Response of a fresh-brackish groundwater system to hydrological management in and around the Naardermeer wetland, the Netherlands

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SUMMARY

Biodiversity decline as an environmental concern has been introduced to the world relatively recently but it has quickly become one of the main environmental challenges of this millennium. In the Netherlands fen meadows, a type of wetland, represent an important rare ecosystem, but the last few centuries its unique vegetation composition has been threatened by human activities such as land reclamation and groundwater extraction. Species rich fens are frequently located at edges of river plains fed by nutrient poor, alkaline groundwater at the base of sandy glacial ridges via regional groundwater systems. Groundwater flow patterns in the Netherlands can be complex due to century-long human intervention. Adding to this complexity is the presence of brackish groundwater in Dutch aquifers. In coastal areas intrusion of seawater has been identified as a major influence on groundwater composition. In the Netherlands this influence is intensified by brackish groundwater also being present further inland. This paper aims to provide insight into the response of regional groundwater flow to hydrological management with specific focus on the behavior of fresh-brackish groundwater within the system.

In this paper the Naardermeer nature reserve in the Gooi- and Vechtstreek is used as a case study. In the past few decades hydrological management there has been adjusted with the goal to restore and conserve nutrient poor, alkaline groundwater flow to the Naardermeer wetland. In order to determine the response of the regional, fresh-brackish groundwater system of the Naardermeer, seven possible hydrological management scenarios were tested using a 2-dimensional, density dependent groundwater model based on the computer code MOCDENS3D. The code combines the MODFLOW module, adjusted to density dependent groundwater flow, and the MOC3D module respectively describing groundwater and particle transport.

The model shows that extraction of groundwater in the hill ridge, upstream of the nature reserve, mostly affects fresh-brackish groundwater distribution in the discharge area nearest to the hill ridge and does not have as much effect on areas further downstream in the valley. Regional hydrological management also needs to consider that adjusting controlled surface water levels in downstream polders directly adjoining as well as more distant to the polder of interest affects the brackish groundwater distribution underneath the polder of interest. Furthermore, hydrological management aimed at improving quality or quantity of groundwater supplied to vegetation in one polder might have adverse effects on groundwater conditions in adjoining polders. Overall, based on this research it can be concluded that the presence of brackish water in deep aquifers adds another dimension to the complexity of groundwater systems, and that behavior of brackish groundwater needs to be considered by authorities when deciding hydrological management strategies aimed at preserving or restoring nature.

Introduction

Biodiversity decline as an environmental concern has been introduced to the world relatively recently but it has quickly become one of the main environmental challenges of this millennium. The importance of biodiversity for the functioning of ecosystems is mostly still unclear but on many aspects the scientific community has come to a broad consensus (Hopper et al., 2005). The survival of local species populations in particular has been identified as essential (Millennium Ecosystem Assessment, 2005). Counteracting loss of biodiversity is therefore a top priority in governmental plans of many countries, including the Netherlands (VROM, 2001). To ensure biodiversity, it is important to identify, understand, conserve and, if necessary, restore rare ecosystems (Turner et al., 2000).

Fen meadows, a type of wetland, represent an important rare ecosystem in the Netherlands, but in the last few centuries its unique vegetation composition has been threatened by human activities, such as land reclamation (Wolff, 1993). An example is the Naardermeer nature reserve in the Vecht river plain, which is known for its high biodiversity (Vermaat et al., 2007). However, throughout the 20th century a rapid decline in plant species diversity has been observed (Barendregt et al., 1995; Wassen et al., 1988).

The species richness of fens is suggested to be related to the availability of nutrient poor, alkaline groundwater (Grootjans et al., 2006; Jansen et al., 2000; Jansen et al., 2004). Ensuring availability of this groundwater type is therefore considered essential for conservation of species rich fens (Wheeler and Shaw, 1995). In the Netherlands, species rich fens are frequently located at edges of river plains at the base of sandy glacial ridges and are fed by nutrient poor, alkaline groundwater via regional groundwater systems (Schot et al., 1988).

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In the Netherlands, groundwater flow patterns can be complex due to century-long human intervention such as groundwater extraction and reclamation of polders, each with their own embankment and controlled surface water levels (Schot and Molenaar, 1992). Adding to this complexity is the presence of brackish groundwater in Dutch aquifers. In coastal areas, intrusion of seawater has been identified as a major influence on groundwater composition (Custodio, 2010; Oude Essink, 2001a-b). In the Netherlands this influence is intensified by brackish groundwater being present further inland. The origin of brackish groundwater in Dutch aquifers is theorized to be due to Holocene transgression (Post et al., 2003).

Hydrological management is necessary for economic, social-economic and safety reasons and is common practice throughout the Netherlands. These human interventions lead to changes in regional groundwater flow intensities and quality. A shift in distribution of fresh and brackish groundwater in groundwater systems might occur and consequently effect biodiversity. Considering the transient character of groundwater flow, it may take decennia or even centuries for disturbed systems to reach a new equilibrium (Oude Essink, 2001a) and for changes in vegetation to manifest.

In this paper, the Naardermeer nature reserve in the Gooi- and Vechtstreek is used as a case study. In the past few decades hydrological management there has been adjusted with the goal to restore and conserve nutrient poor, alkaline groundwater flow to the Naardermeer wetland. Effectiveness and feasibility of such hydrological restoration measures remains debated. A combination of topsoil removal and seed transfer (Klimkowska et al., 2010) or turf-stripping (Van der Hoek and Heijmans, 2007) have been suggested as effective measure to restore species-rich fen meadows. However, to achieve long-term results, restoration of upward seepage of base-rich groundwater is considered essential.

The Naardermeer wetland nature reserve was chosen as the study area due to presence of rare plant species, which are thought to be dependent on outflow of regional groundwater at the base of a glacial sand ridge (Wassen et al., 1989). Furthermore, the Naardermeer is suitable for this research due to the presence of upwelling brackish groundwater (Schot, 1989), which might be affected by large-scale hydrological restoration measures recently implemented in the area (Boosten et al., 2006).

In previously conducted research in the area, several important hydrological moments in time were reconstructed to demonstrate how anthropological interferences in the past changed groundwater flow from a simple pattern under natural conditions to a complex flow pattern dominated by man-controlled hydraulic heads at the end of the 20th century (Schot and Molenaar, 1992). Palaeohydrological reconstructions suggest that environmental degradation in the river valley was not caused by reduced influx of regional groundwater as previously suggested by Barendregt et al. (1995), but rather by the decrease of the area of groundwater discharge and the shift in predominant groundwater discharge mechanism from regional overland flow to local drainage (Van Loon et al., 2009). Both studies do not simulate the effects of more recent hydrological restoration measures aimed at increasing inflow of regional groundwater. Furthermore, the effects of density differences, due to the presence of brackish groundwater, on groundwater flow patterns were not considered. Oude Essink and Stuurman (2006) emphasized the need to use a density dependent model especially for groundwater flow below -100 m mean sea level (M.S.L.). However, their density-dependent groundwater model of the Gooi- and Vechtstreek did not look at effects of management on groundwater flux and quality.

This paper aims to provide insight into the response of regional groundwater flow to possible future hydrological management, with specific focus on the behavior of fresh-brackish groundwater within the system. The purpose is to determine the change in amount, location and chloride concentration of groundwater reaching the plant root zone in the Naardermeer polder as a consequence to changes in groundwater extraction in the nearby hill ridge and adjustment of controlled phreatic water levels in the Naardermeer polder itself and in adjacent polders. Obtaining this knowledge will help to focus future management strategies aimed at conserving and restoring biodiversity in the nature reserve Naardermeer.

