Effects of climate change on coastal groundwater systems: A modeling study in the Netherlands

G. H. P. Oude Essink,[1] E. S. van Baaren,[1] and P. G. B. de Louw[1]

Received 2 October 2009; revised 26 May 2010; accepted 17 June 2010; published 14 October 2010.

[1] Climate change in combination with increased anthropogenic activities will affect coastal groundwater systems throughout the world. In this paper, we focus on a coastal groundwater system that is already threatened by a relatively high seawater level: the low-lying Dutch Delta. Nearly one third of the Netherlands lies below mean sea level, and the land surface is still subsiding up to 1 m per century. This densely populated delta region, where fresh groundwater resources are used intensively for domestic, agricultural, and industrial purposes, can serve as a laboratory case for other low-lying delta areas throughout the world. Our findings on hydrogeological effects can be scaled up since the problems the Dutch face now will very likely be the problems encountered in other delta areas in the future. We calculated the possible impacts of future sea level rise, land subsidence, changes in recharge, autonomous salinization, and the effects of two mitigation countermeasures with a three-dimensional numerical model for variable density groundwater flow and coupled solute transport. We considered the effects on hydraulic heads, seepage fluxes, salt loads to surface waters, and changes in fresh groundwater resources as a function of time and for seven scenarios. Our numerical modeling results show that the impact of sea level rise is limited to areas within 10 km of the coastline and main rivers because the increased head in the groundwater system at the coast can easily be produced though the highly permeable Holocene confining layer. Along the southwest coast of the Netherlands, salt loads will double in some parts of the deep and large polders by the year 2100 A.D. due to sea level rise. More inland, ongoing land subsidence will cause hydraulic heads and phreatic water levels to drop, which may result in damage to dikes, infrastructure, and urban areas. In the deep polders more inland, autonomous upconing of deeper and more saline groundwater will be responsible for increasing salt loads. The future increase of salt loads will cause salinization of surface waters and shallow groundwater and put the total volumes of fresh groundwater volumes for drinking water supply, agricultural purposes, industry, and ecosystems under pressure.

Citation: Oude Essink, G. H. P., E. S. van Baaren, and P. G. B. de Louw (2010), Effects of climate change on coastal groundwater systems: A modeling study in the Netherlands, *Water Resour. Res.*, *46*, W00F04, doi:10.1029/2009WR008719.

1. Introduction

[2] Man has always been attracted to low-lying delta areas throughout the world because of the abundance of food available (e.g., fisheries and agriculture) and the opportunities for economic activities (e.g., ease of travel, trade, harbors and ports, and infrastructure). Fresh groundwater resources in these delta areas are used intensively for domestic, agricultural and industrial purposes, while the availability of huge quantities and the high quality of the fresh water relative to the surface water makes it a popular resource [*Custodio and Bruggeman*, 1987; *Food and Agriculture Organization*, 1997; *Van Weert et al.*, 2008; *Post and Abarca*, 2010]. In the future, the exploitation of fresh groundwater resources will increase due to population and economic growth, intensified agricultural development, and the loss of surface water resources due to contamination [*Arnell*, 1999; *Jelgersma et al.*, 1993; *Ranjan et al.*, 2006]. In addition, the anticipated sea level rise and changes in recharge and evapotranspiration patterns will exacerbate the pressures on the coastal groundwater system. It is not clear how far delta areas will be threatened by these future stresses from the point of view of groundwater. Conceptually, it is obvious that coastal aquifers will become more saline at an accelerating rate (due to salt water intrusion) and that this could lead to a loss in fresh groundwater resources. This phenomena of salt water intrusion as a threat to fresh groundwater resources has been studied already since the 1960s with an increasing intensity [e.g., *Cooper et al.*, 1964; *Lee and Cheng*, 1974; *Voss*, 1984; *Voss and Souza*, 1987]. Low-lying delta areas have another process that will lead to a more saline groundwater and surface water system: seepage water (i.e., upward flow of groundwater because a higher hydraulic head in the first aquifer, which is situated just below the Holocene confining layer, exceeds the phreatic and surface water levels) will probably have a higher salinity than at present, mainly

[1] Department of Soil and Groundwater, Deltares, Utrecht, Netherlands.

0043-1397/10/2009WR008719

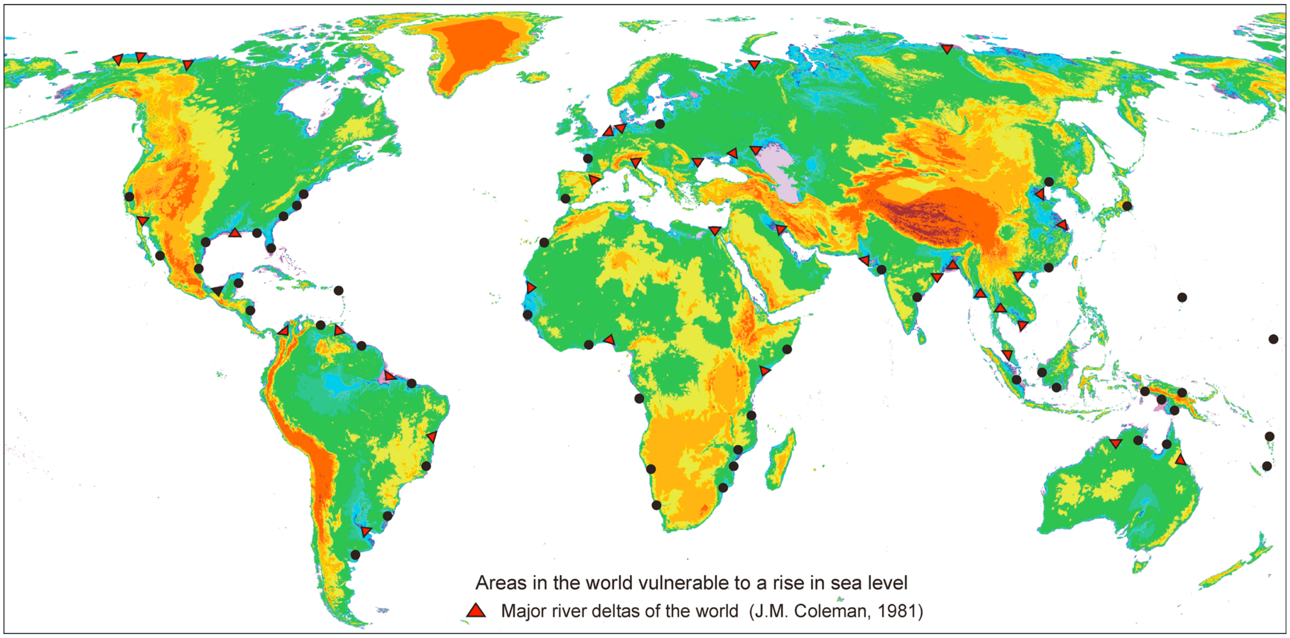

Figure 1. Major river deltas in the world vulnerable to sea level rise [*Coleman*, 1981].

due to upconing of brackish to saline groundwater from old marine deposits. This could result in poor crop yields due to salt damage. If crops with an even higher salt tolerance cannot withstand the higher salinities, the fertile delta areas may eventually be transformed into barren land.

[3] In this article, we focus on the coastal groundwater system of the Dutch Delta for several reasons: the enormous amount of different types of hydro(geo)logical data to support our research on processes in the groundwater system; the hundreds of studies on groundwater in our delta that have already been executed since 1889 [*Badon Ghijben and Drabbe*, 1889]; the urgency at a national level to make our delta fresh water supply climate change proof; the intense socioeconomical activities; and last but not least, the fact that our delta is already being threatened by a relatively high seawater level. In fact, nearly one third of the Netherlands is already below mean sea level (msl) [*Huisman et al.*, 1998; *van de Ven*, 1993], and half of the country would be flooded regularly without flood protection infrastructure.

[4] As the Dutch Delta lies partly below mean sea level and its economic activities are important, it will be one of the first delta areas to face the impacts of climate change in combination with increased anthropogenic activities. The Dutch Delta can thus serve as a laboratory case for many other low-lying deltas in the world (Figure 1). Our findings can be scaled up since the problems we face now will very likely be the problems for other delta areas in the future. On top, stresses on the groundwater system are similar throughout the world. The way we cope with the threats and the strategies we adopt for adaptation and mitigation can be seen as a blueprint for other deltas in the future. We believe the impact patterns on the Dutch fresh water resources due to future changes could be similar to other delta areas worldwide with similar hydro(geo)logical conditions (Figure 1), including the Po, Mississippi, Nile, Mekong, Chinese and Indian deltas and the U.S. Atlantic coast [*Meisler et al.*, 1984; *Navoy*, 1991; *Sherif and Singh*, 1999; *Bobba*, 1998, 2002; *Barlow*, 2003; *Masterson and Garabedian*, 2007; *Giambastiani et al.*, 2007; *Vandenbohede et al.*, 2008; *Deltares*, 2009; *Post and Abarca*, 2010; *Custodio*, 2010; *Barlow and Reichard*, 2010]. Although the characteristics of these delta areas are obviously different, the general picture is that groundwater management in the coastal zone must face serious impact from future stresses [*Ranjan et al.*, 2009].

[5] Our aim is to quantify the possible impacts of climate change in combination with anthropogenic activities on the coastal groundwater system in the Dutch Delta. We therefore constructed a three-dimensional numerical model of the variable density groundwater flow and coupled solute transport. Innovative aspects in this research is combining at this regional scale in three dimensions climate change, sea level rise, human activities, land subsidence as well as countermeasures, while the different chloride concentrations are combined to one chloride and density distribution in three dimensions. When assessing the effect of countermeasures it might become a tool to be used for future analysis on the case of a whole delta with enough detail.

[6] We determine the zones of influence of sea level rise, salinization of groundwater systems, salt loads into surface water systems, and the changing volumes of fresh water, and quantified the impact of two possible mitigation countermeasures. Salt loads from the groundwater system to the surface water system are calculated by multiplying seepage flux and the corresponding chloride concentration, and expressed in tons of chloride per year.

2. Methods

2.1. Study Area

[7] The major part of the Netherlands consists of lagoon and delta sediments of the rivers Rhine, Scheldt and Meuse. Before this area was occupied by man, it was easily flooded by water from rivers and the sea. Starting from approximately 300 B.C., the inhabitants built dwelling mounds and

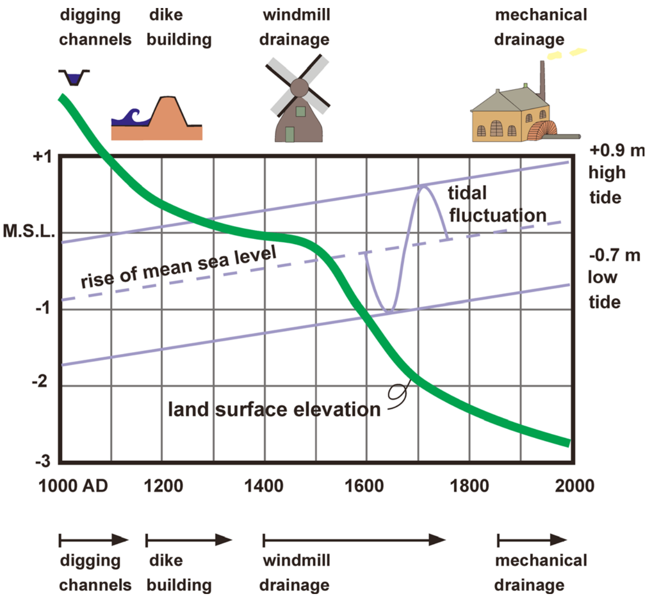

Figure 2. Scheme of land subsidence in the Netherlands during the past 1000 years [*van de Ven*, 1993].

drained floodplains (Figure 2). From about 1100 A.D., the inhabitants built embankments along the main rivers and sluices 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 in a pattern of small polder areas surrounded by dikes. A polder is an area which is protected from water outside the area and which has a controlled water level. Later, the land surface was lowered by cutting peat for fuel and this created freshwater lakes. Water from the polders could be removed more easily after the introduction of windmills and the paddle wheel in the sixteenth century; these were followed by the use of steam, electrical and diesel engines. It became possible to reclaim larger and deeper lakes. What remains of the swampy, flat area with some streams and lakes is a pattern of small and large polders, each surrounded by its own dikes and with a controlled surface water level. The improved draining of the polders caused further land subsidence due to oxidation of the peat and shrinkage of clay deposits (Figure 2). Nowadays, nearly one third of the Netherlands lies below msl.

