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# Groundwater salinisation in the Wadden Sea area of the Netherlands: quantifying the effects of climate change, sea-level rise and anthropogenic interferences

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## Abstract

Hydrogeological research in coastal areas has gained considerable attention over the last decades due to increasing stresses on fresh groundwater resources. Fundamental groundwater flow and solute transport analyses remain essential for a concise understanding of the governing processes that lead to salinisation of fresh groundwater resources. However, the challenge of modern research is the application and quantification of these processes in real world cases. In this context, deltaic areas are amongst the most difficult study areas as they often have a complex groundwater salinity distribution. The Wadden Sea area in the northern part of the Netherlands is an example of such an area.

We quantified salt water intrusion and salinisation of groundwater flow systems in two representative case studies in the Wadden Sea area, using the density dependent groundwater flow and transport code MOCDENS3D. The results indicate that sea-level rise and autonomous processes will cause severe salinisation in the future, especially in the low polder areas close to the sea. In addition, we show that enhanced land subsidence due to salt exploitation accelerates this process. Salinisation can be mitigated to some extent by raising surface water levels in polders and by creating saline groundwater collection areas that maintain a low controlled water level.

***Keywords***: Fresh-saline distribution, numerical modeling, regional groundwater flow, salinisation, sea-level rise, climate change, mitigation strategy

## Introduction

Fresh groundwater is one of the most vital natural resources. Proper aquifer management to prevent contamination and overexploitation is essential for a sustainable use of this resource (e.g., Bear & Cheng, 1999; Konikow & Kendy, 2005; Lee & Song, 2006; Werner et al., 2012). The presence of saline groundwater in coastal areas makes groundwater management more complicated, as salt water intrusion and salinisation of groundwater and surface water can easily occur (e.g., Custodio & Bruggeman, 1987; FAO, 1997; Giambastiani et al., 2007; Vandenbohede et al., 2008a; Oude Essink et al., 2010). Salt water intrusion is defined here as the invasion of saline groundwater into fresh water aquifers. It is commonly associated with excessive pumping activities and sea-level rise (Fig. 1). Salinisation is the increase of salt concentration in groundwater or surface water systems. Salt water intrusion is therefore a type of salinisation. This definition is adopted here to emphasise the reduction of fresh groundwater volumes. Chloride concentration is used here as a representative proxy of salinity, which is common in many studies on groundwater flow in coastal aquifers.

Severe groundwater salinisation by upward flow of saline groundwater takes place in the subsurface of the coastal plain of the Netherlands. Within the Holocene and Pleistocene deposits, the groundwater salinity generally increases with depth, although the spatial distribution is in many cases much more complex. This is related to groundwater salinisation and freshening processes during Holocene transgressions and regressions (Post, 2003) and the fact that the response time to changing hydrological boundary conditions is higher for hydraulic than for hydrochemical systems (Oude Essink, 1996). The groundwater salinity distribution in large parts of the subsurface of the Netherlands is therefore not in equilibrium with its present hydrological boundary conditions. Similar response time phenomena were observed in the North Atlantic

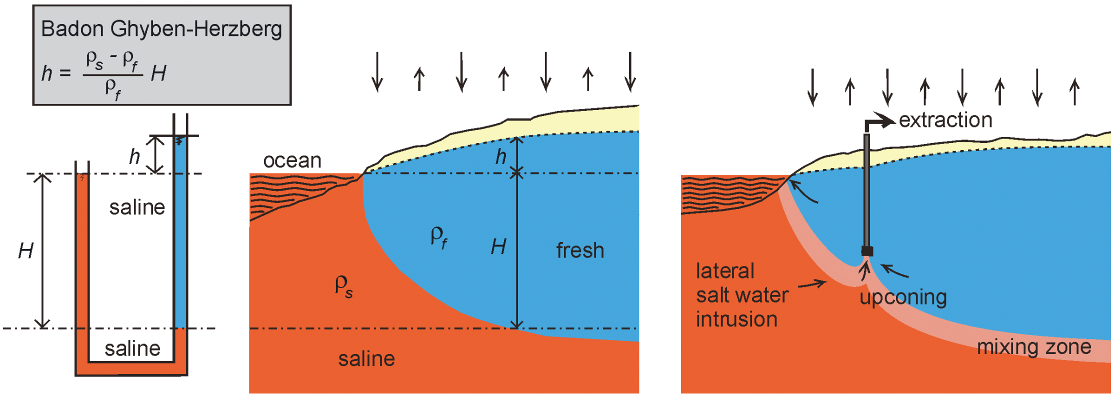
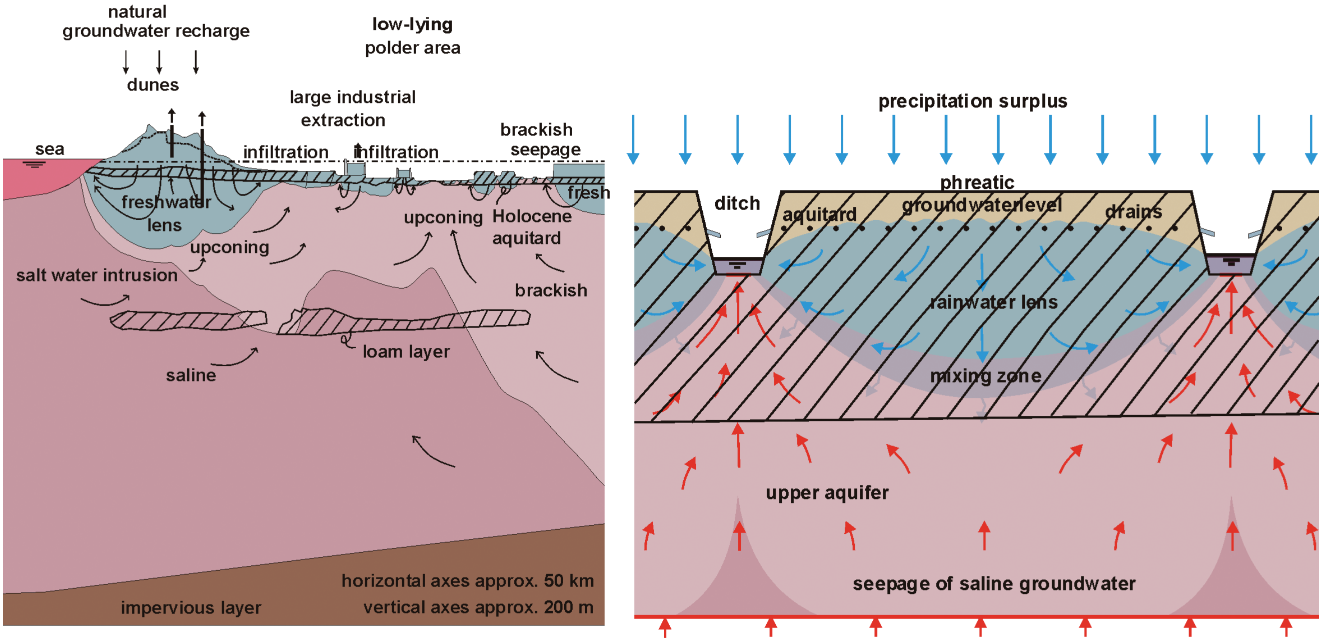