Study area and its historical developments

The Naardermeer is part of the Gooi- and Vechtstreek area, which is located east of Amsterdam in the Central Netherlands (Fig. 1). The climate can be classified as moderate maritime with yearly average temperatures of 10 °C and a precipitation surplus of 200-400 mm yr^{-1} (Schot et al., 2004). In the east the Naardermeer polder is bordered by the ice-pushed ridge 'Het Gooi', formed during the Pleistocene, which reaches an elevation of up to 30 m above M.S.L. The ridge functions as a regional infiltration area with groundwater levels of up to 2 m above M.S.L. In the West of the study area lays the Vecht river plain with elevation between 0 and -3 m M.S.L. The elevation difference between the ridge and the valley results in a continuous groundwater flow from east to west (Schot and Molenaar, 1992).

Water infiltrating in the hill ridge flows through sediments of Quaternary age and eventually seeps into the eastern part of the nature reserve. At -200 to -260 m M.S.L. a hydrogeological barrier can be found in form of early Pleistocene marine clays and fine-grained silty sands with on top fluvial sand and gravel deposits (Schot and Molenaar, 1992).

The river valley harbors many fen reserves, one of which is the Naardermeer nature reserve. It consists of shallow lakes with depths ranging from 1 to 2 meters and marshlands alternating with reed- and haylands, scrubs and forests. The topography of the Naardermeer polder is flat, with the eastern part being slightly more elevated (M.S.L. -0.3 m) than the central and western parts (M.S.L. -0.8 m) (Schot et al., 1988).

The hydrology underlying the Naardermeer nature reserve has been significantly altered by human activities over the last couple of centuries. In 1883 the lakes were reclaimed but abandoned shortly afterwards because of high drainage costs due to high groundwater seepage intensities and low agricultural yields due to high salt concentrations in the soil. Water supply companies have been extracting groundwater in 'Het Gooi' since 1888 and demand for drinking water has risen drastically due to urbanization of the area after World War II. As a consequence natural groundwater flow to the wetlands in the river plain has diminished significantly (Witmer, 1986). Being aware of implications of reduced groundwater discharge in the Naardermeer on biodiversity in the nature reserve, provincial authorities decided to reduce drinking water extraction

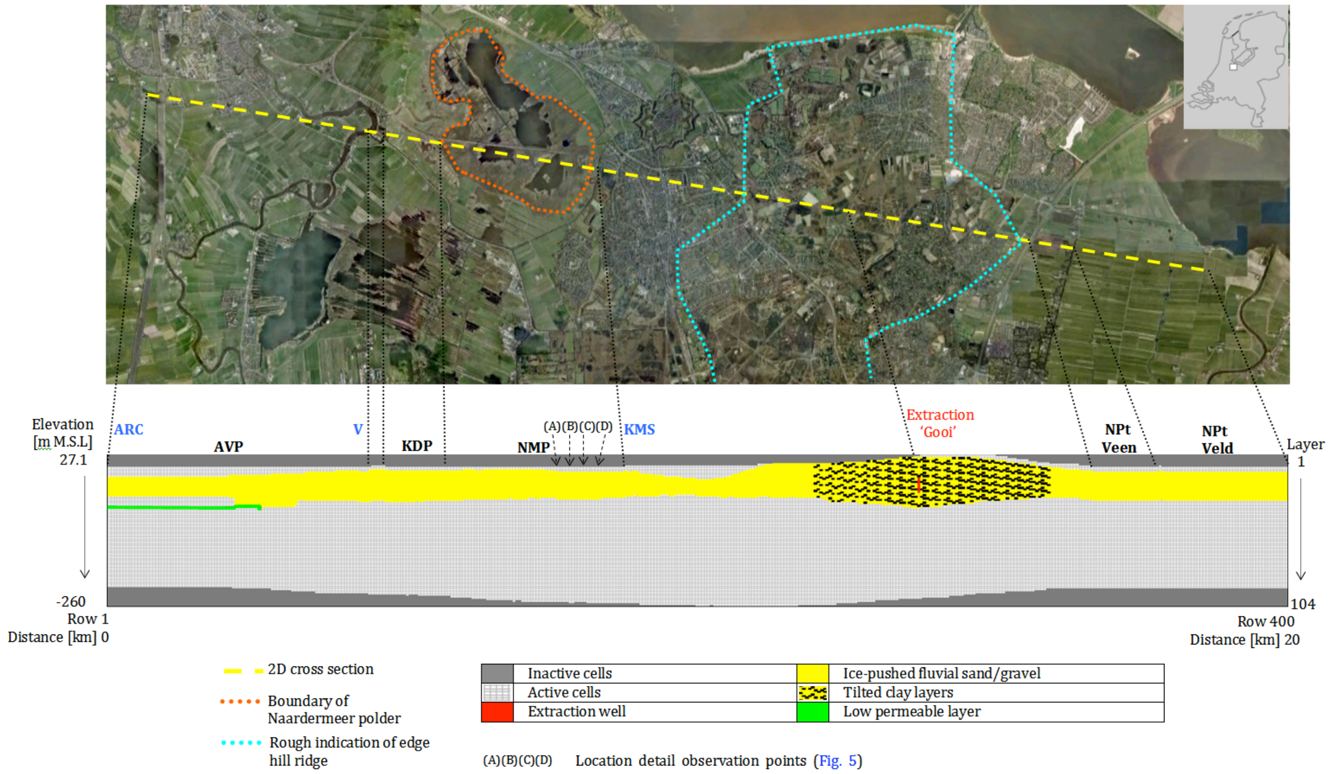
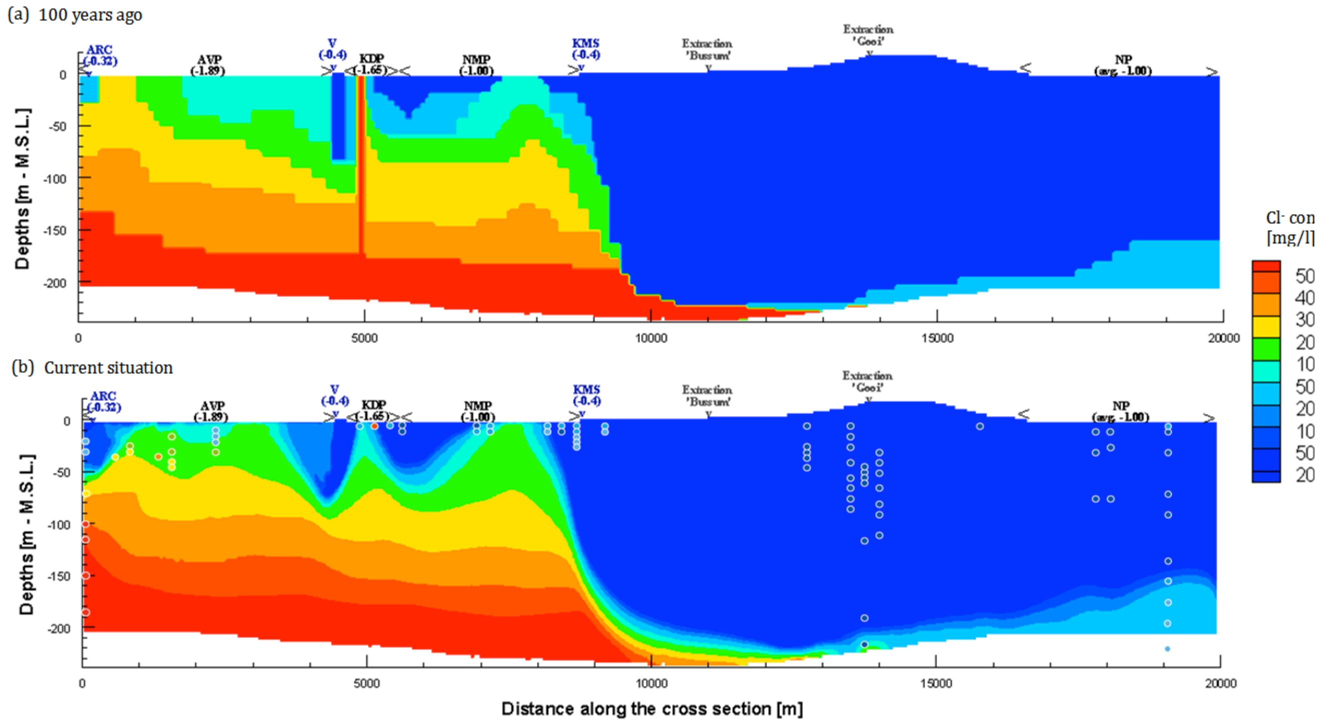