[8] For centuries, numerous human activities have threatened the coastal lowlands of the Netherlands [*Zagwijn*, 1989; *Schultz*, 1992; *van de Ven*, 1993]. Examples include the draining of lakes, land reclamation, peat digging for fuel, sand excavation for building activities, and groundwater extraction for drinking, agricultural and industrial water supply. At present, the availability of enough fresh water of high quality has always been an important issue in the Netherlands [*Pulles*, 1985]. If there is a water shortage during a summer drought, the priority of the end users who are allowed to claim fresh water is determined by the Dutch Water Management Act. The order of preference for use is (1) stability of embankments, shrinkage and oxidation of peat, sensitive nature; before (2) domestic water supply and power generation; before (3) industry and sprinkling water of expensive crops (horticulture); before (4) other end users such as agriculture, nature, industry, recreation, navigation. Climate change is jeopardizing the Dutch Delta even more. Although immediate safety against flooding is the most important water management issue for the Dutch government, fresh water supply is second best. The vulnerable fresh surface water and groundwater resources are also threatened by sea level rise, land subsidence, increasing river discharge, and changes in recharge and evapotranspiration patterns [*Kwadijk et al.*, 2007; *Stuurman et al.*, 2008].

[9] The study area is situated in the southwest of the Netherlands in the delta of the rivers Rhine, Scheldt and Meuse (Figure 3). It has a surface area of 100 km by 92.5 km. This coastal area is the most densely populated part of the Netherlands (more than 8 million people) and includes the four largest cities: Amsterdam, Rotterdam, The Hague and Utrecht. It is characterized by a diversity of land types, including the sea, dunes, rivers, polders, peatlands and lakes. Large amounts of groundwater are extracted from the dunes and from the eastern part of the study area to supply the demand for drinking water. Phreatic water levels in the dunes can rise to more than 7 m above msl. The land side of the dunes consists of deep polders, the so-called reclaimed lake areas, with controlled surface water levels of −4 m to −7 m msl. This leads to upward groundwater seepage from the first aquifer under these deep polders. The Haarlemmermeer polder is the largest reclaimed lake area, while the Groot Mijdrecht polder has the largest seepage fluxes (more than 5 mm/d). The deep polders are surrounded by higher-lying peatlands (−1 to −4 m msl), which are subject to infiltration. Water must be constantly admitted to maintain the high water levels needed to slow down the continuous process of land subsidence due to peat mineralization.

2.2. Numerical Method and Model Setup

[10] To quantify changes in the coastal groundwater flow regime, we modeled the transient variable density groundwater flow and coupled solute transport in three dimensions with the model code MOCDENS3D [*Vandenbohede et al.*, 2009; *Vandenbohede*, 2008; *Bakker et al.*, 2004; *Oude Essink*, 2001a]. The Oberbeck-Boussinesq approximation is valid for the circumstances in the Dutch coastal aquifers: we suggest that density variations due to concentration changes remain small to moderate in comparison with the reference density ρ [*Holzbecher*, 1998; *Nield and Bejan*, 1992]. As such, a substantial simplification of the governing differential equations can be derived. The most simplified form is that only the Darcian specific discharge is coupled with the variable density groundwater flow and solute transport equations:

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} = S_s \frac{\partial \phi_f}{\partial, t} + W \qquad (1)$$

$$q_x = -\frac{\kappa_x}{\mu}\frac{\partial p}{\partial x} q_y = -\frac{\kappa_y}{\mu}\frac{\partial p}{\partial y} q_z = -\frac{\kappa_z}{\mu}\left(\frac{\partial p}{\partial z} + \rho g\right) \qquad (2)$$

where q_x, q_y, and q_z are the Darcian specific discharges in the principal directions (L T^{-1}); S_s is the specific storage of the porous material (L^{-1}); ϕ_f is the freshwater head; W is the source function which describes the mass flux of the fluid into (negative sign) or out of (positive sign) the system (T^{-1}); κ_x, κ_y, and κ_z are the principal intrinsic permeabilities (L^2); μ is dynamic viscosity of water (M L^{-1} T^{-1}); g is gravitational

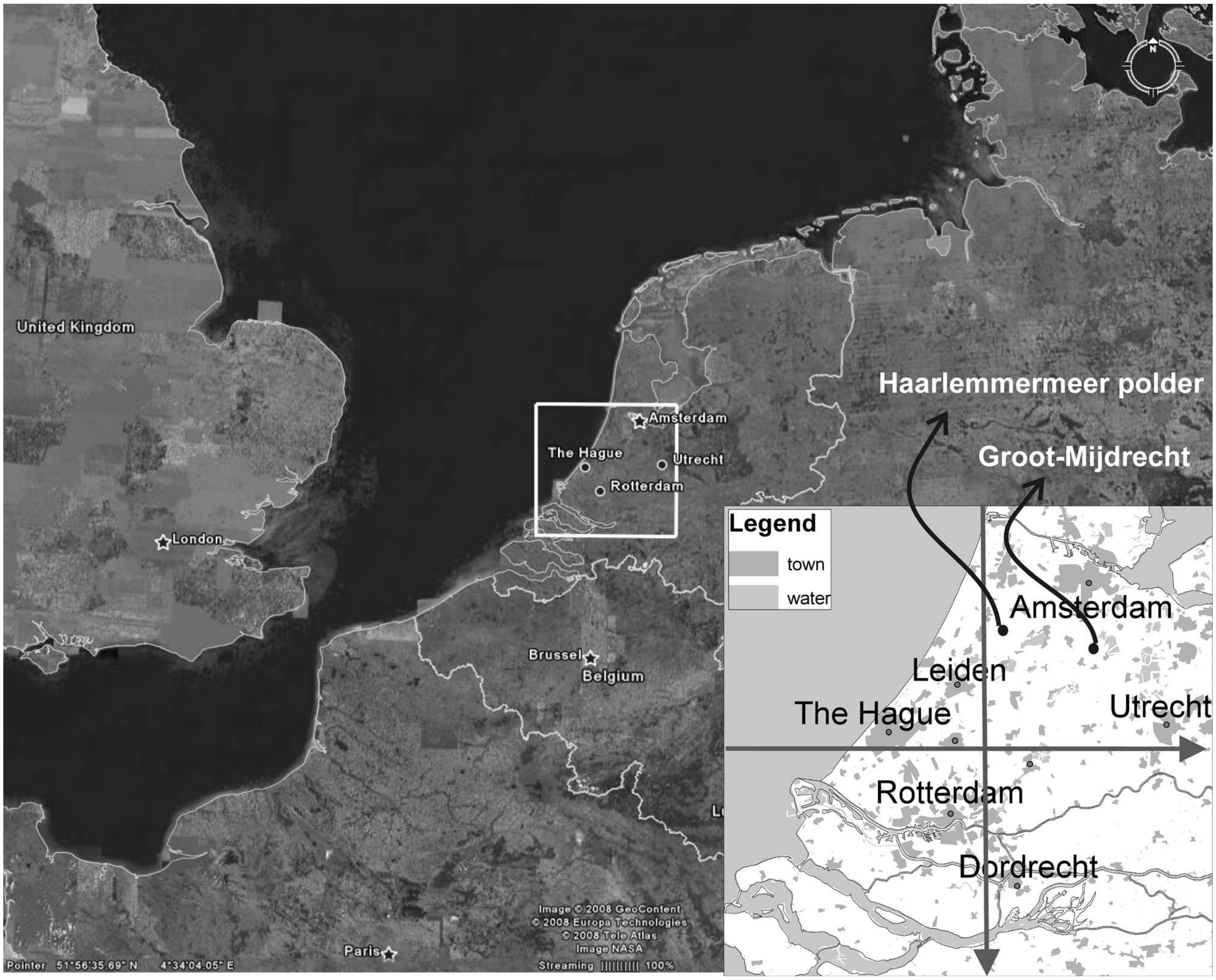

Figure 3. Study area located in the Dutch delta region of the Rhine, Meuse, and Scheldt rivers.

acceleration (L T^{-2}); p is pressure (M L^{-1} T^{-2}); and ρ is the density (M L^{-3}). A so-called freshwater head ϕ_f is introduced to take into account differences in density in the calculation of the head [*De Wiest*, 1965; *Holzbecher*, 1998]:

$$\phi_f = \frac{p}{\rho_f g} + z \quad (3)$$

where ρ_f is the density of fresh groundwater and z is the elevation head (L). With the freshwater head, piezometric heads of fresh, brackish and saline groundwater can easily be aligned with each other [*Oude Essink*, 2001b; *Post et al.*, 2007]. In many cases, the small viscosity differences can be neglected if the density differences in normal hydrogeological systems are considered [*Verruijt*, 1980; *Bear and Verruijt*, 1987]. Rewriting the Darcian specific discharge in terms of freshwater head gives

$$\frac{\kappa_i \rho_f g}{\mu} = k_i \quad (4)$$

$$q_x = -k_x \frac{\partial \phi_f}{\partial x} q_y = -k_y \frac{\partial \phi_f}{\partial y} q_z = -k_z \left(\frac{\partial \phi_f}{\partial z} + \frac{\rho - \rho_f}{\rho} \right) \quad (5)$$

where ρ_i is the density of groundwater (M L^{-3}). Note that when $\rho = \rho_f$, the buoyancy term vanishes. The basic water balance used in MODFLOW is given below [*McDonald and Harbaugh*, 1988]:

$$\sum Q_i = S_s \frac{\Delta \phi_f}{\Delta t} \Delta V \quad (6)$$

where Q_i is the total flow rate into the model cell (L^3 T^{-1}), S_s is the specific storage of the porous material (L^{-1}) and ΔV is the volume of the model cell (L^3). For a detailed description of how the MODFLOW basic equation is adapted to variable density groundwater flow, see *Oude Essink* [2001b]. Solute (namely salt) transport in porous media is represented by the advection-dispersion equation [*Konikow et al.*, 1996]:

$$R_d \frac{\partial C}{\partial t} = \frac{\partial}{\partial x_i} \left(D_{ij} \frac{\partial C}{\partial x_j} \right) - \frac{\partial}{\partial x_i} (C V_i) + \frac{(C - C')W}{n_e} - R_d \lambda C \quad (7)$$

and

$$D_{ij} = (D_m + \alpha_T |V|) \delta_{ij} + (\alpha_L - \alpha_T) \frac{V_i V_j}{|V|} \quad (8)$$