*Fig. 1. The figures at the left and in the middle show the Badon Ghyben – Herzberg principle. Under the assumption of a hydrostatic pressure distribution, the pressures of fresh (indicated in blue) and saline (indicated in red) groundwater at their interface are equal. If the onshore groundwater is fresh and the water table is elevated relatively to the sea level (h), the relative depth of the salt-fresh groundwater interface (H) can be related to the densities of the fresh ($\rho_f$) and salt ($\rho_s$) groundwater and h. Upon sea-level rise, both h and H will rise. If h is fixed or limited due to drainage onshore, salt water intrusion will occur. The figure at the right hand side shows lateral salt water intrusion due to (over)extraction. The brown region denotes the part where salt water has intruded into the fresh coastal aquifer. These figures assume a sharp, stagnant and absolute interface of fresh and salt groundwater.*

Coastal Plain, USA, where Meisler et al. (1984) investigated the broad transition zone induced by strong sea-level fluctuations over thousands of years.

The salinisation by upward groundwater flow began around 300 BC when the human intervention in the landscape started, in essence by maintaining a lower surface water level than the hydraulic head in the underlying aquifer (Van de Ven, 1993). At first, small-scale drainage activities for agricultural purposes and the subsequent consolidation of peaty and clayey sediments resulted in a gradual decline of surface water levels. Around 800 AD this decline increased due to large-scale mining of peat bogs. As a result, inland lakes arose in the landscape. The most outspoken decline of surface water levels was caused by the reclamation of these inland lakes and tidal areas (Schultz, 1992). In this way, the typical Dutch polders were realised. Because the elevation of polders is generally well below mean sea level, salinisation also occurs by lateral migration of the modern seawater (Fig. 2a). This process is accelerated by sea-level rise. Currently, modern sea water has already intruded about 2 to 6 km from the coastline (Stuyfzand, 1993).

As the aforementioned processes are likely to continue in the Netherlands, the future water availability from both fresh groundwater and surface water systems will be jeopardised (Oude Essink et al., 2010). Considering fresh groundwater resources, a decline of so-called freshwater lenses (Fig. 2) can be expected due to salt water intrusion. Large and medium sized lenses,