Fig. 1. Naardermeer nature reserve (The Netherlands) and surroundings (Google Earth, 2010). In the schematic cross section overview the dimensions of the model, important hydrogeological layers and the groundwater extraction sites are indicated. Abbreviations refer to: ARC – Amsterdam-Rhine Canal; AVP - Aetsveldsche Polder; V – Vecht; KDP – Keverdijksche Polder; NMP – Naardermeer Polder; KMS – Karnemelksloot; ExtB – Groundwater extraction in Bussum; ExtG – Groundwater extraction in 'het Gooi'; NPtVeen – Noordpolder te Veen; NPtVeld – Noordpolder te Veld.


(a) 100 years ago

(b) Current situation

Fig. 2. 2-dimentional chloride concentration distribution along the model cross section. (a) Assumed concentration distribution 100 years ago [mg/l]. (b) Modelled concentration distribution of the current situation including measurements of recent chloride concentrations [mg/l]. Abbreviations see Fig. 1.

in 'Het Gooi' by fifty percent before 1998, with expectations to, at least partly, restore the regional hydrology (Boosten et al., 2006).

The hydrology of the study areas is also significantly influenced by drainage of the river plain for agricultural purposes, which started as early as the twelfth century. Polders were created by digging ditches and artificially controlling surface water levels with windmills and later steam- or diesel engines or electrical pumps. Low groundwater levels in the region led to subsidence of ground surfaces due to oxidation and mineralization of the top peat layer (Schot & Molenaar, 1992). In the early 1990s, surface water levels of polders adjoining the nature reserve were raised as part of the restoration plan for the Naardermeer (Boosten et al., 2006).

Data of periodical vegetation mapping in fen meadows on the east shore of the lake 'Bovenste Blik' in the Naardermeer shows that abundance of rare plant species varies per year but has generally increased from 1994 onward (Bouman, 2004). More detailed statistical analysis of this data confirms that vegetation has, at least partly, recovered to the state it was in at the beginning of the 20th century (Schnitzer, 2007). Recovery of rare vegetation suggests improved conditions for plants but no evidence has been provided yet that the original regional hydrology has indeed improved due to hydrological management change.

Method

General

In order to determine the response of the regional, fresh-brackish groundwater system of the Naardermeer, seven possible hydrological management scenarios were tested one at a time.

(1) Continuation of current hydrological management
(2) Stopping groundwater extraction in the upstream hill ridge 'Het Gooi'
(3) Lowering controlled surface water levels in the Naardermeer polder
(4+5)Raising and lowering controlled surface water levels in a downstream, lower-lying polder directly adjoining the nature reserve (Keverdijksche polder)
(6+7)Raising and lowering controlled surface water levels in a downstream, lower-lying polder some distance away from the nature reserve (Aetsveldsche polder)

Current hydrological management implies management in 2006; after reduction of groundwater extraction was implemented in accordance with the restoration plan 'Naardermeer'. Surface water level adjustments in management scenarios were set at +/- 0.5m. Simulation time was set at 250 years, during which climate as well as geohydrological input parameters were kept constant. Scenarios 'continuation of current management' and 'stopping groundwater extraction' were run for 1000 years to get an impression of the behavior of fresh-brackish groundwater over an even longer time period.

As starting point for scenario runs, a 2-dimensional, density dependent groundwater model of the current situation was constructed. A 2D model written for an environmental impact assessment (EIA) in the same area (Oude Essink and Stuurman, 2006) functioned as a base. To model density dependent, non-stationary groundwater flow of saline groundwater, MOCDENS3D (Oude Essink, 1998; 1999) was used. The code combines the MODFLOW module (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996), adjusted to density dependent groundwater flow, and the MOC3D module (Konikow et al., 1996) respectively describing groundwater and particle transport.

A linear cross section was implemented as far as possible in line with groundwater flow direction; spanning from the Amsterdam-Rhine Canal in the west, through the southern part of the Naardermeer polder, over the hill ridge 'Het Gooi', until the Noordpolder te Veld in the west (Fig.1). Groundwater was allowed to flow laterally into the system by assigning a hydrostatic pressure distribution to the vertical boundaries calculated using recent chloride concentrations from nearby observation wells. Based on information from previous studies about groundwater flow in the region (Oude Essink and Stuurman, 2006; Schot et al., 1988), the start and end point of the cross section were chosen at sufficient distance from the Naardermeer for the boundaries to be considered of no influence to the chloride distribution underneath the Naardermeer polder. The total length of the cross section is 20 km with a maximum elevation of 27.1 m M.S.L. The lowest point of the aquifer was defined as a no-flow boundary at -260 m M.S.L. The cross section was discretized into a grid of 400 columns of $\Delta x = 50$ m and 104 layers of $\Delta z = 2.5$ m. From the total of 41600 elements, 35523 (85.4%) were considered active. Inactive cells define ground surface elevations (AHN, 2010) and the contour of the impermeable, hydrological base at the bottom of the system (DINO, 2010). Each active cell contains 16 particles to calculate advective transport of chloride over time which MOC3D models by means of particle tracking. Molecular diffusion, D_{mol}, was set at $8.64 * 10^{-5}$ m^2/day.

To take into account effects of density differences due to dissolved particles in brackish and saline groundwater on heads the fictive parameter freshwater head was introduced:

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

where Φf is the freshwater head [L], ρf is the reference density [ML^{-3}] which was set at 1000 kg/m^3, p is the pressure [$ML^{-1}T^{-2}$] and z is the elevation [L] (Oude Essink, 2001a).

The frequency at which fresh water heads need to be recalculated depends on the speed of particle displacement. Systems with groundwater extraction have fast particle movement and therefore require small time steps, Δt [T] to prevent unrealistic solutions for advective transport. Based on several test-calculations, Δt was set at 22.8 days (Oude Essink and Stuurman, 2006).

The following paragraphs describe parameters used to define the groundwater system and the way they are implemented in the model.

Geohydrology

The complex geohydrology present in the study area was simplified for use in the model. Throughout the whole system effective porosity was set at 0.3 and the anisotropy factor (ratio vertical and horizontal hydraulic conductivity, k_z/k_x) was set at 1/3. Longitudinal dispersivity, α_L, is generally assumed to be low in Dutch formations from the Holocene and

Pleistocene (Lebbe, 1983; Kooiman, 1989; Stuyfzand, 1993; Oude Essink, 2001b) and was set at 1 m with a ratio transversal to longitudinal dispersivity, α_T/α_L, of 0.1. The MODFLOW Block-Centered Flow package was used to assign transmissivity to each active cell individually based on data from a previous study in the area (Beemster, 2006).