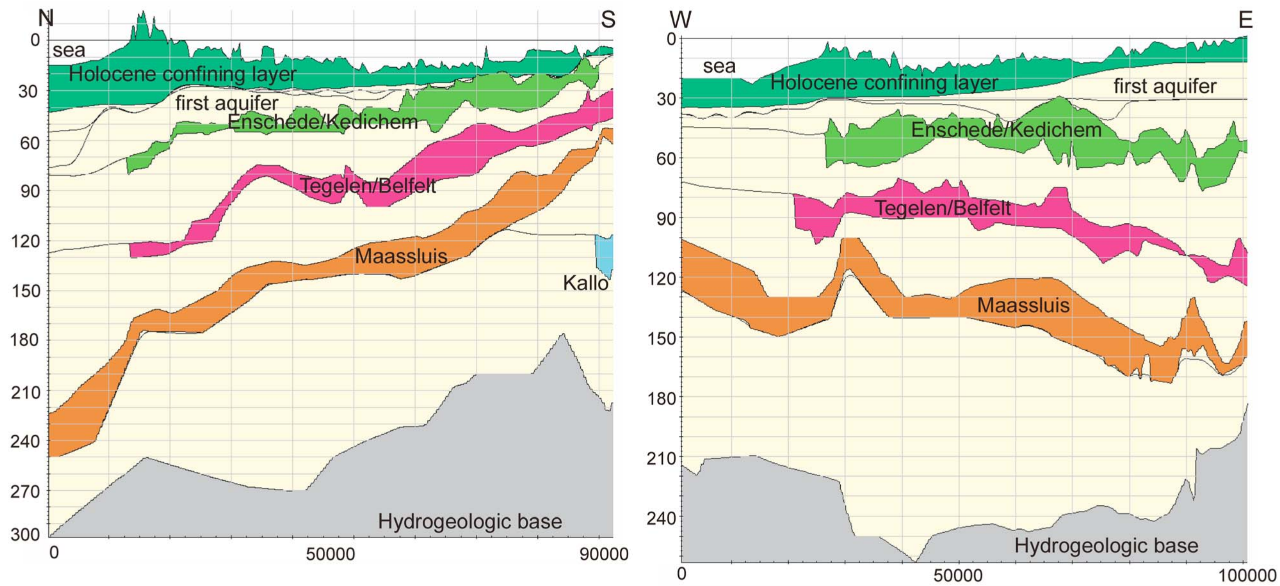

Figure 4. Two geological profiles across the study area; position and names of aquitards in the groundwater system are given (based on the databases of the Geological Survey of The Netherlands).

where C is the chloride concentration (M L^{-3}), D_{ij} is the coefficient of hydrodynamic dispersion (L^2 T^{-1}), D_m is the coefficient of molecular diffusion (L^2 T^{-1}), R_d is the retardation factor (−), V_i, and V_j are the components of the effective velocity in the *i* and *j* directions, respectively (L T^{-1}), |V| is the magnitude of the effective velocity (L T^{-1}), C′ is the concentration of the dissolved solids in a source or sink (M L^{-3}), *W* is the source function, which describes the mass flux of the fluid into (negative sign) or out of (positive sign) the system (T^{-1}), α_L and α_T are the longitudinal and transversal dispersivity of the aquifer (L) and δ_{ij} is the Kronecker delta.

[11] Advective transport of solutes is modeled by the particle tracking method and dispersive transport by the finite difference method. A linear equation of state couples groundwater flow and solute transport:

$$\rho_i = \rho_{\mathrm{f}}[1 + \beta_{\mathrm{C}} C] \tag{9}$$

where ρ_i is the density of groundwater (M L^{-3}) and β_C is the volumetric concentration expansion gradient (L^3 M^{-1}). During the numerical simulation, the density and thus the groundwater flow are affected by changes in solutes that are transported by advection, dispersion and molecular diffusion. The groundwater flow equation is recalculated regularly to account for density changes.

2.3. Geology and Chloride Concentration

[12] Based on details of the geology (Dutch Geological Survey), we implemented 4 aquifers and 5 aquitards in our model (Figure 4). The top layer (i.e., the Holocene confining layer) consists of poorly permeable Holocene clay and peat deposits, except for the dunes where it consists of sand [*Weerts et al.*, 2005]. The geohydrological properties were taken from the Regional Geohydrological Information System (REGIS) (TNO-NITG, Delft, Netherlands, 1998). REGIS is an interactive and open geohydrological application system with data on the distribution, depth, thickness and hydraulic properties of individual geological layers.

[13] We used chloride to represent salinity and to calculate groundwater density because it is the dominant anion in the Dutch coastal groundwater systems. It is a conservative ion, and the density is linearly related to it within the used interval (see equation (9)). Although numerous classifications of chloride concentrations are possible [*Todd*, 1980; *Stuyfzand*, 1993], here we focus on three main types: fresh ($Cl^- \leq 300$ mg/L), brackish (300 mg/L < Cl^- < 1000 mg/L) and saline groundwater ($Cl^- \geq 1000$ mg/L). The initial three-dimensional chloride and density distribution for the reference time, 2000 A.D., has been constructed with different types of available data: vertical electrical soundings, geoelectrical well logs, and chloride concentration measurements from observation wells [*Oude Essink et al.*, 2005; *Goes et al.*, 2009] (see also DINO, which is the central portal for geoscientific data and information on the subsurface of The Netherlands. The archive contains shallow and deep borings, groundwater data, cone penetration tests, geoelectrical measurements, results from geological, geochemical and geomechanical sample analyses, borehole measurements, and seismic data. Available at www.dinoloket.nl). We used 5772 chloride concentration measurements over the period 1867–2001 A.D. Note that half of the chloride concentration measurements used dated from before 1960 A.D., and that measurements were scarce at great depth. Although these data are relatively "old," they still increase the reliability of the initial density distribution. The present chloride distribution in The Netherlands is not yet in dynamic equilibrium; it is still changing as a result of hydrogeological events over the past hundreds of years, such as transgressions, land subsidence, land reclamation and groundwater extraction. The change in groundwater salinity due to these past changes in the boundary conditions is called autonomous salinization. This process therefore has to be taken into account by deriving the chloride distribution at the reference time, 2000 A.D. Figure 5a shows the derived three-dimensional, initial chloride concentration and Figure 5b shows the depth of the interface between the brackish and saline ground-

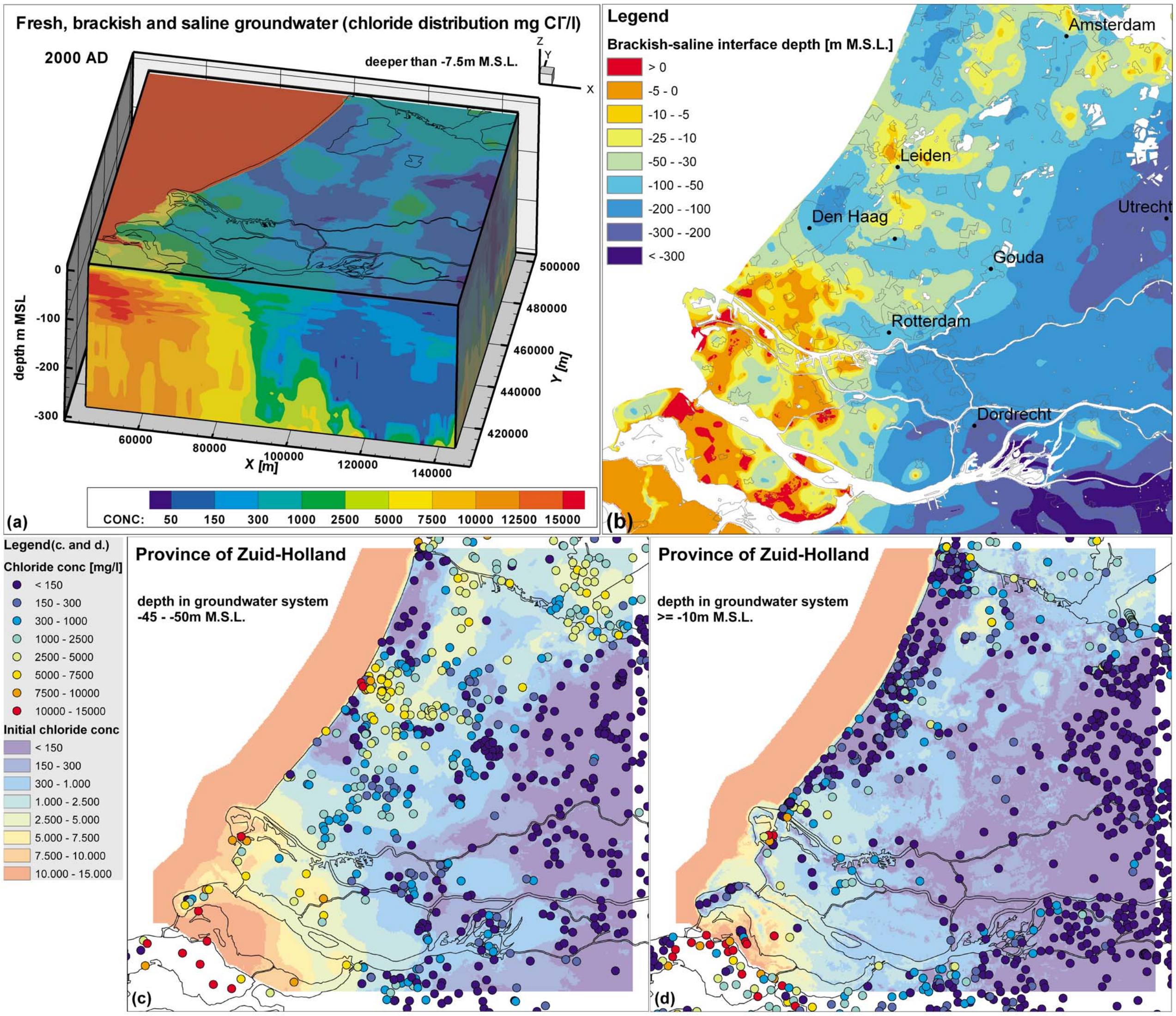

Figure 5. (a) Interpolated chloride distribution of groundwater. (b) Brackish-saline interface depth. Measured chloride concentration of groundwater (c) in a top of the groundwater system and (d) in a first aquifer (the same legend for Figures 5c and 5d).

water (Cl^- = 1000 mg/L). In the southwestern part of the study area, saline groundwater with chloride concentrations exceeding 5000 mg Cl^-/L is often found within five meters below surface level. Figures 5c and 5d show two examples of chloride concentration measurements from observation wells at two depth intervals. Note that the distribution of fresh, brackish and saline groundwater is closely related to the Holocene transgressions. During these transgressions, saline water could easily and rapidly infiltrate the aquifers via free convection [*Kooi et al.*, 2000; *Post*, 2003; *Vos and Kiden*, 2005].

2.4. Model Input

[14] The regional three-dimensional density-dependent groundwater model has been constructed with model cells of 250 × 250 m^2. The model covers an area of 100 km × 92.5 km with a grid containing 370 rows and 400 columns. The bottom of the groundwater system at –300 m msl is a no-flow boundary. In the vertical direction, 40 model layers are created to deal with the complex distribution of fresh, brackish and saline groundwater as well as the complex geology in the subsoil. The top 20 layers are 5 m thick and the lower 20 layers are 10 m thick. This relatively fine grid for a regional three-dimensional model is necessary due to the rugged coastline of the system and the irregular shape of what is assumed to be an impervious hydrogeological base (Figure 4). Hence, our model has nearly four million active model cells. Each model cell initially contains eight particles, which means some 31.8 million particles in total, for which the advection term of the solute transport equation is solved. The hydraulic conductivity of the aquifers varies spatially between 0.1 and 40 m/d and the hydraulic resistance (i.e., vertical hydraulic conductivity/thickness) of the aquitards per m thickness between 20 and 1000 d/m. The effective porosity is assumed to be 0.3 and the volumetric concentration expansion gradient β_C equals 1.34 × 10^{-6} L/mg Cl^-. Saline groundwater in the lower layers does not exceed 16800 mg Cl^-/L, which corresponds with a density of

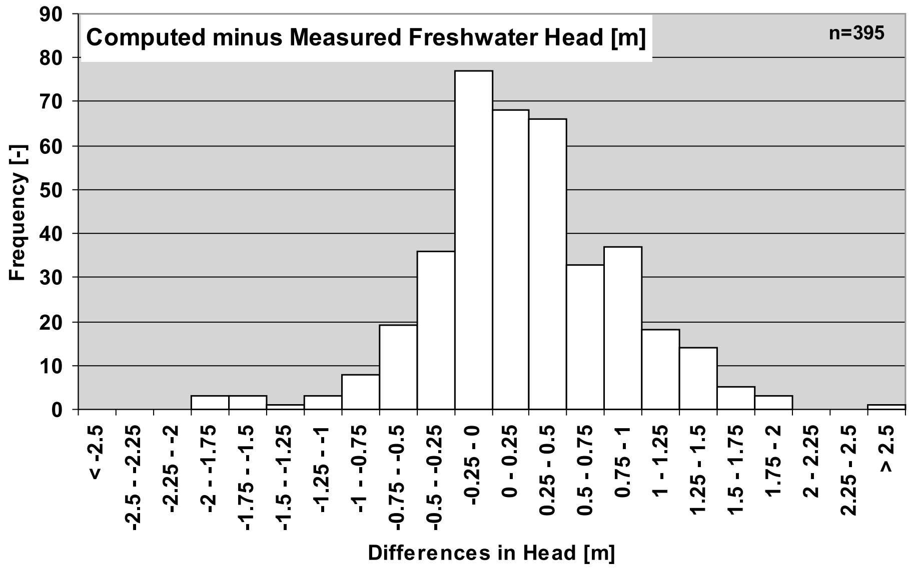

Figure 6. Histogram of differences between calculated and measured freshwater head in meters, after calibration.

