DENSITY DEPENDENT GROUNDWATER FLOW AT THE ISLAND OF TEXEL, THE NETHERLANDS

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ABSTRACT

Salt water intrusion is investigated at Texel, which is a Wadden island in the northern part of The Netherlands with a surface area of approximately 130 km^2. In this coastal groundwater system of Quatenary deposits, salinisation of the upper layers is taking place. At present, brackish water already occurs close to the surface of the low-lying polder areas at the eastern part of the island. Freshwater occurs up to –50 m M.S.L. in the sand-dune area at the western part. Density dependent groundwater flow in this system is modelled in three-dimensions by MOCDENS3D. The model is dimensioned 20 km by 29 km by 302 m depth, whereas about 125,000 active elements and one million particles simulate groundwater flow and salt transport during 500 years. The salinity in the top layer as well as the salt load at the surface of the polders will increase substantially during the next centuries. In addition, a relative sea level rise of 0.75 meter per century definitely intensifies the salinisation process, causing a further increase in salt load in the polders. As such, the increased salinisation of the top layer will affect the surface water system from an ecological as well as a socio-economical point of view.

INTRODUCTION

Texel is the biggest Dutch Wadden island in the North Sea. It is often called Holland in a nutshell (figure 1a). The population of the island is about 13,000, whereas in summertime, the number of people can be as high as 60,000. A sand-dune area is present at the western side of the island, with phreatic water levels up to 4 metres above mean sea level. At the eastern side, four low-lying polder areas with controlled water levels are present (figure 1b). The lowest phreatic water levels can be measured in the so-called Prins Hendrik polder, with levels as low as –2.0 m N.A.P.[1] In addition, a dune area called De Hooge Berg, which is situated in the southern part of the island in the polder area Dijkmanshuizen, has a phreatic water level of some +4.75 m N.A.P. The nature reserve 'De Slufter' in the northwestern part of the island is a tidal salt-marsh.

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

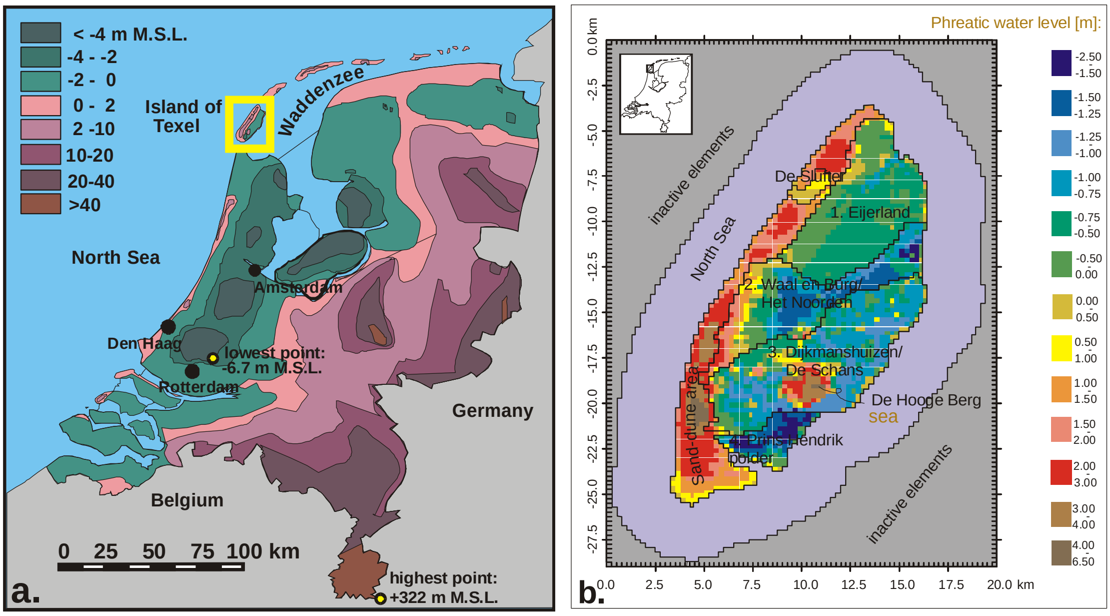

Figure 1: ***a.*** *map of The Netherlands: position of the island of Texel and ground surface of the Netherlands;* ***b.*** *map of the island of Texel: position of the four polder areas and sand-dune area as well as phreatic water level in the top aquifer at –0.75 m N.A.P.*

First, the computer code, which is used to simulate variable density flow in this groundwater system, is summarised. Second, the model of Texel will be designed, based on subsoil parameters, model parameters and boundary conditions. The numerical results of two scenarios of sea level rise are discussed in the next section, and finally, some conclusions are drawn.