The top formation in the Vecht river valley is a Holocene aquitard of clayey and peat composite varying in thickness from Δz = 0-5.04 m with a low horizontal hydraulic conductivity of k_x = 0.013-0.082 m/d (Beemster, 2006). Underneath is one good permeable aquifer with horizontal hydraulic conductivities varying from 13 to 62 m/d, which in the west is geologically divided by a low permeable clay formation from the Waalre, k_x = 0.0313 m/d (Beemster, 2006). Spanning the whole cross section, a layer of ice-pushed fluvial sand and gravel from the Pleistocene can be found. Under the hill ridge, the presence of highly heterogeneous sloping clay sheets has been suggested but little is known about structure and depth of these pushed deposits (Van Loon et al., 2009; Witmer, 1989). A grid of low permeable cells, k_x=0.125 m/d, roughly describing these tiled clay layers has been introduced in the model (Fig. 1) to achieve an increase in heads under the hill ridge as observed by van Loon et al. (2009) in observation wells in the region and predicted by other groundwater models of the area (Beemster, 2006; Gehrels, 1999).

Water levels

Three different water level types were represented in the model. Under the hill ridge free phreatic groundwater level were permitted whereas in polders and rivers artificially fixed surface water levels were implemented.

In MODFLOW, fluxes between groundwater and fixed surface water levels in the top active layer of the model, Q (m^3/d), are calculated using hydraulic head differences between user-defined water levels, H (m), and calculated hydraulic heads H_{cell} (m):

$$Q = k \cdot (H - H_{cell}) \tag{2}$$

where k denotes the specific hydraulic conductivity in the cell (1/d), which indicated the intensity of the interaction dependent on geohydrology.

The MODFLOW General Head Boundary package was used to assign fixed phreatic groundwater levels to five polders defined in the cross section based on values obtained from a map with resolution 250 x 250 m provided by the National Hydrological Instrument (NHI, 2010). In the Netherlands, artificially controlled polder water levels have strong influence on groundwater levels through relatively good contact via lakes, ponds, underground drainage pipes and extensive networks of ditches. The specific hydraulic conductivity of all polder cells in the model was set to 100 days.

Controlled water levels of surface waters, three rivers and the lakes in the Naardermeer polder, were implemented in the model using the MODFLOW River-package. The Amsterdam-Rhine Canal, the river Vecht, the Karnemelksloot and the lakes 'Veertigmorgen' and 'Bovenste Blik' were assigned fixed surface water levels of respectively -0.32, -0.4, -0.4, -1.0 and -1.0 m M.S.L. (NHI, 2010). The specific hydraulic conductivity of river- and lakebeds was set to 30 days (Beemster, 2006).

Drain types and drainage intensities

In this model two types of drains were applied. Saturated overland flow (sof) drains where implemented to simulate topographic control of groundwater levels by overland flow in areas with free phreatic groundwater. The second type of drain simulates drainage by underground pipes in polder areas (Veldhuizen et al., 2008).

The MODFLOW Drain-package was used to calculate drainage fluxes, Q_{drn} (m^3/d), in cells of the top active layer:

$$Q_{drn} = C_{drn} \cdot (d_{drn} - H_{cell}) \tag{3}$$

where C_{drn} denotes the drain conductance (m^2/d), d_{drn} the user-defined drain elevation (m) and H_{cell} the calculated hydraulic heads (m). Elevations of sof–drains were set equal to ground surface elevations and drain conductance was set to an arbitrary high value to avoid unrealistic heads above ground. Average distances between pipes in the Netherlands are 10-40 m (Dictaat Water, 2009), resulting in approximately 5 m^2 drains (5 x 1 m segment) in each active polder cell. Values for drain depth and conductance were obtained from maps with a 250 x 250 m resolution provided by NHI (2010). When running scenarios with raised groundwater levels, pipe-drains were considered inactive in order to look at the maximum effect.

Groundwater recharge and extraction

Average precipitation, 946 mm yr^{-1}, and reference evaporation, 601 mm yr^{-1}, for the period 2004-2008 were obtained from respectively observation station Abcoude and Schipol (KMNI, 2010). Reference evaporation values were determined by the Royal Netherlands Meteorological Institute (KMNI) conform the method of Makkink.

The MODFLOW Well-package was used to model groundwater recharge by assigning a flux into the top active layer of the system. Groundwater recharge was defined as precipitation surplus, which was calculated using crop factors, f(-), according to:

$$R = P - f \cdot E \tag{4}$$

where R denotes the precipitation surplus (m/d), P the precipitation (m/d) and E the reference evapotranspiration (m/d). Crop factors are dependent on type of land cover and on depth of phreatic groundwater levels (Beemster, 2006). Type of land cover was determined using satellite pictures of the region (Google Earth, 2010). More groundwater recharge was allowed in areas with phreatic groundwater levels of more than 2 m below ground by reducing the crop factor (Table 1).

Table 1
Land cover and corresponding groundwater recharge [mm/d] calculated using crop factors (derived after Beemster (2006) adjusted for areas with phreatic groundwater levels > 2 m below ground) and average Dutch meteorological conditions for 2004-2008 (KMNI, 2010).

Land cover	Groundwater recharge [mm/d] in areas with phreatic groundwater levels	
	< 2 m below ground	> 2 m below ground
Grass	0.94	1.17
Agricultural land	1.19	1.36
Urban areas	0.78	0.80
Deciduous forest	1.03	1.04
Coniferous forest	0.50	0.52
Open water	0.53	0.53

The MODFLOW well-package was also used to model groundwater extraction by assigning negative fluxes to cells. Currently three active pumping stations with groundwater extraction rates exceeding 1 million m^3/year are considered to be the main influence on groundwater flow in the cross section; pumping stations Huizen, Laren and Laarderhoogt. The pumping stations are approximately in one line perpendicular to the cross section and therefore represented in one column in the model. A rough estimation of a combined extraction rate for the relevant section of the hill ridge 'Het Gooi' was made taking into account individual extraction rates and distances to the cross section. To prevent unrealistic fluxes towards the extraction location, the combined groundwater extraction of 3.3 m^3/d was equally spread over 11 cells (Fig. 1).

Model calibration

To run the model scenarios, an initial chloride concentration distribution of the current situation was necessary. The Main MOC3D package was used to implement initial chloride concentrations in each active cell. Chloride concentrations in vertical boundaries were used to calculate the hydrostatic pressure distribution. Data of shallow measurement were used to implement chloride concentrations of polder surface water in the model. The MODFLOW General Head boundary package was used to implement chloride concentrations in boundaries as well as in polders.

The MODFLOW River-package was used to assign chloride concentrations to surface waters. The average chloride concentration in the Amsterdam-Rhine Canal for the years 2004-2008 was 82 mg/l (RIWA, 2010). Chloride concentrations in the river Vecht and Naardermeer lakes were set to 200 and 230 mg/l (Oude Essink and Stuurman, 2006) and for the Karnemelksloot a chloride concentration of 225 mg/l was measured in 2004 and used in the model.

To determine the current chloride concentration distribution throughout the groundwater system, an approximate chloride distribution for the situation 100 years ago was created (Fig. 2). Subsequently the model was run for 100 years under conditions representing that general time period. The chloride distribution 100 years ago was based on chloride measurements from the beginning of the 20th century and was generally assumed to be stratified with the highest chloride concentration at the bottom and decreasing towards the surface. The origin of brackish water at the bottom is theorized to be due to Holocene transgression (Post et al., 2003). Several current chloride point measurements in the area were available. From those 89 measurement points at different locations and depths within a radius of 600m of the cross section and from 1980 onwards were considered. Starting from a stratified situation, the chloride distribution was repeatedly adjusted to improve fit between simulation result and chloride point measurements (Fig. 2).

After calibration, the difference between modelled and observed chloride concentrations was less than 50 mg/l for 54% of the measurement points, less than 100 mg/l for 70% of the measurement points and less than 200 mg/l for 91% of the measurement points (Fig. 3). Deviations of more than 200 mg/l almost exclusively occur at locations with high chloride concentrations. This possibly relates to field measurement inaccuracies due to dependency on season, weather, equipment and sample technique. Furthermore, most of the observations are single time measurements. Overall, the model seems to underestimate chloride concentrations in regions with high salt load. Furthermore, chloride concentrations change significantly over very short distances, making position along the cross section crucial.