1025 kg/m^3. The molecular diffusion D_m for porous media is assumed to be 10^{-9} m^2/s. The longitudinal dispersivity α_L is set equal to 2 m, while the ratio of transversal to longitudinal dispersivity is 0.1. In contrast with some other field sites (e.g., see the cases in the work by *Gelhar et al.* [1992]), the best estimates of the longitudinal dispersivities in Dutch and Belgian large-scale aquifer systems with Holocene and Pleistocene deposits of marine and fluviatile origin appear to yield rather small values. This observation is based on numerous case studies [e.g., *Stuyfzand*, 1993; *Lebbe*, 1999; *Oude Essink*, 2001a; *Vandenbohede and Lebbe*, 2007]. Extraction wells, surface water levels and recharge (Royal Netherlands Meteorological Institute, KNMI) were implemented in the model. The flow time step, Δt, to recalculate the groundwater flow equation is 1 year. The convergence criterion for the groundwater flow equation (freshwater head) is equal to 10^{-3} m. The chosen model parameters were based on numerical accuracy tests. The total simulation time is 100 years, over the period 2000–2100. Nowadays (namely at 2010 A.D.), calculations over these time periods with these large number of model cells and particles are possible on common desktop personal computers by applying the Lagrangian approach to solve the advection-dispersion equation: splitting it up into two components: an advective component that is solved by means of a particle tracking technique (the so-called method of characteristics (MOC)), and a dispersive component that is solved by the finite difference method.

[15] Different MODFLOW packages are used in the top of the active model domain. The so-called Drain, River (linking the surface water system) and Recharge packages of the MODFLOW module are included to make a dynamic top system [*McDonald and Harbaugh*, 1988]. The Recharge package of MODFLOW is based on regional precipitation and evapotranspiration values from the Royal Netherlands Meteorological Institute KNMI. The Well package is used to take into account groundwater extractions. The boundary conditions of the model are implemented by the General Head Boundary package. At the western side, the model is still active 12.5 km offshore into the Noordzee. In addition, a solute concentration is given to every model cell of the packages River, Recharge and General Head Boundary to assure that groundwater that enters the domain of the model has a given concentration (this concentration equals the initial three-dimensional chloride distribution for the reference time, 2000 A.D.).

2.5. Calibration

[16] We used the representer calibration technique for freshwater heads, in which no limitations in the choice of the model parameters are imposed and in which measurements are allowed to optimize the model parameters [*Valstar*, 2001; *Valstar et al.*, 2004]. For the calibration (for 2000 A.D.), we used 395 head measurements which were scattered over all the aquifers (Figure 6) and which were corrected for density differences. The median of the difference between the calculated minus measured freshwater heads is 0.17 m. The median of the absolute difference is 0.36 m with a standard deviation of 0.45 m. We believe these differences are good calibration results (e.g., relative to the maximum and minimum land surface levels in this area), though calibration of heads of the model domain was tough in the northeastern part where push moraines (sediments formed by glacial processes) occur. In addition, the calculated cumulative salt loads of the Haarlemmermeer polder and the Groot-Mijdrecht polder have been compared with measured ones [*Institute for Land and Water Management Research*, 1976]. The transmissivities of the aquifers and the hydraulic resistances of the aquitards, that are improved (i.e., optimized) in the representer calibration technique, were implemented in the model.

2.6. Model Scenarios

[17] The objective of this model study is to calculate future changes in this coastal groundwater system over the next hundred years as a function of climate change. However,

Table 1. One Autonomous and Four Climate Scenarios[a]

Scenario	Autonomous Salinization	Land Subsidence	Sea Level Rise by 2100 A.D. (m)	Change in Precipitation (%)		Change in Evapotranspiration (%)
				Winter	Summer	
Autonomous salinization	Yes	No	0	0	0	0
W	Yes	Yes	0.85	+14	+12	+14
W+	Yes	Yes	0.85	+28	−38	+30
W2	Yes	Yes	2	+14	+12	+14
W+2	Yes	Yes	2	+28	−38	+30

[a]W stands for warm, W+ stands for warm plus a change in circulation pattern over Europe, W2 stands for warm and an extreme 2 m sea level rise, and W+2 stands for warm plus a change in circulation pattern over Europe and an extreme 2 m sea level rise [after *van den Hurk et al.*, 2006].

to calculate the effects correctly we have to take into account ongoing anthropogenic activities (such as groundwater extractions and water level management) and their consequences for the groundwater system such as land subsidence and future autonomous salinization. The effects of the different scenarios are described for the situation at the reference time (2000 A.D.) and for 2100 A.D. (Table 1).

2.6.1. Autonomous Salinization

[18] Solute transport through porous media is a slow process. As a consequence, the solute distribution in the Dutch system is not yet in dynamic equilibrium with the current boundary conditions. Processes which were initiated in the past, like lake reclamations, peat excavation, water level management and land subsidence, still affect the present distribution of groundwater salinity.

2.6.2. Land Subsidence

[19] Land subsidence differs from place to place due to groundwater extraction, compaction and shrinkage of clay, and especially the oxidation of peat. Land subsidence is taken into account in our model by lowering the water level in every model cell with land in the top layer. This is done linearly with time, in accordance with the values in Figure 7.

2.6.3. Climate Change

[20] Apart from autonomous salinization and land subsidence, in the future this low-lying delta region will be jeopardized by climate change due to the anticipated sea level rise and changing precipitation and evapotranspiration. Different scenarios of future global mean sea level rise have been generated by the International Panel on Climate Change (IPCC). However, we have taken the KNMI's results [*van den Hurk et al.*, 2006] because they are based on more detailed and local information, and better fit the Dutch situation. These so-called KNMI06 climate scenarios result from Regional Climate Models and were based on the Global Climate Models in the IPCC's Fourth Assessment report (AR4 [*IPCC*, 2007]). For the Netherlands, different changes of precipitation and evapotranspiration during winter and summer were also predicted by the KNMI.

[21] Beside the autonomous salinization scenario, we distinguish four climate scenarios for which sea level rise and precipitation surplus differs (Table 1). The W climate scenarios deal with a realistic estimation of sea level rise of 0.85 m in 2100 A.D. [*Kwadijk et al.*, 2008]. The W2 climate scenarios incorporate a more extreme, but possible, sea level rise of 2.0 m for the year 2100 A.D., but these scenarios are not official KNMI scenarios. Sea level rise is implemented linearly with time in accordance with the values in Table 1. In agreement with the predictions of changing precipitation surplus by the KNMI, we have distinguished a "wet climate scenario" with increasing precipitation in both summer and winter and a "dry climate scenario" (indicated with "+") with decreasing precipitation in the summer, together with a large increase in evapotranspiration. Both autonomous salinization and land subsidence were incorporated in these four climate scenarios.

2.6.4. Mitigation Countermeasures

[22] Although various countermeasures can be considered [*Oude Essink*, 1996], here just two common countermeasures scenarios were calculated to assess the effectiveness of large-scale, possible compensation measures to reduce the negative impacts on this coastal groundwater flow regime.

[23] 1. Land reclamation offshore in the Noordzee for the autonomous case in the year 2100 A.D. was considered, in order to increase the fresh water resources available in the dunes. The land strip is 1 km width by 55 km length and has a fixed water level of 1.5 m msl. Note that in the Netherlands, land reclamation is considered as a means to use the forces of nature to produce hydraulic engineering infrastructure and to create new opportunities for nature at the same time ("Building with Nature").

[24] 2. Inundation of a large low-lying polder for the autonomous case in the year 2100 A.D. was calculated, in order to reduce the salt load into the surface water system.

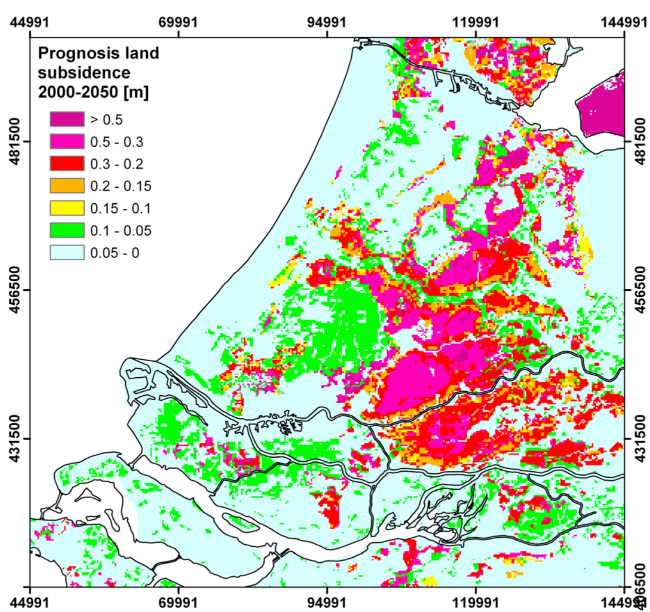

Figure 7. Prognosis of land subsidence in 2050 A.D. relative to 2000 A.D.

The area is 110 km^2 and the induced water level is fixed at −0.6 m msl. Note that in the Netherlands, inundation of agricultural areas is considered as a feasible measure to stop salinization and/or to conserve nature.

[25] It should be noted that various parameters and variables are uncertain, which make the prediction (e.g., of the zone of influence or of the salt load) to a certain degree unreliable. Two aspects are important here: the knowledge about the value of a parameter or variable derived by measurements and the impact such a parameter or variable has on the overall modeling result. For instance, some parameters such as the longitudinal and transversal dispersivities are relatively unknown and difficult to determine, but it can be assumed that the impact on the overall result of different dispersivities are rather limited. Other parameters, however, such as the position of geological layers, the horizontal and vertical hydraulic conductivities of layers and the initial chloride distribution have high impacts on the overall results, but fortunately, these parameters are pretty well known due to the extremely high measurements density in The Netherlands. Based on our present knowledge on these most important parameters such as geology, chloride distribution and top systems characteristics (drainage and interaction with water courses), we believe that our predictions are at least plausible, but that an exact result (e.g., of chloride concentration) at a certain place at a certain moment in time is not reliable, at least not at our used modeling scale of $250 \times 250 m^2$. In addition: it is common knowledge that deviations in future anthropogenic and climate stresses can easily occur [*Anderson and Woessner*, 1992]. As such, we have used different climate change scenarios (namely four other climate scenarios that we have calculated too are not mentioned here).

2.7. Determination of the Model Output

[26] Freshwater heads, chloride concentrations, and three directions of effective velocity are calculated for every model scenario and at different moments in time. The effects of the different scenarios are described for hydraulic heads in the top layers, upward groundwater seepage fluxes, salt loads into the surface water system, and changes of fresh groundwater volumes. We describe the results for the situation at the reference time (2000 A.D.) and for 2100 A.D.