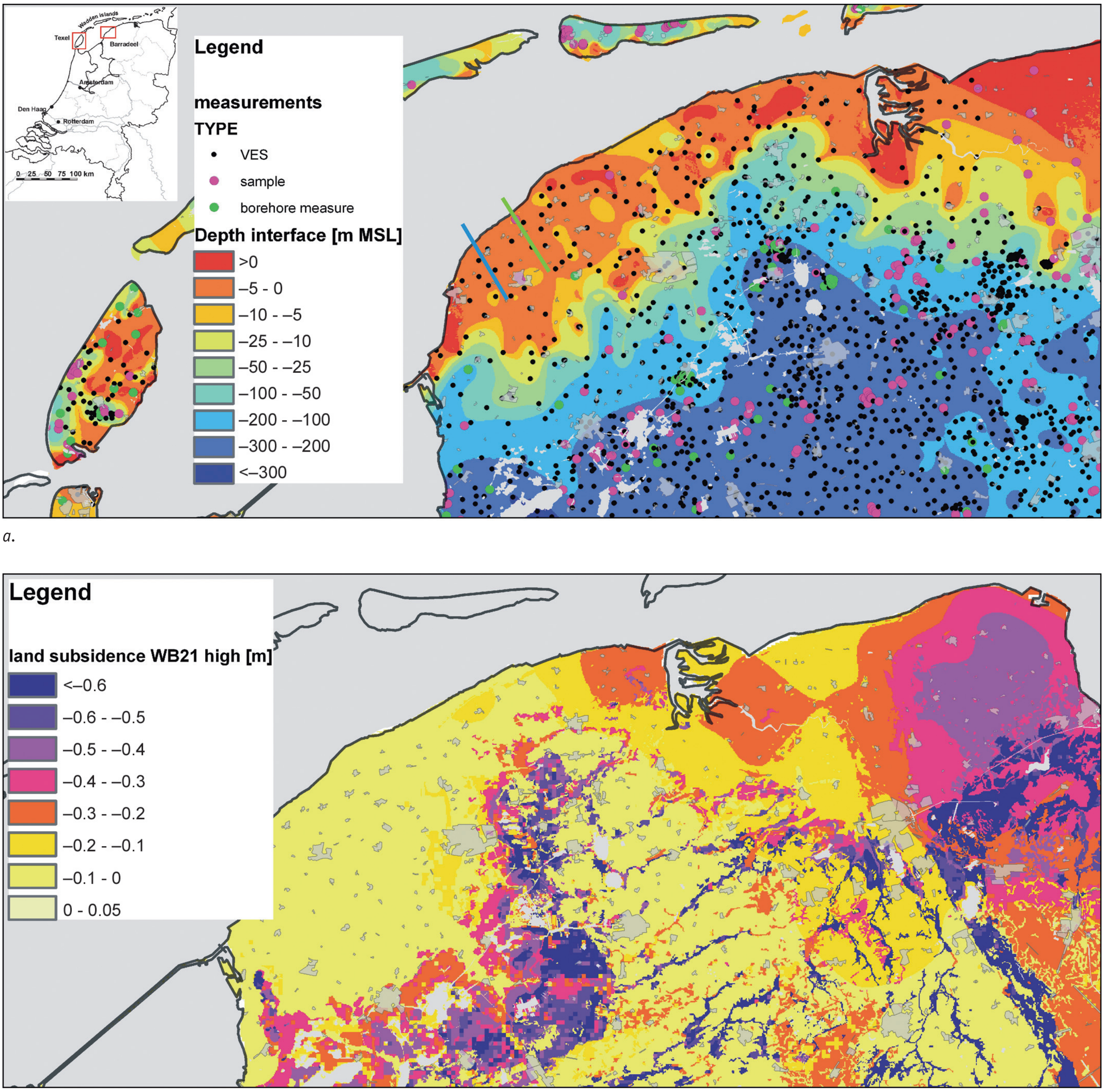
*a.*

*b.*

*Fig. 2. Salinisation process in the western Netherlands on a. regional; and b. local scale.*

having a characteristic fresh-saline interface in the order of tens up to hundred metres, are present beneath the coastal dunes and higher lying sandy fossil creeks. Shallow freshwater lenses are present in low-lying areas that are subjected to upward flow of saline groundwater. These lenses are no more than a few metres thick (De Louw et al., 2010, 2011; Eeman et al., 2011) (Fig. 2b). Salt water intrusion into these shallow systems forms a direct threat for agriculture, as a high salinity in the root zone can lead to crop damage. Regarding surface water resources, the increasing salt load from the groundwater system to the surface water system will deteriorate surface water quality. In order to maintain the irrigation function of the surface water system, increased efforts, such as flushing of the ditches by fresh surface water, will be required.

In this paper, salt water intrusion and salinisation of surface water and groundwater by regional groundwater flow are illustrated and numerically quantified by means of two typical case studies in the northern part of the Netherlands (Fig. 3), namely the Wadden island Texel and the Barradeel area in the coastal area of the province of Friesland. The island of Texel is characterised by an elongated dune area bordering the North Sea. Adjacent to the dunes, a low-lying polder area is present.



*a.*

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*Fig. 3. a. The depth of the brackish-saline interface (1000 mg Cl–/l) in the northern Netherlands. The location of the study areas is shown in the small insert; b. Prognosis of land subsidence in 2100 AD relative to 2000 AD (Haasnoot et al., 1999).*

Because the larger Dutch islands in the Wadden Sea (e.g., Terschelling, Ameland) have a comparable setting, our analysis of Texel is representative for the other Wadden Islands. The Barradeel area is a low-lying polder area bordered by a dike and the Wadden Sea. Likewise, this area is characteristic for many other areas in northern Friesland, as well as the province of Groningen. For the two cases studies, we consider the effect of anthropogenic processes (deep salt mining), climate change and sea-level rise. In addition, the effect of counter measures is investigated.

## Materials and methods

We have combined geological and hydrogeological data with numerical modelling using the computer code MOCDENS3D (Oude Essink, 1998, 2001; Bakker et al., 2004). MOCDENS3D is an integration of the solute transport code MOC3D (Konikow et al., 1996) and the groundwater flow code MODFLOW (McDonald and Harbaugh, 1988). Groundwater flow is adapted to take into account density differences between fresh, brackish and saline groundwater. Previous studies have also used this code to simulate and quantify, amongst others, future salinisation processes in the subsurface, calculate the effect of future climate and anthropogenic scenarios and measures to combat salinisation (e.g., Vandenbohede et al., 2008b; Oude Essink et al., 2010).

The input of the initial conditions (hydraulic heads and chloride concentration of the groundwater) results from interpolation of point measurements. The 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, has to be inserted accurately in each active grid cell. Although the initial chloride distribution is based on about many tens of chloride samples, vertical electrical soundings (VES) and borehole measurements, significant errors can arise upon interpolation of chloride distribution (e.g., Goes et al., 2009). Models are therefore prone to errors, such as artificial inversions of fresh and saline groundwater. For that reason an initialisation simulation period (usually in the order of ten to twenty years) was used to smooth out unwanted, unrealistic density-dependent groundwater flow.