Results

The results of the groundwater model are depicted in Figs. 4-9. The responses of the regional groundwater system to the seven management scenarios are described below. Special attention is given to qualitative and quantitative development of groundwater reaching the plant root zone (1.5m below ground) in the Naardermeer polder (Figs. 7-9).

Continuation of current hydrological management

Continuing current hydrological management leads to a freshening of the groundwater underneath the Naardermeer polder (Fig. 4). The eastern part freshens quickly within 100 years and most of the brackish water is washed out within 500 years (Fig. 4 and Fig. 5 observation points C and D). In the western part of the lake 'Bovenste Blik', groundwater initially becomes more brackish but then quickly freshens as well (Fig. 5 observation point B). Salinity in the middle of the Naardermeer polder fluctuates in the first 100 years but then gradually decreases until, after approximately 1000 years, all brackish water is washed out (Fig. 5 observation point A). Groundwater seepage is strongest near the Karnemelksloot and quickly decreases within the first couple of hundred meters of the polder (Fig. 8). From there on, seepage gradually decreases until, after a small seepage peak on the west shore of the lake 'Bovenste Bilk', slow infiltration occurs in the rest of the polder. Overall the salt load delivered to the polder 250 years from now is the highest near the Karnemelksloot and slightly increased in the west of the lake 'Bovenste Blik' (Fig. 9).

Underneath the hill ridge, extraction of groundwater causes upwelling of brackish water although, after approximately 250 years, the chloride distribution around the extraction well becomes relatively stable. Looking at the Keverdijksche polder, the eastern part freshens whereas the western part becomes more brackish. Eventually, 1000 years from now, groundwater in most of the polder freshens. In the Aetveldsche polder brackish groundwater concentrates in the center whereas on the edges salinity deceases. This process intensifies slightly over time but overall salinity patterns stay the same (Fig. 4).

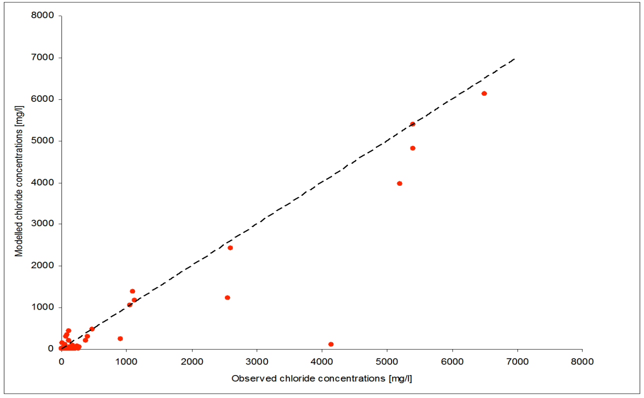


Fig. 3. Modelled versus observed chloride concentrations [mg/l] along the cross section for the current situation.

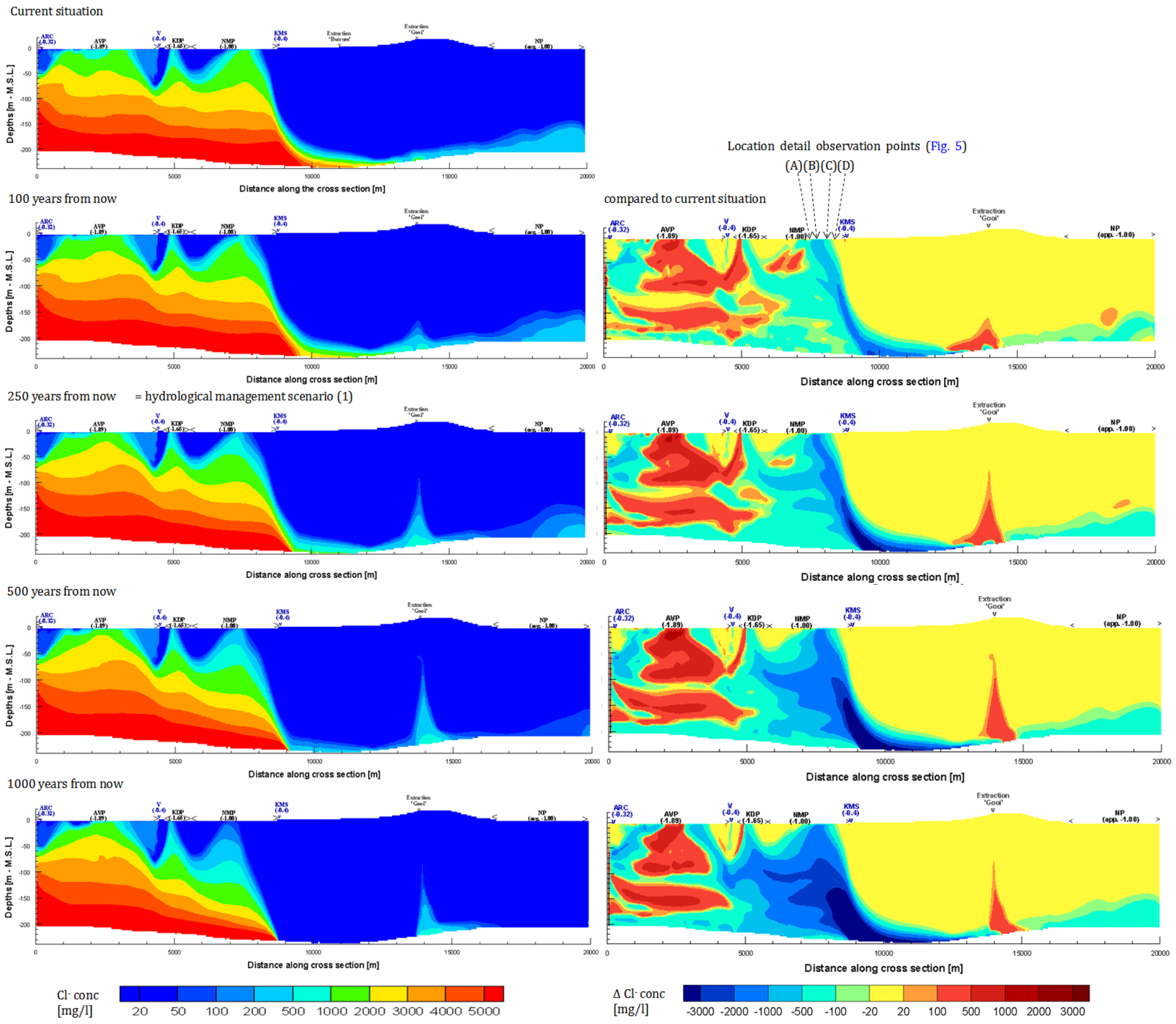


Fig. 4. Chloride concentration distribution [mg/l] of scenario 'continuation of current hydrological management' and chloride concentration difference [mg/l] compared to current situation for runtimes 100, 250, 500 and 1000 years. Abbreviations see **Fig. 1.**

Stopping groundwater extraction

Overall groundwater underneath the Naardermeer polder keeps freshening even after groundwater extraction is stopped, but freshening happens slower than under current hydrological management (Fig. 6). The freshening process mainly stagnates between 100 and 500 years (Fig. 5) and stagnation is most dominant in and around the lake 'Bovenste Blik' (Fig. 7). Vertical flux into and out of the polder is almost the same as under current hydrological management, only close to the Karnemelksloot seepage intensities are higher (Fig. 8). The salt load delivered to the east of the Naardermeer polder 250 years after stopping groundwater extraction is higher than continuation of current hydrological management would have caused (Fig. 9).