CHARACTERISTICS OF THE NUMERICAL MODEL

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

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

where ϕ_f is the freshwater head [L], ρ_f is the reference density, usually the density of fresh groundwater at reference chloride concentration C_0 [M L^{-3}], p is the pressure [M L^{-1} T^{-2}], and z is the elevation head [L]. See Oude Essink (1998, 1999, 2000) for a detailed description of the adaptation of MODFLOW to density differences. A linear equation of state couples groundwater flow and solute transport:

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

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

For the numerical computations the following parameters are applied. The groundwater system consists of a 3D grid of 20.0 km by 29.0 km by 302 m depth. Each element is 250 m by 250 m long. In vertical direction the thickness of the elements varies from 1.5 m at the top layer to 20 m over the deepest ten layers. The grid contains 213440 elements: n_x=80, n_y=116, n_z=23, where n_i denotes the number of elements in the i direction. Due to the rugged coastline of the system and the irregular shape of the impervious hydrogeologic base, only 58.8 % of the elements (125,554 out of 213,440) is considered as active elements. Each element contains eight particles to solve the advection term of the solute transport equation. As such, some one million particles are used initially. The flow time step Δt to recalculate the groundwater flow equation equals one year. The convergence criterion for the groundwater flow equation (freshwater head) is equal to 10^{-5} m. The total simulation time is 500 years.

The groundwater system consists of permeable aquifers, intersected by loamy aquitards and aquitards of clayey and peat composite. The system can be divided into six main subsystems. The top subsystem (from 0 m to –22 m N.A.P.) and the second subsystem (from –22 m to –62 m N.A.P.) have hydraulic conductivities k_x of approximately 5 m/d and 30 m/d, respectively. The third subsystem is an aquitard of 10 m thickness and has hydraulic conductivities k_x which varies from 0.01 to 1 m/d. The fourth subsystem (from –72 m to –102 m N.A.P.) and fifth subsystem (from –102 m to –202 m N.A.P.) have hydraulic conductivities k_x of some 30 m/d and only 2 m/d, respectively. The lowest subsystem, number six, has a hydraulic conductivity k_x of approximately 10 m/d to 30 m/d. Note that the first, second and fourth subsystems are intersected by aquitards.

The following subsoil parameters are assumed: the anisotropy ratio k_z/k_x equals 0.4 for all layers. The effective porosity n_e is 0.35. The longitudinal dispersivity α_L is set equal to 2 m, while the ratio of transversal to longitudinal dispersivity is 0.1. Note that no numerical 'Peclet' problems occurred during the simulations (Oude Essink and Boekelman, 1996). On the applied time scale, the specific storativity S_s [L^{-1}] can be set to zero.

The bottom of the system as well as the vertical sea-side borders are considered to be no-flux boundaries. At the top of the system, the mean sea level is –0.10 m N.A.P. and is constant in time in case of no sea level rise[2]. A number of low-lying areas is present in the system with a total area of approximately 124 km^2. The phreatic water level in the polder areas differs significantly, varying from –2.05 m to +4.75 m N.A.P. (De Hooge Berg) (figure 1b), and is kept constant in time. Small fluctuations in the phreatic water level are neglected. The constant natural groundwater recharge equals 1 mm/d in the sand-dune area.

At the initial situation (1990 AD), the hydrogeologic system contains saline, brackish as well as fresh groundwater. The salinity increases with depth, whereas freshwater lenses exist at the sand-dune areas at the western side of the island, up to some –50 m N.A.P. A freshwater lens of some fifty metres thickness has evolved at the sandy hill De Hooge Berg. The volumetric concentration expansion gradient β_C is 1.34 x 10^{-6} l/mg Cl^-. Saline groundwater in the lower layers does not exceed 18000 mg Cl^-/l, as sea water that intruded the groundwater system has been mixed with water from the river Rhine. The corresponding density of that saline groundwater equals 1024.1 kg/m^3.