## Analyses and Results

### *Case study 1: Groundwater flow on the island of Texel*

#### *Introduction to the study area*

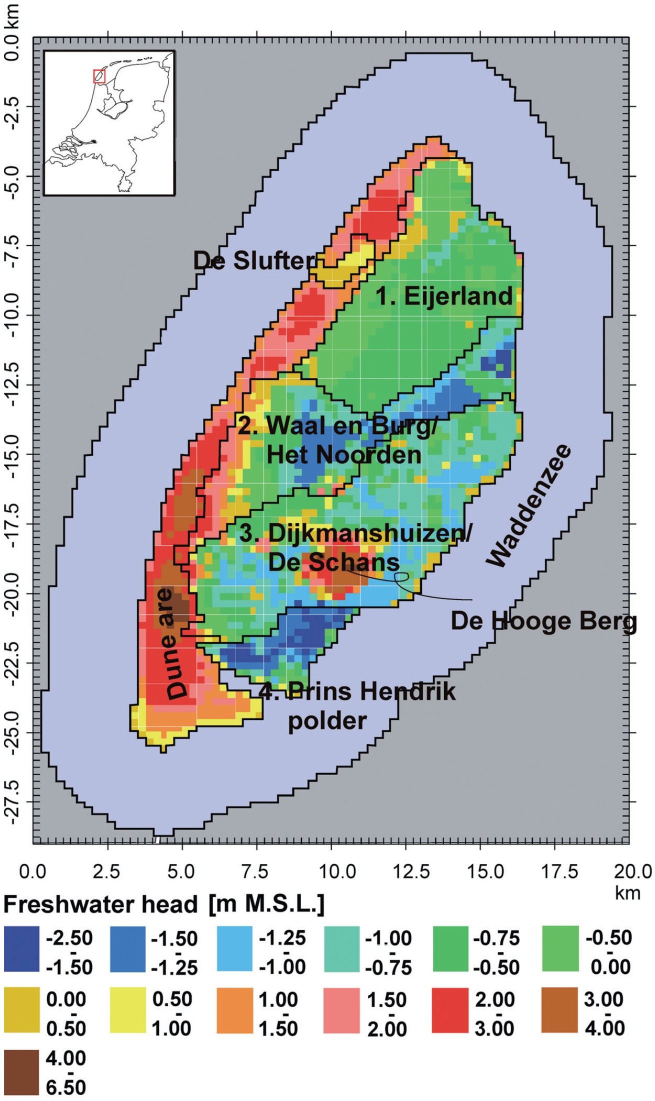

*Fig. 4. Map of the island of Texel: position of the four polder areas and sand-dune area as well as phreatic water level in the top aquifer at −0.75 m MSL.*

Texel is the largest Wadden Island (~170 km$^2$), bordered by the North Sea and Wadden Sea (Fig. 4). A coastal dune area is present on the western side of the island, with phreatic water levels up to 4 metres above mean sea level (MSL). In the north, the tidal inlet The Slufter discontinues this dune area. On the eastern side, four low-lying areas with controlled water levels (polders) are situated. The lowest phreatic water levels are found in the Prins Hendrik polder, with levels as low as −2.0 m MSL. In the southern part of the island in the polder area Dijkmanshuizen, a small ice pushed hill comprising glacial till deposits causes the phreatic water level to reach about +4.7 m MSL.

#### *Objective and methodology*

The objective of this case is to quantify the extent of salt water intrusion and salinisation due to future sea-level rise on a typical Wadden island. We consider a long period, viz. from 2000 AD to 2500 AD, to clarify the long-term effect, knowing that groundwater flow is a very slow process. Because peat and clay are relatively sparsely present in the subsurface, land subsidence in this area is of minor importance. 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: 1) no sea-level rise; and 2) a sea-level rise of 0.75 m per century. In scenario one, autonomous salinisation is quantified. Autonomous salinisation refers to the increase of the groundwater salinity due to past changes in hydrological boundary conditions, such as the reclamation of inland lakes (Oude Essink et al., 2010). In scenario 2, autonomous salinisation as well as sea-level rise are considered.

A 3D finite difference grid of 20.0 km by 29.0 km by 302 m depth was constructed for the spatial discretisation of the subsurface. Each element is 250 m by 250 m long. In vertical direction the thickness of the grid cells varies from 1.5 m at the top layer to 20 m over the ten deepest layers. The grid contains 213,440 elements; 80 by 116 elements in the west-east and north-south direction, respectively. In the vertical, 23 model layers are implemented. The hydrogeologic system has been divided into six main hydrogeological units having distinct hydrogeological properties (Table 1).

*Table 1. Hydraulic properties of the hydrogeological units of the case study Texel. The anisotropy ratio (vertical hydraulic conductivity divided by the horizontal hydraulic conductivity) is 0.4.*

| **Unit no.** | **Horizontal hydraulic conductivity (m/d)** | **Depth range (m MSL)** |
|---|---|---|
| 1 | 5 | 0 - −22 |
| 2 | 30 | −22 - −62 |
| 3 | variable (0.01 - 0.1) | −62 - −72 |
| 4 | 30 | −72 - −102 |
| 5 | 2 | −102 - −202 |
| 6 | 10 - 30 | −202 - −302 |

The following parameters are constant throughout the model domain: the effective porosity (35%), longitudinal dispersivity ($\alpha_L$ = 2.0 m), transverse dispersivity ($\alpha_T$ = 0.2 m) and the molecular diffusion coefficient ($D_{mol} = 1.0 \cdot 10^{-9}$ m$^2$/s or $8.64 \cdot 10^{-5}$ m$^2$/d). The dispersivity values are based on field measurements and/or numerical studies of Dutch and Belgian aquifer systems with marine and fluvial deposits (e.g., Stuyfzand, 1993; Van Meir, 2001; Vandenbohede & Lebbe, 2007). We modelled groundwater flow as steady state because we are interested in long term changes and therefore neglect the seasonal variations of groundwater storage. The bottom of the system as well as the vertical sea-side borders (expected to be far enough from the zone of interest) are no-flow boundaries. At the top of the system, the mean sea level is −0.10 m N.A.P. (the Amsterdam Ordnance Datum, approximately equal to mean sea level) and is constant in time for the case of no sea-level rise. The phreatic water levels in the polder have been implemented directly in the model using constant head (Dirichlet) boundary conditions. In the sand-dune area, a fixed flux (Neuman) boundary condition was used to simulate the natural groundwater recharge. The recharge flux varies between 0.46 and 1.18 mm/d. Ten years of simulation, from 1990 to 2000 AD, were long enough to smooth out unwanted, unrealistic density-dependent groundwater flow.

### Results

At present (2000 AD), the chloride concentration and the seepage rate already result in high salt loads in the polder areas. The chloride concentration in the first model layer and the seepage rate multiplied by this chloride concentration (representing the salt load to the surface water system) are shown in Figs 5 and 6. In the Prins Hendrik polder, they reach up to some 95,000 kg/ha/year, which is high compared to other low-lying polder areas of the provinces Noord- and Zuid-Holland. Even in the scenario without sea-level rise, the salinity increases in most polders (Fig. 5). This increase is most severe where the polders border the Wadden Sea. Apparently, the situation in this groundwater system seems to be non-steady-state with respect to the salinity distribution. Contrary, where the polders border the coastal dune area the salinity decreases. The effects of sea-level rise can be investigated by comparing Figs 5 and 7. sea-level rise leads to enhanced salinisation of polder areas. This effect is again most pronounced where the polders border the Wadden Sea.