The Keverdijksche and the Aetsveldsche polder are hardly affected by discontinuing groundwater extraction (Fig. 6).

Lowering surface water levels in Naardermeer polder

Lowering controlled surface water levels in the Naardermeer polder causes parts of the polder itself to become more brackish instead of fresher after 250 years (Fig. 6).

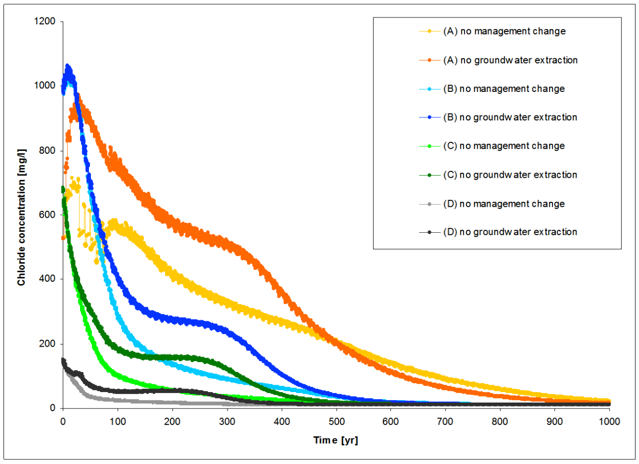


Fig. 5. Chloride concentration [mg/l] over time [yr] of 4 detail observation points in the Naardermeer polder, 1.5 m below ground. (A) 7450 m, (B) 7700 m, (C) 7950 m and (D) 8200 m along the cross section for the scenarios 'continue current hydrological management' and 'stopping groundwater extraction'. Location of observation points along the cross section are indicated in Figs. 1 and 4.

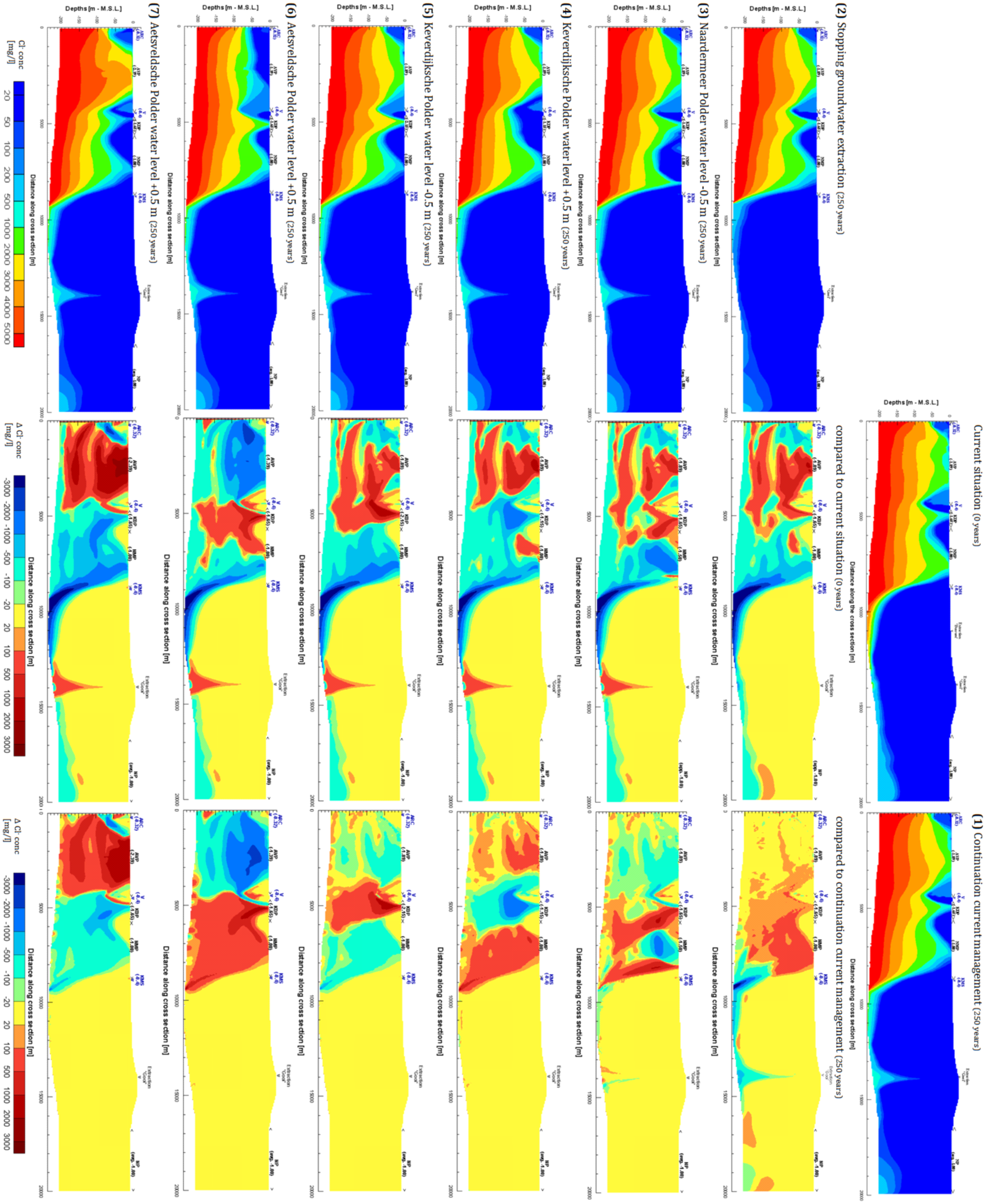


Fig. 6. Simulated chloride concentration distribution [mg/l] after 250 years using seven hydrological management scenarios. Chloride concentration difference [mg/l] of scenarios 2-7 compared to chloride concentration distribution of current situation (0 years) and compared to chloride concentration distribution simulated with continued current management after 250 years. Abbreviations see Fig. 1.

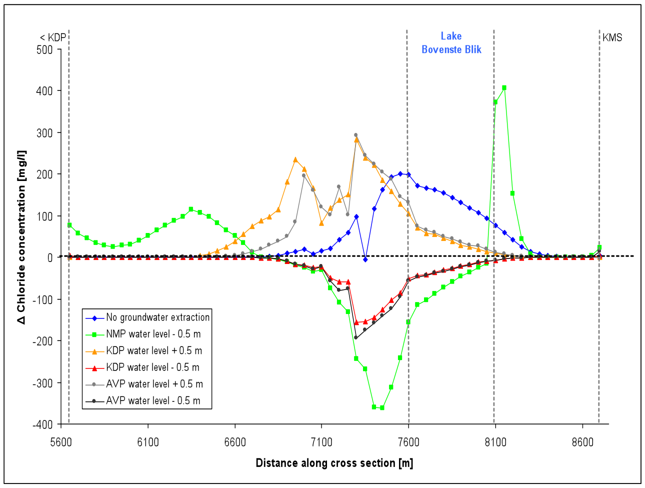


Fig. 7. Chloride concentration in the Naardermeer polder simulated after 250 years 1.5 m below ground of six hydrological management scenarios expressed as the deviation [mg/l] relative to the chloride concentration simulated with continued current management after 250 years. Abbreviations see Fig. 1.

A more detailed look reveals that salinisation occurs on the east shore of the lake 'Bovenste Blik' and in the west of the polder. In the center, freshening is intensified compared to simulations with current hydrological management (Fig. 7). Furthermore, the seepage-infiltration pattern in the Naardermeer polder changes. Seepage intensities near the Karnemelksloot weaken but overall increase in the east of the polder. The switch to infiltration moves eastwards to the east of the lake 'Bovenste Blik'. An additional seepage area develops in the west of the polder (Fig. 8). Overall, 250 years from now, salt pressure on the west shore of the lake 'Bovenste Blik' disappears but strongly increases on the east shore of the lake. On the edge of the new seepage area in the west of the polder, the salt pressure pattern changes as well (Fig. 9).