[2] Note that in reality, the mean sea level in eastern direction towards the Waddenzee is probably somewhat higher over a few hundreds of meters. The reason is that at low tide, the piezometric head in the phreatic aquifer of this tidal foreland outside the dike cannot follow the relatively rapid tidal surface water fluctuations (Lebbe, pers. comm., 2000). It will be retarded which results in a higher low tide level of the sea, and thus in a higher mean sea level.

DISCUSSION

Numerical simulation of the period 1990-2000 AD

Density dependent groundwater flow is not only determined by head differences but also by density differences. Variable density groundwater flow simulated with a numerical model is very sensitive to the accuracy of the initial density distribution. As such, the initial chloride concentration, which is linearly related to the initial density by equation 2, must accurately be inserted in each active element. Though the initial chloride distribution in this Texel case is based on about hundred measurements of chloride, errors can easily occur, mainly because of a lack of enough data. Therefore, artificial inversions of fresh and saline groundwater can easily occur in the numerical model, though they do not exist in reality. These ten years of simulation, from 1990 to 2000 AD, are used to smooth out unwanted, unrealistic density dependent groundwater flow, which was caused by the numerical discretisation of the initial density distribution.

Salt water intrusion during the period 2000-2500 AD

At the year 2000 AD, the chloride concentration is already high in the four polder areas (figure 2). At the hill ‘De Hooge Berg’, fresh

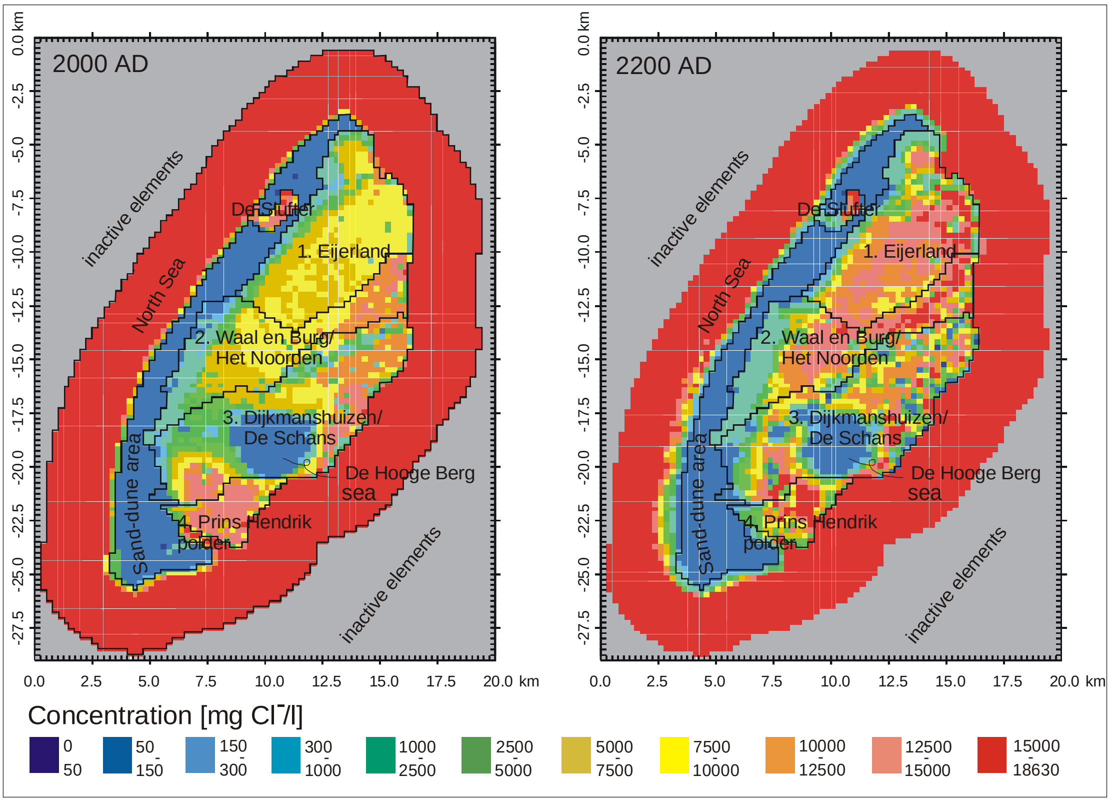

Figure 2: *Chloride concentration in the top layer at –0.75 m N.A.P. for the years 2000 and 2200 AD. No sea level rise is simulated.*

groundwater occurs up to some –45 m M.S.L. Fresh water from the sand-dunes flows towards the sea as well as towards the low-lying polder areas. In these low-lying areas, seepage is quite high (up to some 2.1 mm/day at the western side of the Prins Hendrik polder, see figure 3a). In addition, the salt load is high too, with values up to some 95,000 kg/ha/year in the same polder area (figure 4a).