In Fig. 8, the salt load in the four different polder areas is given as a function of time. The salt load increases over time due to an increase of the seepage flux (Fig. 9) and due to a higher salt content. The increase of seepage, nearly a double amount within two centuries, will force existing surface water pumping stations of the polder areas to increase their current maximum capacity.

## *Case study 2: Salinisation due to accelerated land subsidence in the area of Barradeel*

### *Introduction to the stuy area*

In the former municipality 'Barradeel', salt exploitation (brine mining) at depths of 2500-3000 m −MSL started in 1995. The projected land subsidence amounts up to 0.35 m in about 30 years (Breunese et al., 2003). Along with this land subsidence, the Waterboard Wetterskip Fryslan lowers the absolute surface water level with equal pace in order to compensate the relative rise of the groundwater table. Consequently, seepage fluxes increase and upconing of brackish to saline groundwater is enhanced and the salinisation of the shallow groundwater and surface water is accelerated. Upconing is defined here as upward flow of saline groundwater caused by a relatively small scale entity (e.g., an abstraction well or an area where a low water level is maintained), whereby a distinct 'cone' of saline water is created (Fig. 10). To mitigate the problems related to upconing,

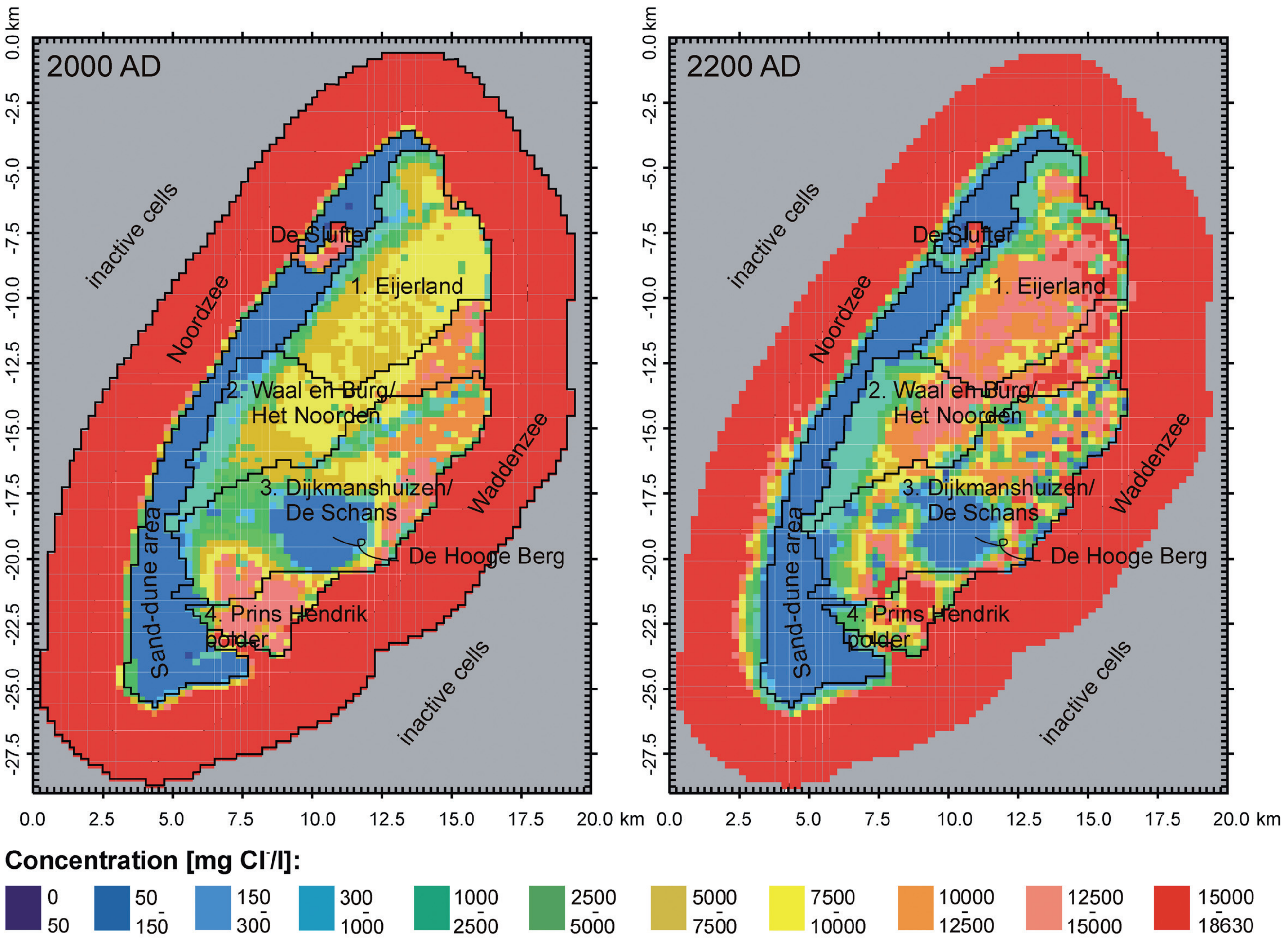

*Fig. 5. Simulated chloride concentration (mg $Cl^-$/l) in the top layer at –0.75 m MSL for the years 2000 (left) and 2200 AD (right), in scenario one, where only autonomous salinisation is taken into account.*

the water board decided to make alternative plans in order to reduce the salinisation. The effects of a reference scenario and two intervention scenarios on the salinisation of the groundwater and surface water system have been quantified.