3. Model Results and Discussion

3.1. Hydraulic Heads

[27] After analyzing the numerical modeling results, it can be shown that hydraulic heads in the first aquifer increase due to sea level rise for all climate scenarios (Figure 8c). Sea level propagation into the main rivers occurs for those which are in direct contact with the sea. This effect is incorporated in the numerical modeling and can be seen in Figure 8c. On the other hand, the increase of hydraulic heads seems to be limited to a zone of influence within 10 km of the coastline and main rivers. At 5 km inlandward from the Dutch coast, the effect of sea level rise on hydraulic heads in the first aquifer is reduced to an average of about 40% of the absolute sea level rise. Hence, an expected sea level rise of 2 m in the year 2100 A.D. (W2 and W+2 climate scenarios) leads to a minimum increase in the hydraulic head of 0.8 m within this area of 5 km of the coastline. All climate scenarios not only involve sea level rise, but also changes in groundwater recharge. The wetter W and W2 climate scenarios, with a yearly average increase in the groundwater recharge, give higher hydraulic heads than the dryer W+ and W+2 scenarios (comparing Figure 8a with Figure 8b).

[28] Inland, outside the zone of influence of the sea level rise, land subsidence and declining recharge (W+ and W+2 climate scenarios) cause hydraulic heads to drop a maximum of 1 m. The effects are the largest in the peat areas, where the land subsidence is expected to be largest (Figure 7). Based on the calculated effects on hydraulic heads of all the climate scenarios, land subsidence and autonomous processes, the study area can be subdivided into three zones (Figure 8d): (1) increase in hydraulic head, (2) drop in hydraulic head, and (3) change of head depending on climate scenario. The area, for which the hydraulic head always increases, independent of the climate scenario, is limited to a small zone along the Rhine mouth, the southwestern islands (Zeeland) and the southern part of the coast. This is purely caused by the process of sea level rise. Here, we assume that the interconnection between surface water and the groundwater system remains the same, as dredging of the main water courses is very likely to continue. For approximately 65% of the study area, where land subsidence is the dominant process, a decrease in the hydraulic head is calculated. Note that to the prognosticated land subsidence (Figure 7) will only occur when we continue to drain via extensive pumping our land, to keep our feet dry; when we stop draining, the large parts of the land will very likely inundate. Only in a small zone is the change of head dependent on the climate scenario. The dryer W+ and W2+ climate scenarios cause hydraulic heads to drop, whereas the wetter W and W2 climate scenarios, with larger recharge, cause heads to increase.

[29] The propagation of sea level rise into the aquifers is determined by the geohydrological setting, in particular by the sequence of aquifers and aquitards and their hydraulic properties. The transmissivity of the first aquifer, and thickness and vertical hydraulic conductivity of the top Holocene confining layer, are the dominant factors that determine the zone of influence of sea level rise. Analytical solutions for this zone in 2-D profiles using the so-called leakage factor are given by *Mazure* [1932] and *Huisman* [1972]. Since the composition of the Holocene confining layer is spatially highly variable, effects are strongly attenuated in areas with a thin and highly permeable Holocene confining layer. This will result locally in high seepage rates and also in a small zone of influence. As such, numerical modeling approaches are preferred above analytical solutions when dealing with a heterogeneous and shallow subsoil. In our three-dimensional modeling approach with proper characteristics of the Holocene confining layer, the increase in pressure due to sea level rise can easily be released when it enters the groundwater system; we believe that the same process will occur in other delta areas worldwide.

3.2. Saline Seepage and Salt Loads

[30] Present groundwater seepage occurs in 40% of the study area (Figure 9a). These seepage areas are characterized by low-lying polders where hydraulic heads in the first aquifer exceed the phreatic and surface water levels (Figure 10). Seepage was introduced in the water system after the reclamation of these polder areas (1550–1900 A.D.), when even-

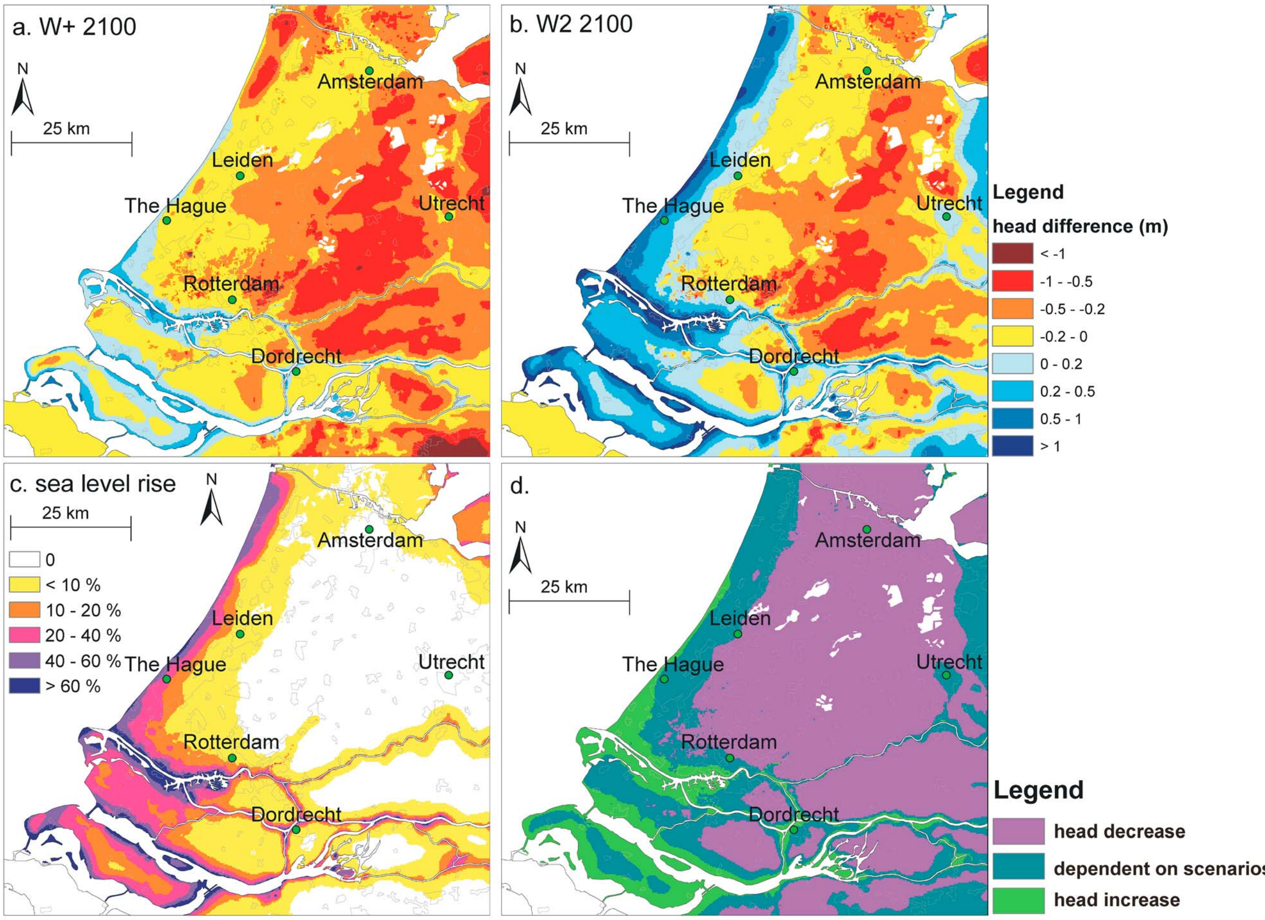

Figure 8. (a) Calculated head change in 2100 A.D. for W+ climate scenario. (b) Calculated head change in 2100 A.D. for W2 climate scenario. (c) Increase of hydraulic heads in the first aquifer caused by sea level rise, expressed in percentage of absolute sea level rise. (d) Effects on hydraulic heads summarized for all climate scenarios (W, W+, W2, and W+2) including land subsidence, compared to the autonomous salinization scenario in 2000 A.D.

tually artificial drainage networks and pumps lowered the polder water levels by up to 6 m [*van de Ven*, 1993]. Salt loads into the surface water system of the polders are determined by seepage flux and groundwater salinity. Large salt loads (>1000 kg Cl^-/ha/y) already occur in the present situation in the deep polders with surface levels lower than −5 m msl, like the Zuidplas polder, Haarlemmermeer polder and Groot-Mijdrecht polder and in the southwestern islands (Figure 9a). Since groundwater salinity in the study area normally increases with depth, and deeper and more saline groundwater is flowing slowly to the surface since the beginning of the reclamations, salt loads into the surface water system are continuously increasing. Figure 9b shows that this autonomous salinization process will continue for the next hundred years in the large and deep polder areas like the Zuidplas polder, Haarlemmermeer polder and Groot-Mijdrecht polder. In some parts of these polders, salt loads will double within the next hundred years due to this autonomous salinization process.

[31] The autonomous salinization is only caused by increasing salt concentrations, whereas seepage fluxes remain relatively constant. However, seepage fluxes are significantly changed by climate change, land subsidence and sea level rise, because these processes cause hydraulic heads and phreatic water levels to change. These effects on salt loads for the W2 climate scenario in the year 2100 A.D. are shown in Figure 9c. The large increase of salt loads in the southwestern part of the study area is caused by sea level rise. In the rest of the study area, land subsidence (i.e., we continue to drain our land) is the main cause of increasing salt loads. Land subsidence causes both a decrease of phreatic water levels and hydraulic head in the first aquifer, but the effect is larger for phreatic water levels. This results in larger head gradients and it therefore results in larger seepage fluxes. What is remarkable is the slightly increase or even decrease of salt loads in the deep polders compared to the rest of the seepage areas. Here, land subsidence is minimal because the subsoil consists of sandy clay rather than peat and phreatic water level drops are therefore minimal. In addition, the large amount of subsidence in the surrounding peatlands has caused a regional drop in the hydraulic head in the first aquifer. The zone of influence of this drop extends to the deep polders and the net effect is a decrease in the seepage pressure and salt loads. The effect of climate change with respect to precipitation surplus recharging the groundwater system is small and local. The effects are small because polder water levels are mainly