The salinisation of the groundwater flow system of the island of Texel is visualised in figure 2. It shows the change in chloride concentration in the top layer at the years 2000 AD and 2200 AD. The level of sea is kept constant during these two hundred years. The salinity in the top layer increases, especially in the areas close to the coastline.

Effect of sea level rise on salt water intrusion during the next 500 years

According to the Intergovernmental Panel of Climate Change (IPCC) Second Assessment Report (Warrick *et al.*, 1996), a sea level rise of 0.49 m is to be expected for the year 2100, with an uncertainty range from 0.20 to 0.86 m. This rate is 2 to 5 times the rate experienced over the last century. Two scenarios of sea level variation are considered for the next millenium: no sea level rise and a sea level rise of 0.75 m per century. This figure includes land

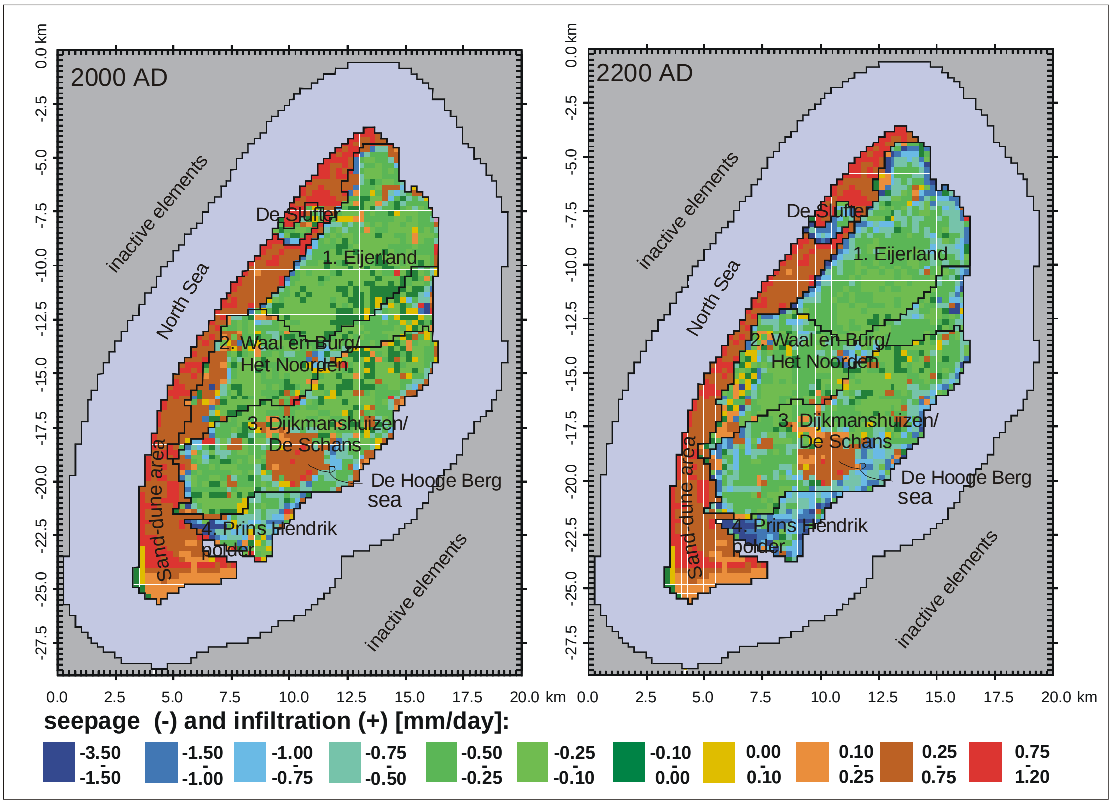

Figure 3: *Seepage through the top layer at –0.75 m N.A.P. for the years 2000 and 2200 AD. Sea level rise is 0.75 meter per century.*

subsidence caused by groundwater recovery, the compaction and shrinkage of clay, and the oxidation of peat.