## *Objective and methodology*

A shore-perpendicular transect (Fig. 3a; blue transect line) was used to quantify groundwater salinisation for three scenarios. It is hereby assumed that the flow perpendicular to this transect is negligible. In the reference scenario, the effect of sea-level rise (0.18 m for the simulation period) and land subsidence are incorporated. In scenario one, the surface water level is increased along a large part of the model transect, except for a polder called Roptavaart where surface water levels are lowered dramatically (surface water level is 2.5 metre below sea level). In this way, the polder Roptavaart is expected to attract saline groundwater, whereas the surrounding polders receive less. Scenario two is similar to scenario one except for the polder Roptavaart, where surface water levels are at higher elevation (1.1 metre below sea level) in order to reduce salinisation of ground water and surface water here. In this situation, agricultural activities in the polder Roptavaart are no longer possible due to these high water levels.

The horizontal extent of the system has been discretised into 200 columns of equal size (50 m). The upper 50 layers of the model are 1 m thick, the lower 50 layers amount 5 m. The transect has a length of 10 km and a vertical extent of 300 m. Eight hydrogeological units have been distinguished. Their hydraulic properties are listed in Table 2.

*Table 2. Hydraulic properties of the hydrogeological units of the case study Barradeel.*

| Unit no. | Horizontal hydraulic conductivity (m/d) | Depth range (m MSL) |
|---|---|---|
| 1 | 0.3 | 0 - –8 |
| 2 | 2 | –8 - –14 |
| 3 | 0.06 | –14 - –24 |
| 4 | 25 | –24 - –30 |
| 5 | 0.1 | –30 - –31 |
| 6 | 26 | –31 - –206 |
| 7 | 1 | –206 - –208 |
| 8 | 20 | –208 - –300 |

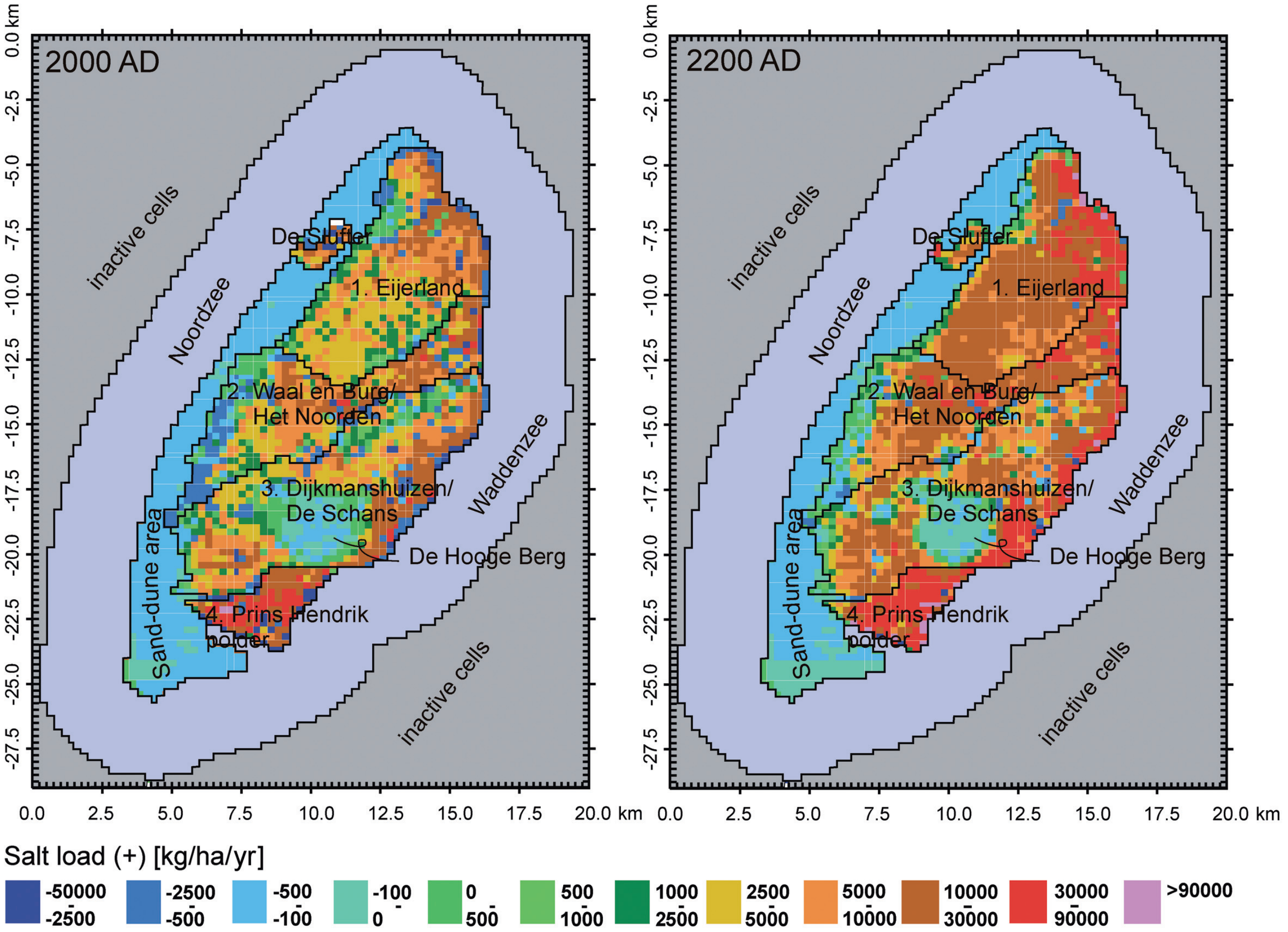

*Fig. 6. Simulated salt load (in kg/ha/year) in the top layer at –0.75 m MSL for the years 2000 (left) and 2200 AD (right), using scenario with sea-level rise of 0.75 metre per century.*