This hydrological management choice increases the salinisation of the Keverdijksche polder even in sections which under current management would become fresher. The chloride distribution pattern in the Aetveldsche after 250 years stays the same, but the whole polder slightly freshens as a consequence of the hydrological management change (Fig. 6).

Adjusting surface water levels in directly adjoining polder

Increasing controlled surface water levels in the Keverdijksche polder causes the freshening process in the Naardermeer polder to stagnate 250 years from now. In the center of the polder, chloride concentrations increase to the extend that salinisation occurs compared to the current situation. Decreasing controlled groundwater levels in the Keverdijksche polder on the other hand, intensify freshening of the Naardermeer polder; especially in the west of the lake 'Bovenste Blik' (Figs. 6 and 7). Vertical fluxes and salt pressures in the Naardermeer polder are mostly unaffected compared to continuation of current hydrological management (Figs. 8 and 9).

In the Keverdijksche polder, increasing or decreasing controlled surface water levels causes respectively freshening or salinisation throughout the whole polder. Looking at the Aetsveldsche polder, raising surface water level in the Keverdijksche polder causes fresh areas to become fresher and brackish areas to increase in size and become more brackish compared to continuation of current management.

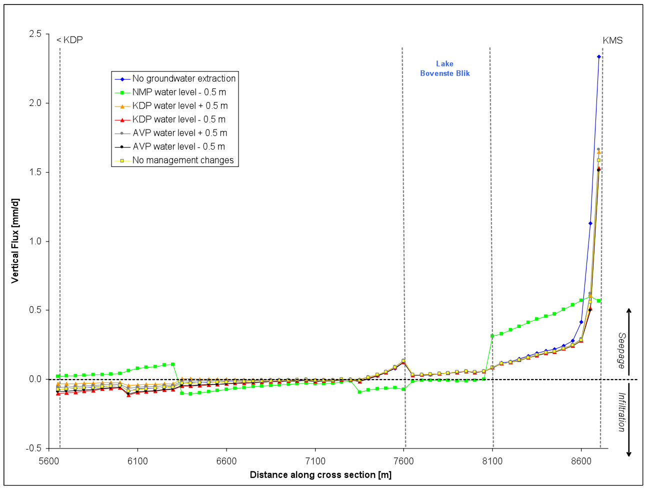


Fig. 8. Simulated vertical flux [mm/d] in the Naardermeer polder 1.5 m below ground for 7 management scenarios after 250 years. Abbreviations see Fig. 1.

Lowering surface water levels in the Keverdijksche and the Naardermeer polder has approximately the same effect on groundwater in the Aetveldsche polder (Fig. 6).

Adjusting surface water levels in distant polder

Adjusting controlled surface water levels in the Aetveldsche polder has a similar effect on chloride distribution in the shallow regions of in the Naardermeer polder as adjusting controlled surface water levels in the Keverdijksche polder (Figs. 6 and 7). Vertical fluxes and salt pressures in the Naardermeer polder are mostly unaffected by adjustment of groundwater levels in the Aetsveldsche polder compared to continuation of current management (Figs. 8 and 9).

Raising or lowering controlled groundwater levels in the Aetsveldsche polder causes respectively salinisation or freshening of the Keverdijksche polder. In the Aetveldsche polder itself this hydrological management results in respectively freshening or salinisation of most of the polder compared to now (Fig. 6).

Discussion

Methodological approach

To evaluate the response of a regional groundwater system to hydrological management, this study developed a 2-dimensional, density dependent groundwater model. The choice to use a 2-dimensional model, motivated by control over preparation and computation time, can be justified by placing the linear cross section in line with groundwater flow from the hill ridge over the river valley. A sensitivity analysis was performed to determine the robustness of the model to uncertain climate and geohydrological parameters (Fig. 10). The sensitivity analysis shows that the model is quite robust to variations of the conductivity of riverbeds and presence of clay sheets under the hill ridge. Higher sensitivities were found for the conductivity of the ice-pushed fluvial sand layer and recharge intensities. The most sensitive parameter turns out to be the conductivity of the lakebeds in the Naardermeer polder. Nevertheless, we considered the model presented in this paper of sufficient quality to describe the response of the groundwater system to different hydrological management scenarios for two reasons.

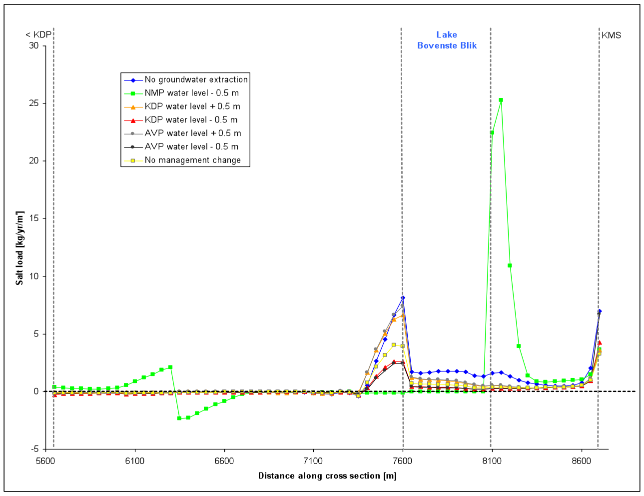


Fig. 9. Calculated salt load [kg/yr/m'] in the Naardermeer polder 1.5 m below ground for 7 management scenarios after 250 years. Abbreviations see Fig. 1.

Firstly, the current chloride concentration distribution is calibrated using current observation data. Although modelled and observed chloride concentrations do not coincide at all measurement points, the overall chloride distribution pattern of the region could be reproduced by the model. The calibration process also showed that groundwater flow patterns suggested for the region (Schot en Molenaar, 1992) and more specifically for the Naardermeer (Schot et al., 1988) can be simulated by the model. Secondly, the effects of hydrological management scenarios are compared to development of the groundwater system under current management using the same input parameters. This way, effects of management changes are separated from changes in groundwater quality and quantity caused by uncertain input parameters.

Development of groundwater quality and quantity

The results of this study show that under current hydrological management, using the presented parameters, salinity underneath the Naardermeer polder decreases. Continuous inflow of regional groundwater from the hill ridge transports brackish water underneath the Naardermeer polder towards lower-lying polders in the west. The groundwater system has no input of additional brackish water and therefore becomes fresher, pushing salt particles towards the west. After initial fluctuation of chloride concentrations in the center, the Naardermeer polder seems to freshen quickly within the first 100 years from now.

Stopping groundwater extraction in the hill ridge causes brackish groundwater, formerly being pulled towards the extraction well, to surface in the Naardermeer polder. More rainwater infiltrating in the hill ridge flows towards the Naardermeer polder and passes through deeper segments of the aquifer. Increased flux and depth cause more salt particles to be transported upwards and become noticeable in the Naardermeer polder about 50 to 100 years from now by stagnating freshening of the polder. The biggest effect can be observed in the center of the polder but also on the east shore of the lake 'Bovenste Blik', where ecological important fen meadows lie. After about 500 years most of the brackish water, changing flow direction by stopping groundwater extraction, has reached the surface and freshening continues.