Figure 5 shows the change in chloride concentration in the top layer at –0.75 m N.A.P. for the sea level rise scenario at two moments in time: 200 years (2200 AD) and 500 years (2500 AD) after 2000 AD. During the next centuries, the salinity in the groundwater system will increase very serious when the sea level rises 0.75 m/c. By comparing the figures 2b and 5a, the effect on the chloride concentration in the top layer of a sea level rise relative to no sea level rise can be seen: the salinity increases rapidly.

Seepage (figure 3) as well as the salt load (figure 4) at –0.75 m N.A.P. for the years 2000 AD and 2200 AD increase because of the salinisation in the subsoil. Sea water, with a high content of chloride, is attracted by the polder areas, as the phreatic water level in these areas is low relative to the level of the sea.

In figure 6, the seepage in the four different polder areas is given as a function of time. As can be seen, seepage quantities increases which will probably has its effect of the capacity of the pumping stations in the polder areas. Their capacity should be increased because e.g. in two hundred years, the seepage quantity is about doubled in all four areas.

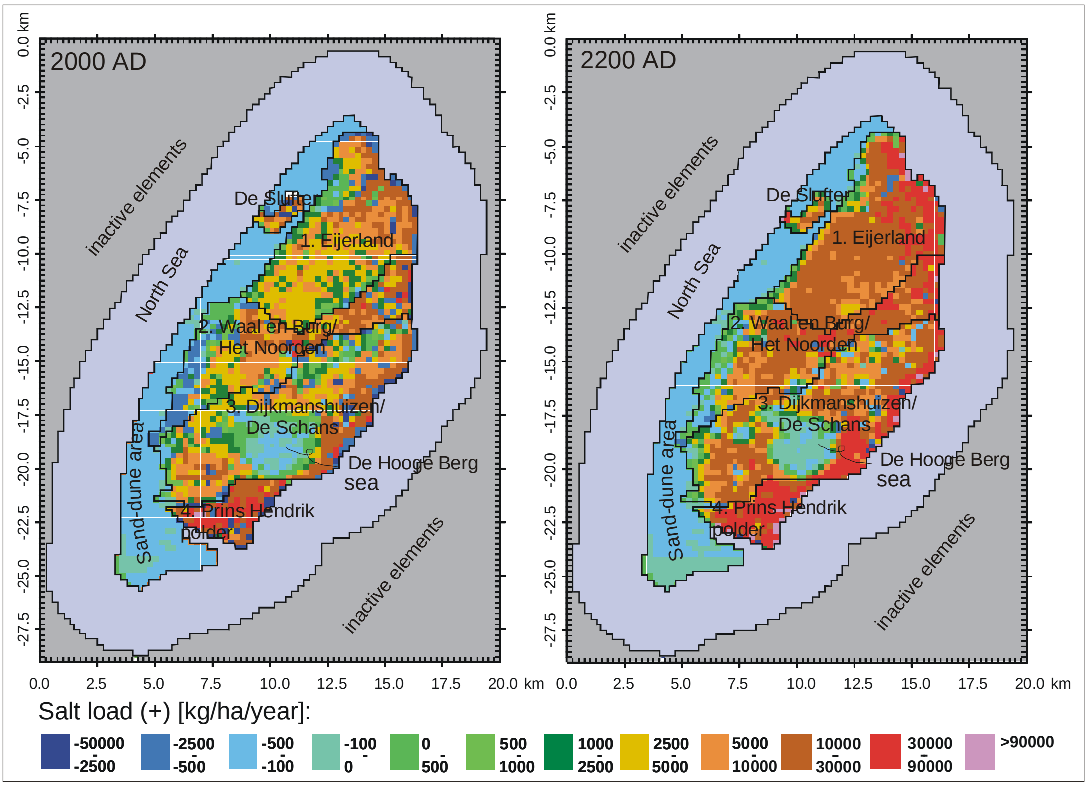

Figure 4: *Salt load (in kg/ha/year) in the top layer at –0.75 m N.A.P. for the years 2000 and 2200 AD. Sea level rise is 0.75 meter per century.*

The salt load as a function of time demonstrates that the effect of sea level rise is substantial in all four low-lying polder areas of the island of Texel. The increase in salt load will be enormous due to the sea level rise of 0.75 m per century. This will definitely affect environmental aspects. A doubling of the salt load is probably already reached within (only) one century in the polder areas Eijerland and Dijksmanhuizen.