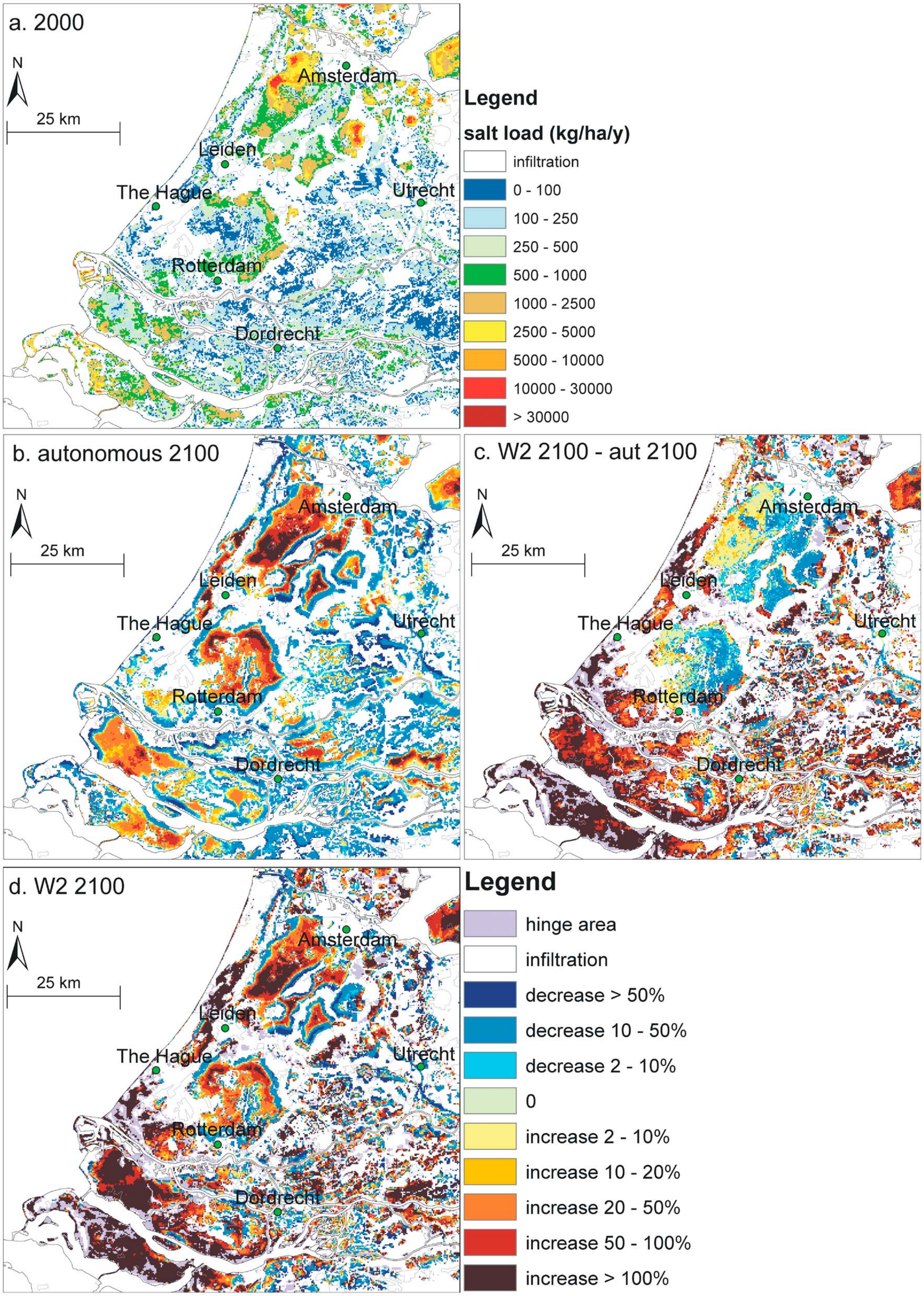

Figure 9. (a) Calculated present salt loads to surface water systems in 2000 A.D. (autonomous salinization scenario), (b) change in salt loads due to only autonomous salinization (autonomous salinization scenario 2100 A.D. minus autonomous salinization scenario 2000 A.D.), (c) change in salt loads in 2100 A.D. for the W2 climate scenario compared to the autonomous salinization scenario (W2 climate scenario 2100 A.D. minus autonomous salinization scenario 2100 A.D.), and (d) total change in salt loads for the W2 climate scenario (W2 climate scenario 2100 A.D. minus autonomous salinization scenario 2000 A.D.). A hinge area is an area where infiltration of surface water changes to seepage of groundwater.

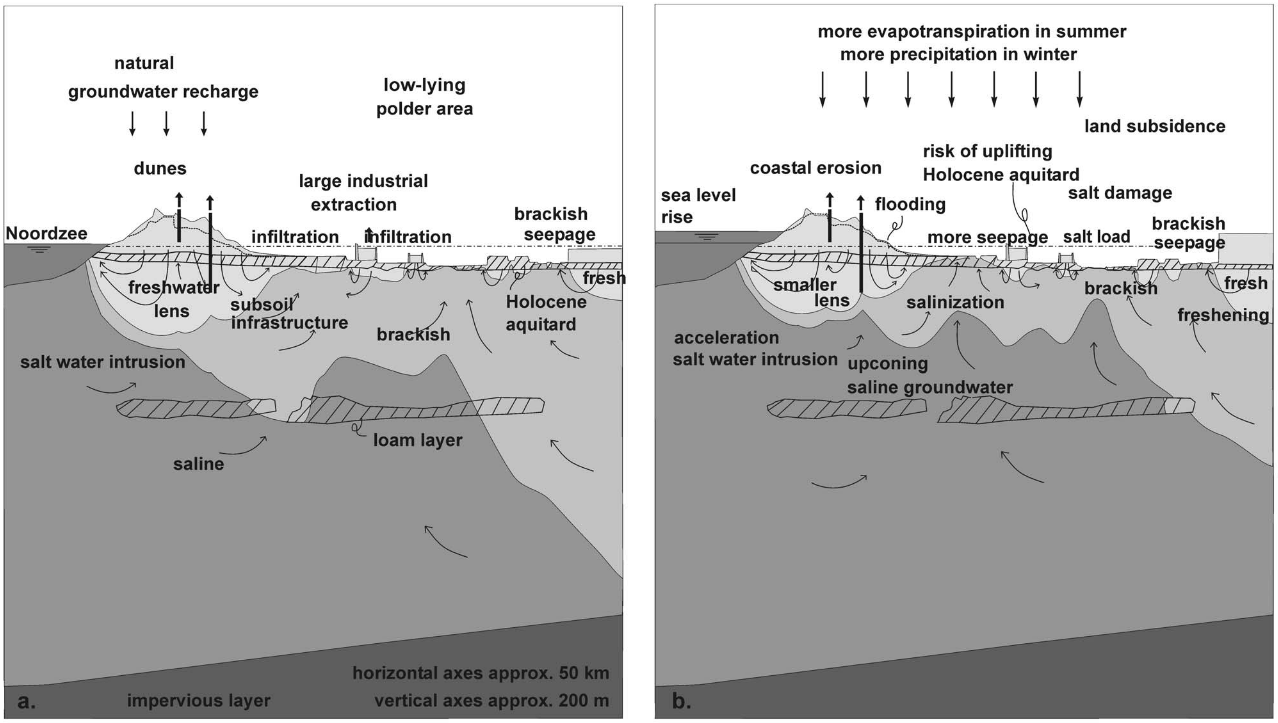

Figure 10. A conceptualization of (a) the present and (b) the future Dutch coastal groundwater system.

controlled by weirs and pumps. However, more or less rainwater as a dilution factor will have an effect on surface water salinity.

[32] The combined effect of the autonomous process and future changes like climate change, land subsidence and sea level rise are shown in Figure 9d for the wetter W2 climate scenario. Our numerical modeling results show that, for more than 80% of the seepage areas in the study area, salt loads will significantly increase due to this W2 climate scenario. The total salt load is 245000 ton.y^{-1} in the year 2000 A.D. and will increase with 6% in the year 2100 A.D. due to the autonomous process. For the W and W+ climate scenarios with 0.85 m sea level rise the salt load increase compared to 2000 A.D. is 40%–50% and for the W2 and W+2 climate scenarios with 2 m sea level rise even 130%–140%.

3.3. Salinization of Fresh Groundwater Volumes

[33] Based on the initial chloride distribution, the present fresh groundwater volume in the whole study area is equal to 118×10^9 m^3 of groundwater (≤300 mg Cl$^-$/L). The largest part of this fresh water body is located in the eastern part of the area, far from the impacts of sea level rise and land subsidence. The study area has at present 23% fresh, 11% brackish (>300 mg Cl$^-$/L and <1000 mg Cl$^-$/L) and 66% saline groundwater (≥1000 mg Cl$^-$/L). The fresh groundwater volumes will decrease due future changes in climate, land subsidence and sea level. Although the decrease fresh groundwater volume in percentage in the whole area is limited, less then 1%, the absolute values of losses of fresh groundwater (≤300 mg Cl$^-$/L) are substantial in 2100 A.D. for all four climate change scenarios: between −200 and −2750 million m^3, relative to the autonomous salinization scenario in 2100 A.D. Groundwater is becoming more saline because salt water intrusion is an ongoing process since the hydraulic heads in the polder areas are much lower than sea level. In addition, upconing of deeper and more saline groundwater is ready to occur because of large extractions for drinking water purposes. Upconing of brackish to salt water also occurs under the deep polders as part of the autonomous process, since the polders also act like large groundwater extraction (Figure 10).

3.4. Social Economic Effects

[34] Changes in hydraulic heads, seepage fluxes and salt loads due to future changes like sea level rise, climate change and land subsidence may have implications for the residential and economic aspects of urban parts as well as for agricultural parts of the delta areas [*Wind*, 1987]. Some possible effects from a groundwater perspective are summarized for the study area in Table 2.

[35] Increasing and decreasing hydraulic heads are likely to become a problem for urban areas as well as agricultural areas. The consequences of low groundwater levels include rotting (wooden) poles, subsidence of buildings, and land subsidence of peat areas [*Buma et al.*, 2006]. High groundwater levels may cause water logging in cellars or basements of buildings or uplifting underground infrastructures like car parks. Significant parts of the cities of Utrecht and Amsterdam might face a decrease in hydraulic head of more than 0.2 m in 2100 A.D. (Table 3). The coastal cities of The Hague and Rotterdam will probably have to deal with an increase of head. In terms of damage in urban areas this problem can be dealt with by using better drainage systems. Other problems associated with changing head are dike failures (piping) and the instability of the underground infrastructure.

Table 2. Possible Socioeconomic Effects Associated With Future Impacts on Coastal Groundwater Systems

Theme	Problems From Groundwater Perspective	Physical Aspects
Safety/flooding	Failure of dikes (piping)	Change in hydraulic head
Fresh water supply	Shortages in drinking and industrial water supply	Decrease fresh water resources
Nature	Drought in terrestrial nature; damage to aquatic ecosystems due to variable salt concentrations	Decreasing hydraulic head; saline seepage
Agriculture	Shortage of fresh water from surface water for irrigation; salt damage to crops	Saline seepage and cracking of Holocene confining layer (boils); saline seepage
Infrastructure and urban areas	Instability of underground infrastructure; rotting poles and building subsidence	Change in hydraulic head

[36] Saline seepage affects the quality of surface water and shallow groundwater (P. De Louw et al., Upward groundwater flow in boils as the dominant mechanism of salinization in deep polders, the Netherlands, submitted to *Journal of Hydrology*, 2010). Surface water is often used as irrigation water for agriculture, which requires low salt concentrations. In the future the availability of fresh water will decrease due to increasing saline seepage. Less precipitation and higher evaporation rates are expected to occur in the summers, which will amplify the depleted fresh water. Saline seepage may also affect the salinity of the root zone. Especially those areas where thin, fresh water lenses (from rainfall) that lie on top of saline groundwater will be vulnerable to increasing saline seepage and decreasing recharge [*Oude Essink et al.*, 2009]. For example, the areas economically important for Dutch flower bulbs or orchard trees will be very sensitive to changes in salt concentration. There is already salt damage to bulbs when soil moisture in the root zone contains more than 150 mg Cl^-/L [*Flowers*, 2004]. The increasing salinization of fresh groundwater resources used for drinking water purposes is already a problem. In the past, groundwater extractions in the dunes were closed due to upconing of saline groundwater and river water from the Rhine was artificially infiltrated into the aquifers to secure fresh groundwater volumes. Saline groundwater upconing and the decrease of fresh water volumes will continue due to the changes likely in the future.

3.5. Mitigation Countermeasures to Reduce Surface Water Salinization

[37] Salinization due to the autonomous process and future changes could be compensated by taking mitigation measures to prevent or to retard the salinization process. Six technical countermeasures will be considered [*Oude Essink*, 2001c]: (1) freshwater injection barriers through injection or (deep-well) infiltration of fresh (purified sewage) water near the shoreline; (2) extraction of saline and brackish groundwater; (3) modifying pumping practice through reduction of withdrawal rates or adequate relocation of extraction wells; (4) land reclamation and creating a foreland where a freshwater body may develop which could delay the inflow of saline groundwater; (5) increase of (artificial) recharge in upland areas to enlarge the outflow of fresh groundwater through the coastal aquifer and to reduce the length of the salt water wedge; and (6) creation of physical barriers, such as sheet piles, clay trenches and injection of chemicals. There is probably no measure effective enough to be used under all conditions: a freshwater injection barrier could create unwanted high hydraulic heads and phreatic water levels, and an extraction could lead to undesirably low piezometric heads whereas the disposal of the extracted saline or brackish groundwater could meet with (ecological) problems. Modifying pumping practice (i.e., well doublets or scavenger wells) has probably only some local positive effects whereas horizontal direction drilled wells could reduce the upconing of brackish to saline groundwater. In addition, the space for artificial recharge in upland areas is very likely limited in The Netherlands, and physical barriers cannot be implemented deep enough in the Dutch aquifer system (up to −300 m msl) to fully stop saltwater intrusion. Nevertheless, we will demonstrate the results of two possible mitigation countermeasures. The first measure is to reclaim land from the coast offshore. A large freshwater lens will be created, salt water intrusion will reduce, and, on the long run, the salt load into surface waters at the hinterland will reduce. However, numerical model results show that in this example, the high fixed water level of 1.5 m msl is probably too high. The salt loads near the coast increases significantly due to this man-made intervention (Figure 11a). Especially in the area to the north of the city of Leiden (the traditional Dutch "bulb/flower" area), salt loads would increase by 20%–50%. The increase of the total salt load in the study area due to this "mitigation countermeasure" will be 7%.