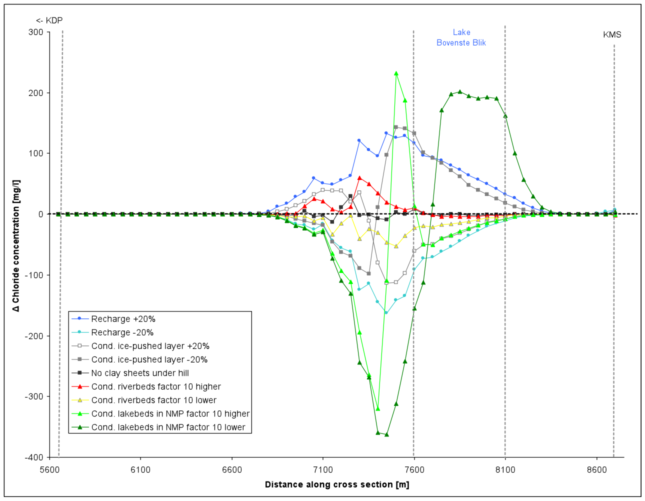


Fig. 10. Sensitivity of the model to uncertain climate and geohydrological parameters. Sensitivity was defined as the change in chloride concentration [mg/l] after 250 years, 1.5m below ground in the Naardermeer polder caused by variation of input parameters. Varied input parameters and their range were: recharge +/- 20%; conductivity of the ice-pushed fluvial sand layer +/- 20%; removal of clay sheets under the hill ridge; conductivity of riverbeds factor 10 higher or lower; conductivity of lakebeds in the Naardermeer polder factor 10 higher or lower. Abbreviations see Fig. 1.

Polders further away from the hill ridge are mostly unaffected by this hydrological management change. Stopping groundwater extraction therefore seems to, at least partly, recover the original, regional groundwater flow to the Naardermeer polder as aimed for by introduction of the restoration plan Naardermeer (Boosten et al., 2006). However, the natural freshening process stagnates, at least temporarily, due to additional salt being transported to the polder.

Lowering controlled surface water levels in the Naardermeer polder itself is a possible management development because currently water from the IJmeer, in the north of the Gooi- Vechtstreek is pumped into the polder during hot summers to prevent the wetland from drying out. In order to return to a more natural state, it could an option to let the wetland dry out in summer, which would result in average lower yearly surface water levels. This research shows that this would result in a shift of the seepage-infiltration areas within the polder. The area of regional groundwater discharge in the east of the polder intensifies but becomes smaller. The lake 'Bovenste Blik' starts to infiltrate and part of the water flows back towards the east shore of the lake. These two processes combined cause a strong increase of salt load delivered to the fen meadows on east shore of the lake. Water infiltrating in the center of the Naardermeer polder discharges in the western part of the polder, creating a new discharge area but consisting of lake- and rainwater rather than of nutrient poor, alkaline groundwater. This new local groundwater flow pattern causes most of the salt particles to bypass the Naardermeer polder, flowing directly towards the Keverdijksche polder instead.

Lowering surface water levels in the Keverdijksche and Aetveldsche polder both increase freshening of the Naardermeer polder by pulling brackish groundwater towards the east and therefore preventing it from reaching the near root zone in the Naardermeer. However, as a consequence the polders themselves become more saline. Raising surface water levels in the Keverdijksche and

Aetveldsche polder has the exact opposite effect; the freshening process in the Naardermeer polder is slowed down. Looking at fluxes in and out of the Naardermeer polder it can also be seen that this hydrological management would not significantly decrease outflow of groundwater from the Naardermeer to adjoining polders.

Consequences for vegetation

To ascertain the impact on biodiversity by looking at ecological effects, decreased discharge of nutrient poor, alkaline groundwater was thought to be the reason for environmental degradation in the fen meadows of the Vecht river valley (Barendregt et al., 1995). Based on results of this research it seems unlikely that increasing discharge by discontinuing groundwater extraction in the hill ridge alone would help recover rare plant species in Naardermeer nature reserve because increase in discharge occurs mainly near the Karnemelksloot and less in ecologically important fen meadows. Lowering controlled surface water levels in the Naardermeer polder itself leads to more intense discharge into fen meadows but the delivered salt load is also increased which would hamper vegetation recovery. Loon et al. (2009) suspected, apart from a shift in predominant discharge mechanism from overland flow to drain discharge, a decrease in discharge area under 20th century hydrological management to be the underlying cause of environmental degradation in fen meadows. This research showed no increase in discharge area fed by regional groundwater in the Naardermeer under any tested hydrological management scenario. Therefore it seems unlikely that discharge areas were larger before introduction of hydrological management in the 20th century. The model presented in this paper did not include the option of re-infiltration of overland flow and therefore we can not judge the importance of a possible mechanism shift.

This research also shows that a more natural management in the Naardermeer by allowing lower surface water levels might, besides having a negative effect due to temporarily drying out of the wetland (Grootjans et al., 2005), also have a negative effect on the quality of groundwater available to vegetation. The salt content of groundwater discharged into fen meadows might hamper vegetation recovery. Furthermore, vegetation in the west of the polder will be affected by the area changing from infiltration to an area supplied by discharge of lake- and rainwater. Additional research would have to be conducted to find out if river water pumped in from the IJmeer or regional groundwater with increased salinity is more favorable for fen vegetation on the east shore of the lake ‘Bovenste Blik’. Particularly considering that the spread of water pumped into the Naardermeer polder is mostly restricted to the northwestern part of the Naardermeer (Schot et al., 1988).

Lowering controlled surface water levels in directly adjoining and distant polders increases the freshening process in the Naardermeer polder and therefore improves the change for recovery of fen species, especially in combination with restoration measurements directly applied in the fen meadows (Klimkowska et al., 2010; Van der Hoek and Heijmans, 2007). On the other hand, vegetation in the polders themselves will suffer from lower groundwater levels and increased salinity. In the Aetveldsche polder, which is used for agriculture, conditions for agricultural machinery improve with lower water levels, but in the long-term increased salinity might hamper crop growth (Katerji et al., 2001, 2003). Results also show that raising controlled surface water levels in directly adjoining and distant polders would lessen salt pressure on vegetation in the polders themselves. The freshening process in the Naardermeer polder on the other hand is slowed down, which possibly delays recovery of the vegetation there. This hydrological management action does not significantly reduce infiltration fluxes in the west of the Naardermeer polder to adjoining polder, which would create more favorable conditions for vegetation.

Conclusion

The results of this research confirm that changes in hydrological management affect the distribution of brackish groundwater throughout the groundwater system as predicted by Schot and Molenaar (1992). Under current management brackish groundwater will eventually be washed out from underneath the Naardermeer polder. The model presented in this paper shows that the quality of groundwater supplied to vegetation in the nature reserve would be negatively affected by discontinuing extraction in the hill ridge, because the freshening process in the polder would stagnate. Also allowing lower surface water levels in the Naardermeer polder would cause an unfavorable increase in salinity of groundwater supplied to ecological important fen meadows. The most successful hydrological management to increase freshening in the Naardermeer polder would be lowering controlled surface water levels in directly adjoining polders or even in bigger, more distant polders. However, consequences for natural vegetation as well as agricultural crops in those polders themselves would be negative.

Looking at the bigger picture, based on this research it can be concluded that extraction of groundwater in a hill ridge mostly affects fresh-brackish groundwater distribution in the discharge area nearest to the hill ridge and does not have as much affect on areas further away in the valley. Regional hydrological management also needs to consider that adjusting surface water levels in polders directly adjoining as well as more distant to the polder of interest affects the brackish groundwater distribution underneath the polder of interest. Furthermore, hydrological management aimed at improving quality or quantity of groundwater supplied to vegetation in one polder might have adverse effects on groundwater conditions in adjoining polders. Overall, it can be concluded that the presence of brackish water in deep aquifers adds another dimension to the complexity of groundwater systems, and that behavior of brackish groundwater needs to be considered by authorities when deciding hydrological management strategies aimed at preserving or restoring nature.

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