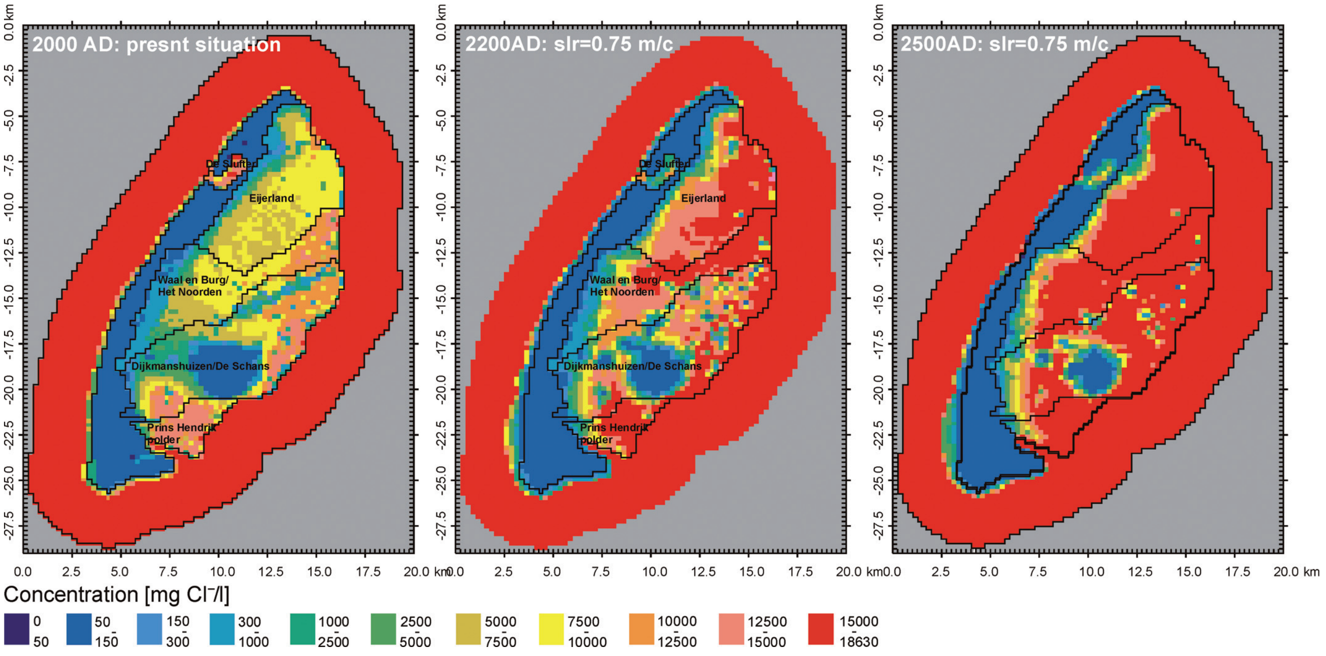

*Fig. 7. Simulated chloride concentration in the top layer at –0.75 m MSL for the years 2000 (left), 2200 (middle) and 2500 AD (right), using the scenario with sea-level rise of 0.75 metre per century.*

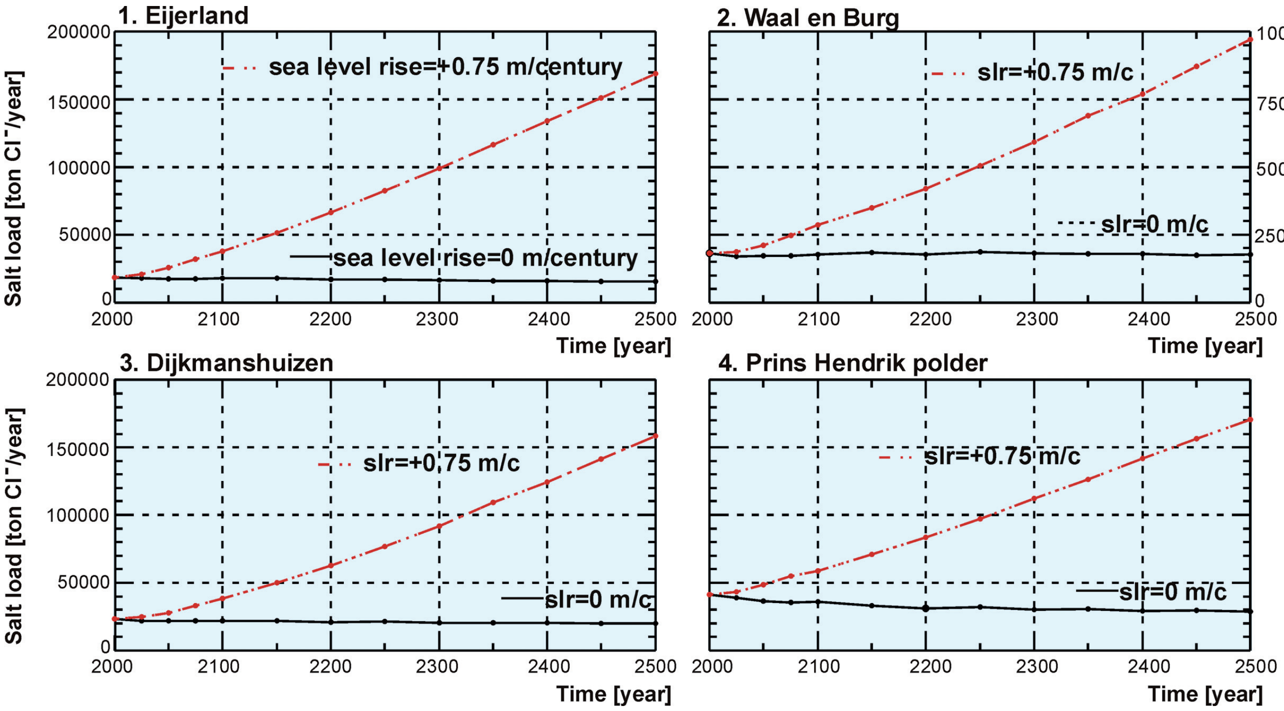

*Fig. 8. Simulated salt load as a function of time in the four polder areas of Texel.*