[38] Another measure is to inundate a low-lying polder area. The head differences will be reduced, and, consequently, seepage fluxes will reduce too. The 3-D groundwater model shows that salt load reduces to zero in the inundated part of the deep polder because this area becomes an infil-

Table 3. Percentage of Surface Area of the Four Largest Dutch Cities That Will Suffer a Change of Hydraulic Head of More Than 0.2 m Between 2000 A.D. and 2100 A.D.[a]

	Percent of the City Surface Area With Increasing Hydraulic Head > 0.2 m
The Hague	
W scenario	25
W2 scenario	60
Rotterdam	
W scenario	10
W2 scenario	40
	Percent of the City Surface Area With Decreasing Hydraulic Head > 0.2 m
Amsterdam	
W+/W+2 scenario	15
Utrecht	
W+/W+2 scenario	70

[a]W, warm; W+, warm plus a change in circulation pattern over Europe; W2 stands for warm and an extreme 2 m sea level rise, and W+2 stands for warm plus a change in circulation pattern over Europe and an extreme 2 m sea level rise.

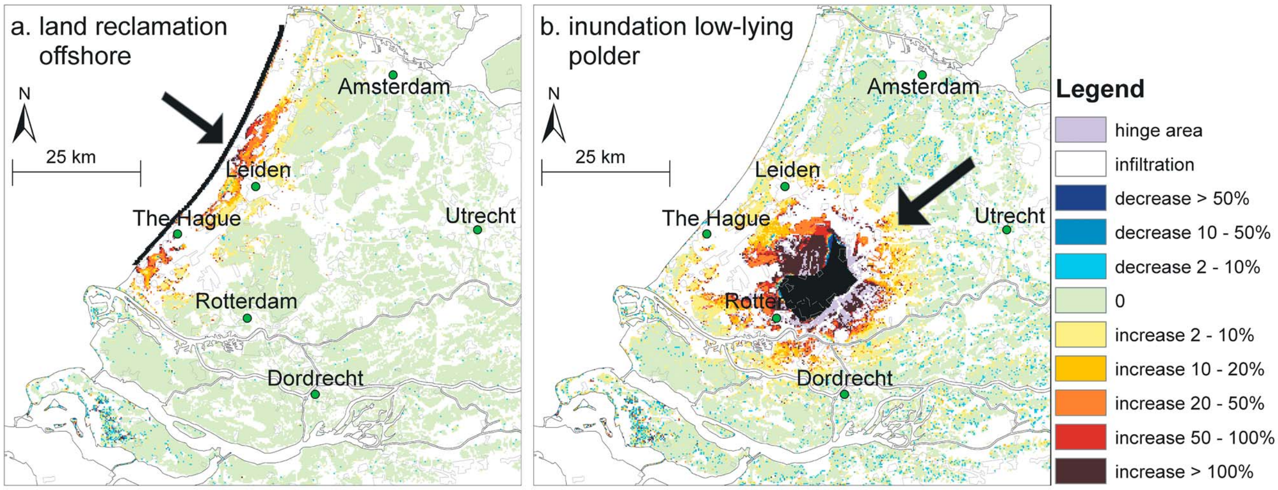

Figure 11. Change in salt loads as a result of two mitigation countermeasures in combination with the autonomous salinization scenario (2100 A.D. minus 2000 A.D.): (a) land reclamation offshore and (b) inundation of a low-lying polder.

tration area. However, the inundation causes an increase of hydraulic head in the first aquifer to far outside the boundaries of the inundated part of the polder area, causing the increase of seepage fluxes and the increase in salt loads in those adjacent areas (Figure 11b). Some areas change from being an infiltration area to a seepage area, the so-called hinge areas. The net effect of the implemented mitigation measure (namely inundation of a large low-lying polder) in reducing salt loads is only 750 ton.y^{-1} (equal to only 9% of the current salt load in the polder area). This is small compared to the effort required.

4. Conclusions

[39] Climate change in combination with increased anthropogenic activities will affect coastal groundwater systems throughout the world. In this paper, we focus on a coastal groundwater system that is already being threatened by a relatively high seawater level: the low-lying Dutch Delta. As such, the Dutch Delta can serve as a laboratory case for other low-lying delta areas in the world, and developed adaptive and mitigative countermeasures can be exposed. We calculate the effects of future sea level rise, land subsidence, changes in recharge and autonomous salinization, and the effect of two mitigation countermeasures with a three-dimensional numerical model of variable density groundwater flow and coupled solute transport. We consider the consequent effects on hydraulic heads, seepage fluxes, salt loads to surface waters, and changes in the fresh groundwater resources.

[40] Our numerical modeling results show that hydraulic heads in the groundwater system will indeed increase due to sea level rise. However, the zone of influence of sea level rise is limited to a small zone within 10 km of the coastline and main rivers. The reason is that the highly permeable characteristics of Holocene confining layer have been implemented in the 3-D numerical model and that the increase in head due to sea level rise can easily be released when it enters the groundwater system. In the major part of our study area, hydraulic heads in the aquifer will decrease as a result of land subsidence due to peat oxidation and clay shrinkage (i.e., we continue to drain our land). This might have major implications for cities like Amsterdam, where the wooden piles supporting many buildings might rot or decay if phreatic water levels drop. In addition, land subsidence will cause phreatic water levels to fall more than the hydraulic heads in the underlying aquifers, which would result in an increase of seepage fluxes. Along the coast, seepage fluxes would also increase due to sea level rise. Since seepage water in the Dutch Delta is brackish to saline, salinization of shallow groundwater and surface waters would intensify. Salt loads in the larger deep polders are already considerable and the load might double in some polder areas. However, our numerical modeling results from different scenarios show that the majority of these increased salt loads in the deep polders would be due to autonomous salinization. This process is the result of draining lakes and developing polders over the past 500 years, which have caused deeper and more saline groundwater to flow upward toward the deep polders. This enhanced salt water intrusion in the future will affect surface water quality and reduce shallow fresh groundwater volumes. Thus, in the future, fresh water resources for drinking water, agricultural purposes and ecosystems will come under increasing pressure.

[41] The relative decrease in fresh groundwater volume in 2100 A.D. is marginal for the four climate scenarios in comparison with the autonomous salinization scenario as fresh groundwater volumes are enormous in the subsurface of this delta area. In absolute figures, the fresh groundwater resources reduce approximately between −200 and −2750 million m^3.

[42] The two mitigative countermeasures are not effective: (1) land reclamation offshore in the Noordzee induces a strong salt load to the existing surface water system, and (2) inundation of a large-scale low-lying polder area leads only to a marginal decrease in salt load. It is not easy to stop salinization of the groundwater and surface water system: a combination of different human interventions is possibly needed to decrease the salt load for the future. As such, the Dutch will very likely have to cope with much more saline groundwater in their coastal water system than at present.

[43] **Acknowledgments.** This work was made possible through grants from the position paper program organized by TNO within the Dutch climate change program "Knowledge for Climate."

References

Anderson, M. P., and W. W. Woessner (1992), *Applied Groundwater Modeling: Simulation of Flow and Advective Transport*, Academic, San Diego, Calif.

Arnell, N. W. (1999), Climate change and global water resources, *Global Environ. Change*, *9*, S31–S49, doi:10.1016/S0959-3780(99)00017-5.

Badon Ghijben, W., and J. Drabbe (1889), Nota in verband met de voorgenomen putboring nabij Amsterdam, *Tijdschr. K. Inst. Ing.*, *1888–1889*, 8–22.

Bakker, M., G. H. P. Oude Essink, and C. D. Langevin (2004), The rotating movement of three immiscible fluids, *J. Hydrol.*, *287*, 270–278, doi:10.1016/j.jhydrol.2003.10.007.

Barlow, P. M. (2003), Ground water in freshwater-saltwater environments of the Atlantic Coast, *U.S. Geol. Surv. Circ.*, *1262*.

Barlow, P. M., and E. G. Reichard (2010), Saltwater intrusion in coastal regions of North America, *Hydrogeol. J.*, *18*(1), 247–260.

Bear, J., and A. Verruijt (1987), *Modeling Groundwater Flow and Pollution*, D. Reidel, Dordrecht, Netherlands.

Bobba, A. G. (1998), Application of a numerical model to predict freshwater depth in islands due to climate change: Agatti Island, India, *J. Environ. Hydrol.*, *6*(10), 1–13.

Bobba, A. G. (2002), Numerical modelling of salt-water intrusion due to human activities and sea-level change in Godavari Delta, India, *Hydrol. Sci. J.*, *47*, 67–80.

Buma, J. T., R. J. Stuurman, B. D. van Etten, and J. D. de Jong (2006), Research on damage to foundations due to low groundwater levels in Dordrecht (in Dutch), Rep. 2006-U-R0071/A, 103 pp., TNO, Utrecht, Netherlands.

Coleman, J. M. (1981), *Deltas: Processes of Deposition and Models for Exploration*, 124 pp., Int. Human Resour. Dev. Corp., Boston, Mass.

Cooper, H. H., Jr., F. A. Kohout, H. R. Henry, and R. E. Glover (1964), Sea water in coastal aquifers, *U.S. Geol. Surv. Water Supply Pap., 1613-C*, 84 pp.

Custodio, E. (2010), Coastal aquifers of Europe: An overview, *Hydrogeol. J.*, *18*(1), 269–280, doi:10.1007/s10040-009-0496-1.

Custodio, E., and G. A. Bruggeman (Eds.) (1987), *Groundwater Problems in Coastal Areas, Studies and Reports in Hydrology*, Int. Hydrol. Programme, UNESCO, Paris.

Deltares (2009), Towards sustainable development of deltas, estuaries and coastal zones: Description of eight selected deltas, Delft, Netherlands. (Available at http://www.deltares.nl/txmpub/files/?p_file_id=12971.)

De Wiest, R. J. M. (1965), *Geohydrology*, John Wiley, New York.

Flowers, T. J. (2004), Improving crop salt tolerance, *J. Exp. Bot.*, *55*, 307–319, doi:10.1093/jxb/erh003.

Food and Agriculture Organization (1997), Effects of sea level rise, in *Seawater Intrusion in Coastal Aquifers: Guidelines for Study, Monitoring and Control*, edited by J. C. van Dam, *Water Rep.* 11, pp. 43–56, Rome.

Gelhar, L. W., C. Welty, and K. R. Rehfeldt (1992), A critical review of data on field-scale dispersion in aquifers, *Water Resour. Res.*, *28*(7), 1955–1974, doi:10.1029/92WR00607.

Giambastiani, B. M. S., M. Antonellini, G. H. P. Oude Essink, and R. J. Stuurman (2007), Saltwater intrusion and water management in the unconfined coastal aquifer of Ravenna (Italy): A numerical model, *J. Hydrol.*, *340*, 91–104, doi:10.1016/j.jhydrol.2007.04.001.

