. 10b shows that the salt load in all five polders at the bottom of the Holocene aquitard. In all five polders, the salt load increases substantially over the next 1000 years. The figure shows that during the first centuries, the salt load has not reached a steady state situation. The initially calculated salt load values in the polders correspond well to the measured ones by ICW (1982). Note that for the other polders closer to the IJssel Lake, the assumed constant water level in this lake dominates the flow process through the Holocene aquitard into the polders nearby.

6 Conclusions

It can be concluded that the computer code MOCDENS3D can be applied to simulate density-driven flow in a large-scale three-dimensional hydrogeologic system. Changes in salinity of a time period of 1000 years are simulated. A severe salt water intrusion is taking place in the groundwater system, due to the low phreatic water levels in the polder areas. Seepage quantities in all five considered polders decrease due to a lowering of the freshwater head in the system, caused in return by an increase in salinity. However, the salt load in all polders increases substantially over the next 1000 years. In general, it is clear that in the future this region in the province Noord-Holland has to cope with much more saline groundwater than at present.

7 Recommendations

Obviously, the initial conditions highly determine the salinisation process in the hydrologic system. Especially in three-dimensional density-dependent groundwater modelling, the initial density or chloride concentration distribution should be known accurately. In addition, the hydraulic resistance of the Holocene top aquitard as well as the longitudinal dispersivity also have significant effects on the modelled salinisation process. Unfortunately, a large amount of reliable data is not available, and more measurements should be carried out. The present salinisation process, the seepage quantity and the chloride load should be monitored as functions of time to detect changes in the long term.

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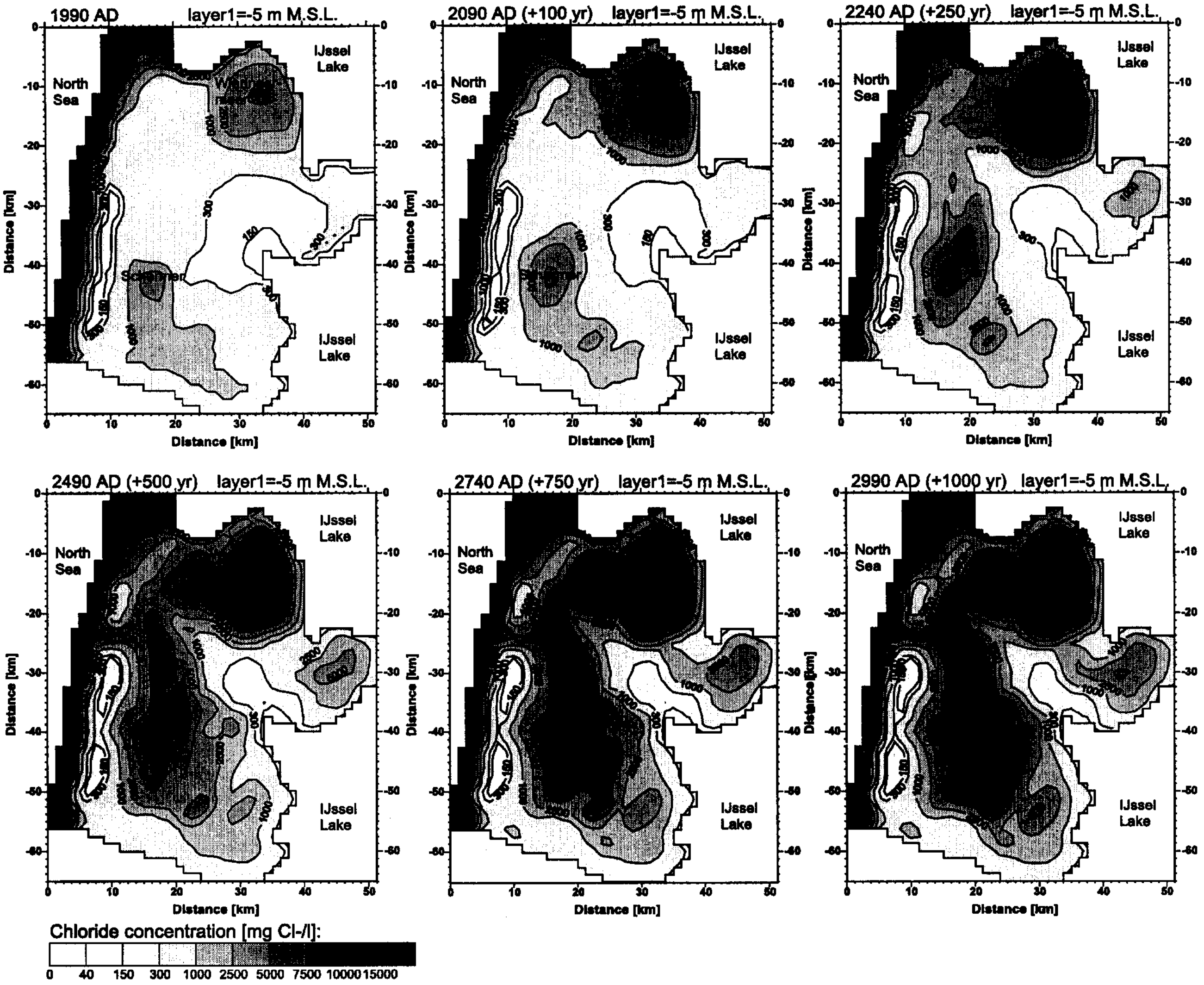