CONCLUSIONS

The computer code MOCDENS3D can be used to simulate density dependent groundwater flow in three dimensions at an island of the size of Texel, 130 km^2 by 300 m thick.

Numerical computations show that salt water intrusion is severe because the polder areas with low phreatic water levels are situated very close to the sea. In case of a relative sea level rise of 0.75 m per century, the increase in salinity is enormous. A doubling of the present seepage quantities can be established within two centuries in all four polder areas. Moreover, the salt load will probably be doubled in two polder areas within only one century. This will definitely affect environmental, as well socio-ecomonis aspects of the island of Texel.

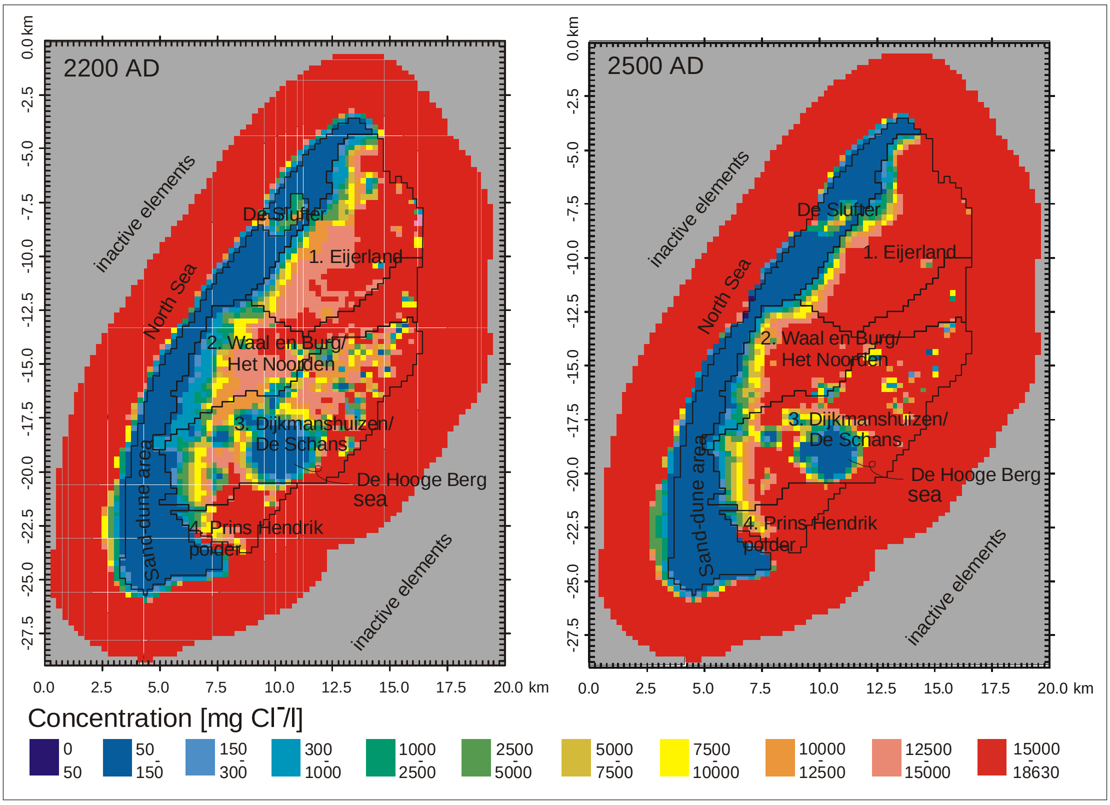

Figure 5: *Chloride concentration in the top layer at –0.75 m N.A.P. for the years 2200 and 2500 AD. Sea level rise is 0.75 m per century.*