Goes, B. J. M., G. H. P. Oude Essink, R. W. Vernes, and F. Sergi (2009), Estimating the depth of fresh and brackish groundwater in a predominantly saline region using geophysical and hydrological methods, Zeeland, the Netherlands, *Near Surface Geophys.*, *7*, 401–412.

Holzbecher, E. (1998), *Modeling Density-Driven Flow in Porous Media: Principles, Numerics, Software*, 286 pp., Springer, Berlin.

Huisman, L. (1972), *Groundwater Recovery*, MacMillan, London.

Huisman, P., W. Cramer, G. van Ee, J. C. Hooghart, H. Salz, and F. C. Zuidema (1998), *Water in the Netherlands*, 186 pp., Neth. Hydrol. Soc., Rotterdam, Netherlands.

Institute for Land and Water Management Research (1976), Hydrology and water quality of the central part of the West-Netherlands (in Dutch), *ICW Reg. Stud. 9*, 101 pp., Werkgroep Midden West-Ned., Wageningen, Netherlands.

Intergovernmental Panel on Climate Change (IPCC) (2007), *Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., Cambridge Univ. Press, New York.

Jelgersma, S., et al. (1993), Sea level changes and their consequences for hydrology and water management, state of the art report, 135 pp., IHP-IV Proj. H-2-2, UNESCO, Paris.

Konikow, L. F., D. J. Goode, and G. Z. Hornberger (1996), A three-dimensional method-of-characteristics solute-transport model (*MOC3D*), *U.S. Geol. Surv. Water Resour. Invest. Rep., 96-4267*, 87 pp.

Kooi, H., J. Groen, and A. Leijnse (2000), Modes of seawater intrusion during transgressions, *Water Resour. Res.*, *36*(12), 3581–3589, doi:10.1029/2000WR900243.

Kwadijk, J. C. J., S. van Vuren, G. Verhoeven, G. H. P. Oude Essink, J. J. J. C. Snepvangers, and E. Calle (2007), Effects of a large sea level rise on the fresh water supply in the Netherlands (in Dutch), *Rep. Q4394*, 73 pp., Deltares, Delft, Netherlands.

Kwadijk, J. C. J., A. Jeuken, and H. van Waveren (2008), The climate durability of the Netherlands waterland: Exploratory investigation of tipping points in management and policy of the major water system (in Dutch), *Rep. T2447*, Deltares, Delft, Netherlands.

Lebbe, L. (1999), Parameter identification in fresh-saltwater flow based on borehole resistivities and freshwater head data, *Adv. Water Resour.*, *22*(8), 791–806, doi:10.1016/S0309-1708(98)00054-2.

Lee, C.-H., and R. T.-S. Cheng (1974), On seawater encroachment in coastal aquifers, *Water Resour. Res.*, *10*(5), 1039–1043, doi:10.1029/WR010i005p01039.

Masterson, J. P., and S. P. Garabedian (2007), Effects of sea-level rise on ground water flow in a coastal aquifer system, *Ground Water*, *45*, 209–217, doi:10.1111/j.1745-6584.2006.00279.x.

Mazure, J. P. (1932), Invloed van een weinig doorlatende afdekkende laag op kwel onder een dijk, *Ingenieur*, *47B*(13), 41–43.

McDonald, M. G., and A. W. Harbaugh (1988), A modular three-dimensional finite-difference ground-water flow model, *U.S. Geol. Surv. Tech. Water Resour. Invest., Book 6, Chap. A1*, 586 pp.

Meisler, H., P. P. Leahy, and L. L. Knobel (1984), Effect of eustatic sea-level changes on saltwater-freshwater relations in the northern Atlantic coastal plain, *U.S. Geol. Surv. Water Supply Pap., 2255*, 28 pp.

Navoy, A. S. (1991), Aquifer-estuary interaction and vulnerability of groundwater supplies to sea level rise-driven saltwater intrusion, Ph.D. thesis, Penn. State Univ., University Park.

Nield, D. A., and A. Bejan (1992), *Convection in a Porous Media*, 408 pp., Springer, New York.

Oude Essink, G. H. P. (1996), Impact of sea level rise on groundwater flow regimes: A sensitivity analysis for the Netherlands, Ph.D. thesis, 428 pp., Delft Stud. in Integrated Water Manage., Delft Univ. of Technol., Delft, Netherlands.

Oude Essink, G. H. P. (2001a), Salt water intrusion in a three-dimensional groundwater system in the Netherlands: A numerical study, *Transp. Porous Media*, *43*(1), 137–158, doi:10.1023/A:1010625913251.

Oude Essink, G. H. P. (2001b), Density dependent groundwater flow: Salt water intrusion and heat transport, lecture notes, 151 pp., Univ. Utrecht, Utrecht, Netherlands.

Oude Essink, G. H. P. (2001c), Improving fresh groundwater supply—Problems and solutions, *Ocean Coastal Manage.*, *44*, 429–449, doi:10.1016/S0964-5691(01)00057-6.

Oude Essink, G. H. P., H. Houtman, and B. J. M. Goes (2005), Chloride concentration at the bottom of the Holocene aquitard in the Netherlands (in Dutch), Rep. NITG 05-056-A, 17 pp., TNO, Utrecht, Netherlands.

Oude Essink, G. H. P., P. G. B. De Louw, S. Stevens, B. De Veen, C. Prevo, V. Marconi, and B. J. M. Goes (2009), Monitoring campaign on the occurrence of freshwater lenses in the Province of Zeeland, *Rep. 2007-U-R0925/A*, 132 pp., Deltares, Utrecht, Netherlands.

Post, V. E. A. (2003), Groundwater salinization processes in the coastal area of the Netherlands due to transgressions during the Holocene, Ph.D. thesis, VU Univ. Amsterdam, Amsterdam.

Post, V. E. A., and E. Abarca (2010), Preface: Saltwater and freshwater interactions in coastal aquifers, *Hydrogeol. J.*, *18*(1), 1–14, doi:10.1007/s10040-009-0561-9.

Post, V. E. A., H. Kooi, and C. Simmons (2007), Using hydraulic head measurements in variable-density ground water flow analyses, *Ground Water*, *45*, 664–671, doi:10.1111/j.1745-6584.2007.00339.x.

Pulles, J. W. (1985), *Policy Analysis for the Water Management in the Netherlands (PAWN)* (in Dutch), Rijkswaterstaat Hoofddir. van de Waterstaat, Den Haag, Netherlands.

Ranjan, P., S. Kazama, and M. Sawamoto (2006), Effects of climate change on coastal fresh groundwater resources, *Global Environ. Change*, *16*, 388–399, doi:10.1016/j.gloenvcha.2006.03.006.

Ranjan, P., S. Kazama, M. Sawamoto, and A. Sana (2009), Global scale evaluation of coastal fresh groundwater resources, *Ocean Coastal Manage.*, *52*, 197–206, doi:10.1016/j.ocecoaman.2008.09.006.

Schultz, E. (1992), Water management of the drained lakes in the Netherlands (in Dutch), Ph.D. thesis, 507 pp., Delft Univ. of Technol., Delft, Netherlands.

Sherif, M. M., and V. P. Singh (1999), Effect of climate change on sea water intrusion in coastal aquifers, *Hydrol. Processes*, *13*, 1277–1287, doi:10.1002/(SICI)1099-1085(19990615)13:8<1277::AID-HYP765>3.0.CO;2-W.

Stuurman, R. J., P. Baggelaar, W. Berendrecht, J. Buma, P. De Louw, and G. H. P. Oude Essink (2008), The future of Dutch groundwater resources under the pressure of climate change (in Dutch), *Rep. 2008-U-R0074/B*, 85 pp., TNO, Utrecht, Netherlands.

Stuyfzand, P. J. (1993), Hydrochemistry and hydrology of coastal dunes of the western Netherlands, Ph.D. thesis, VU Univ. Amsterdam, Amsterdam.

Todd, D. K. (1980), *Groundwater Hydrology*, John Wiley, New York.

Valstar, J. R. (2001), Inverse modeling of groundwater flow and solute transport, Ph.D. thesis, Delft Univ. of Technol., Delft, Netherlands.

Valstar, J. R., D. B. McLaughlin, C. B. M. te Stroet, and F. C. van Geer (2004), A representer-based inverse method for groundwater flow and transport applications, *Water Resour. Res.*, *40*, W05116, doi:10.1029/2003WR002922.

Vandenbohede, A. (2008), *Visual MOCDENS3D: Visualization and Processing Software for MOCDEN3D, a 3D Density Dependent Groundwater Flow and Solute Transport Model—User Manual*, Res. Unit for Groundwater Modell., Univ. Gent, Gent, Belgium.

Vandenbohede, A., and L. Lebbe (2007), Effects of tides on a sloping shore: Groundwater dynamics and propagation of the tidal wave, *Hydrogeol. J.*, *15*(4), 645–658, doi:10.1007/s10040-006-0128-y.

Vandenbohede, A., K. Luyten, and L. Lebbe (2008), Effects of global change on heterogeneous coastal aquifers: A case study in Belgium, *J. Coastal Res.*, *24*, 160–170, doi:10.2112/05-0447.1.

Vandenbohede, A., E. Van Houtte, and L. Lebbe (2009), Sustainable groundwater extraction in coastal areas: A Belgian example, *Environ. Geol.*, *57*, 735–747, doi:10.1007/s00254-008-1351-8.

van den Hurk, B., et al. (2006), KNMI climate change scenarios 2006 for the Netherlands, *Sci. Rep. WR 2006-01*, K. Ned. Meteorol. Inst., De Bilt, Netherlands.

van de Ven, G. P. (1993), *Man-Made Lowlands: History of Water Management and Land Reclamation in the Netherlands*, 294 pp., Uitgeverij Matrijs, Utrecht, Netherlands.

Van Weert, F., J. Van der Gun, and J. Reckman (2008), World-wide overview of saline and brackish groundwater at shallow and intermediate depths, *Rep. GP 2004-1*, 87 pp., Int. Groundwater Resour. Assess. Cent., Utrecht, Netherlands.

Verruijt, A. (1980), The rotation of a vertical interface in a porous medium, *Water Resour. Res.*, *16*(1), 239–240, doi:10.1029/WR016i001p00239.

Vos, P., and P. Kiden (2005), The landscape evolution during the Stone Age (in Dutch), in *The Stone Age of the Netherlands*, edited by J. Deeben et al., pp. 7–37, Kripps B.V., Meppel, Netherlands.

Voss, C. I. (1984), SUTRA—A finite element simulation for saturated-unsaturated, fluid-density-dependent ground-water flow with energy transport or chemically reactive single-species solute transport, *U.S. Geol. Surv. Water Resour. Invest. Rep., 84-4369*.

Voss, C. I., and W. R. Souza (1987), Variable density flow and solute transport simulation of regional aquifers containing a narrow freshwater-saltwater transition zone, *Water Resour. Res.*, *23*(10), 1851–1866, doi:10.1029/WR023i010p01851.

Weerts, H. J. T., W. E. Westerhoff, P. Cleveringa, M. F. P. Bierkens, J. G. Veldkamp, and K. F. Rijsdijk (2005), Quaternary geological mapping of the lowlands of the Netherlands, a 21st century perspective, *Quat. Int.*, *133–134*, 159–178, doi:10.1016/j.quaint.2004.10.011.

Wind, H. G. (Ed.) (1987), *Impact of Sea Level Rise on Society*, 191 pp., A. A. Balkema, Rotterdam, Netherlands.

Zagwijn, W. H. (1989), The Netherlands during the Tertiary and the Quaternary: A case history of coastal lowland evolution, *Geol. Mijnbouw*, *68*, 107–120.

P. G. B. de Louw, G. H. P. Oude Essink, and E. S. van Baaren, Department of Soil and Groundwater, Deltares, P.O. Box 85467, NL-3508 AL Utrecht, Netherlands. (perry.delouw@deltares.nl; gualbert.oudeessink@deltares.nl; esther.vanbaaren@deltares.nl)