Fig. 8. Chloride concentration in the top layer at -5 m N.A.P. in the hydrogeologic system at six moments in time: 1990, 2090, 2240, 2490, 2740 and 2990 AD.

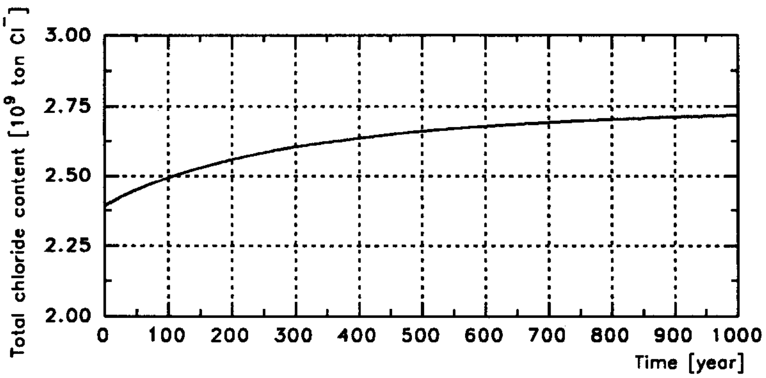

Fig. 9. Total chloride (ton Cl^-) in the whole hydrogeologic system as a function of time.

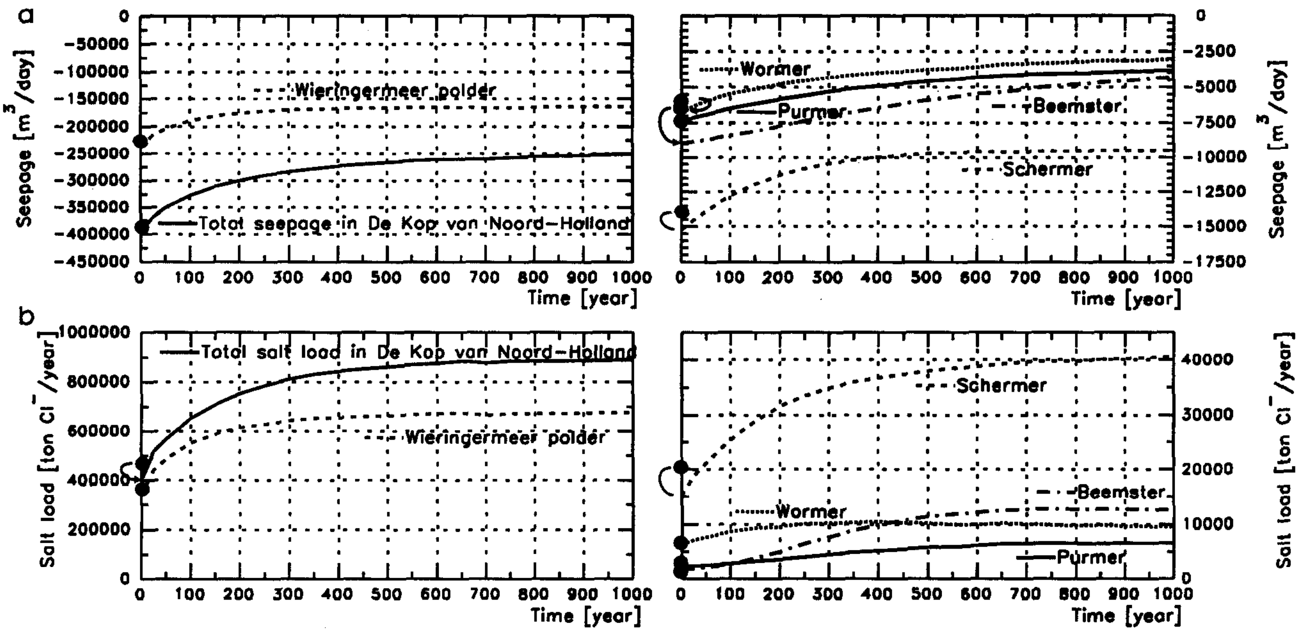

Fig. 10. Seepage in m^3/d (a) and salt load in ton Cl$^-$/ha/yr (b) through the bottom of the Holocene aquitard at -20 m N.A.P. as a function of time in the selected five polders Wieringermeer, Schermer, Beemster, Wormer and Purmer. The • indicates the present measured value in the considered polder (ICW, 1982).

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