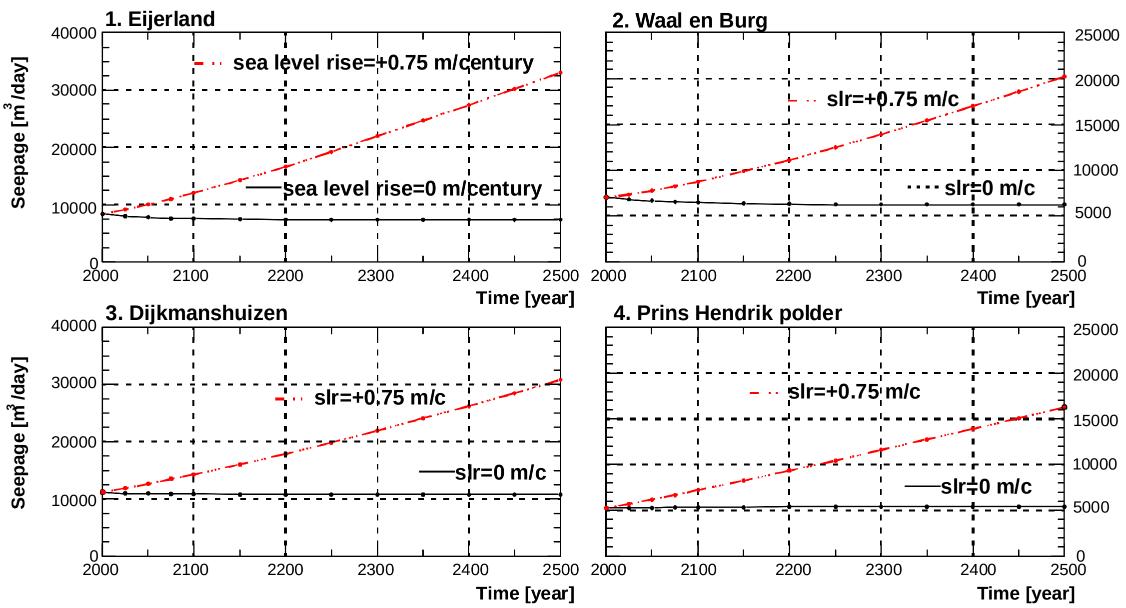

Figure 6: *Seepage (in m^3/day) through the top layer at –0.75 m N.A.P. of the four polder areas as a function of 500 years.*

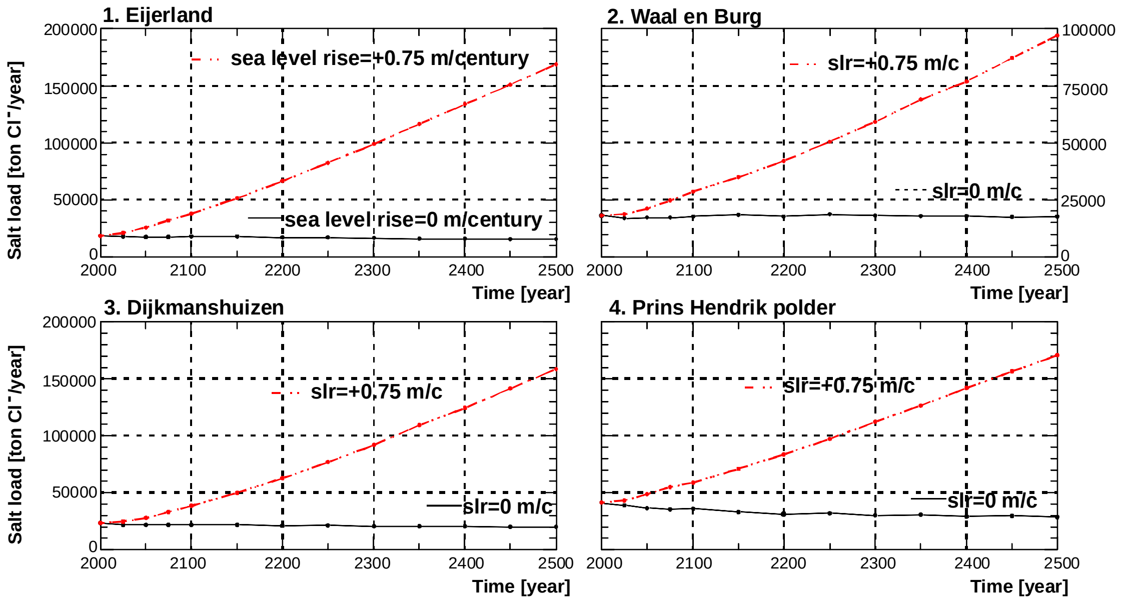

Figure 7: *Salt load (in ton Cl^-/year) through the top layer at –0.75 m N.A.P. of the four polder areas as a function of 500 years.*

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