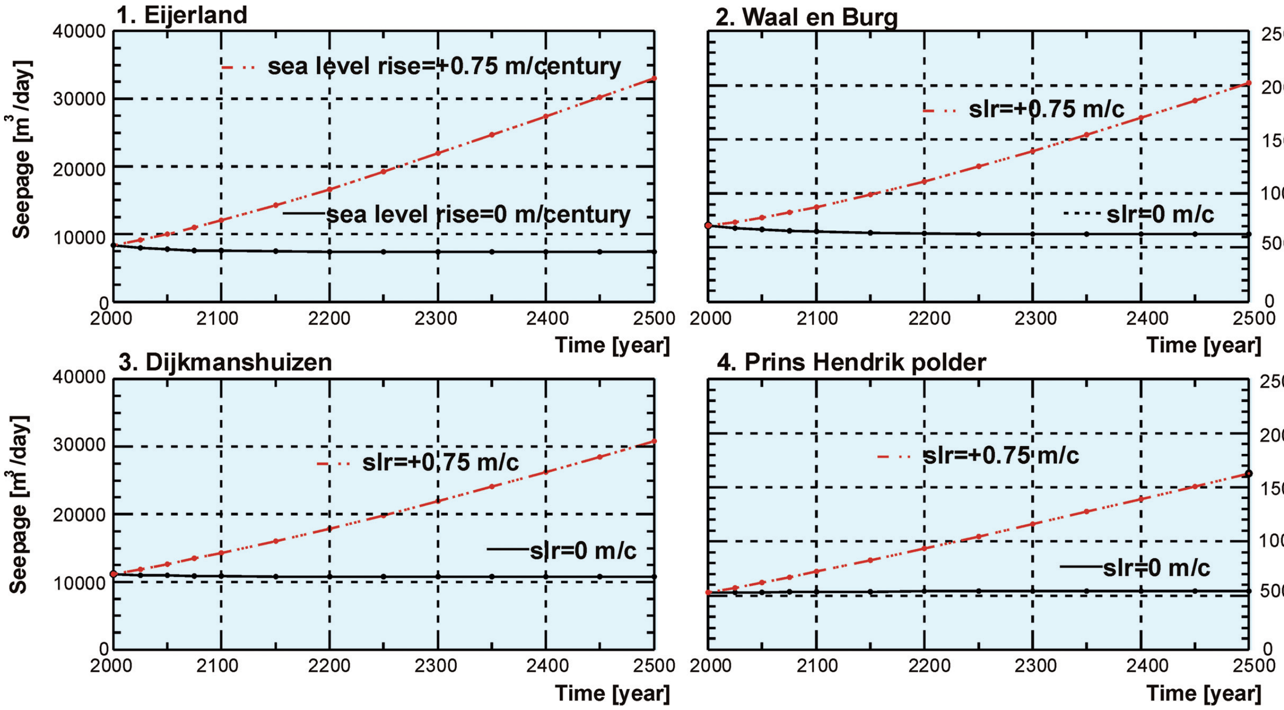

*Fig. 9. Simulated seepage flux as a function of time in the four polder areas of Texel.*

Similar to the Texel model, the groundwater flow is treated as steady state. Furthermore, the following parameters are constant throughout the model domain; anisotropy ratio ($k_z/k_x = 0.33$), porosity ($n = 0.35$), longitudinal dispersivity ($\alpha_L = 1.0$ m) and transverse dispersivity ($\alpha = 0.1$ m) and the molecular diffusion coefficient ($D_{mol} = 1.0 \cdot 10^{-9}$ m$^2$/s or $8.64 \cdot 10^{-5}$ m$^2$/d).

## *Results*

At the starting time (2000 AD) the groundwater salinity increases with depth and decreases with distance from the coast (Fig. 11, left). Near the coast, seepage of groundwater to the surface water system is salt to brackish. Shallow fresh to brackish groundwater is present further inland.

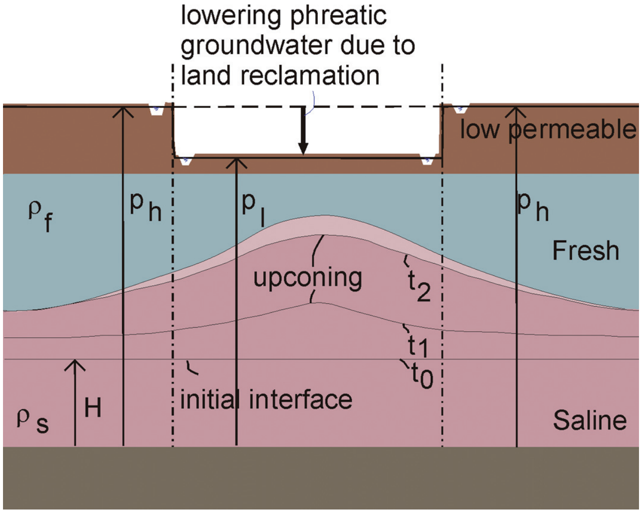

*Fig. 10. Concept of upconing of saline groundwater due to lowering of the polder water level.*

Figure 11 (right) shows the reference scenario, where the groundwater salinity increases significantly along the transect compared to the starting time. Water of higher salinity has been transported further inland and to the surface. Where the surface water level is kept relatively low (i.e., in the deeper polder areas), upconing of salt groundwater leads to severe salinisation of the shallow groundwater and surface water systems. As was mentioned before, this problem has been recognised by the water board and intervention scenarios were defined. Figure 12 depicts the groundwater salinity distribution along the transect for the two intervention scenarios.

Comparing Figs 11 and 12 indicates enhanced upconing of saline groundwater in polder Roptavaart in scenario one. Contrary, in the area between the coast and the polder and 2 km southeast of the polder, the salinity of the shallow groundwater decreases, which implies a freshening of the surface water system. Along the most southeastern 2.5 km of

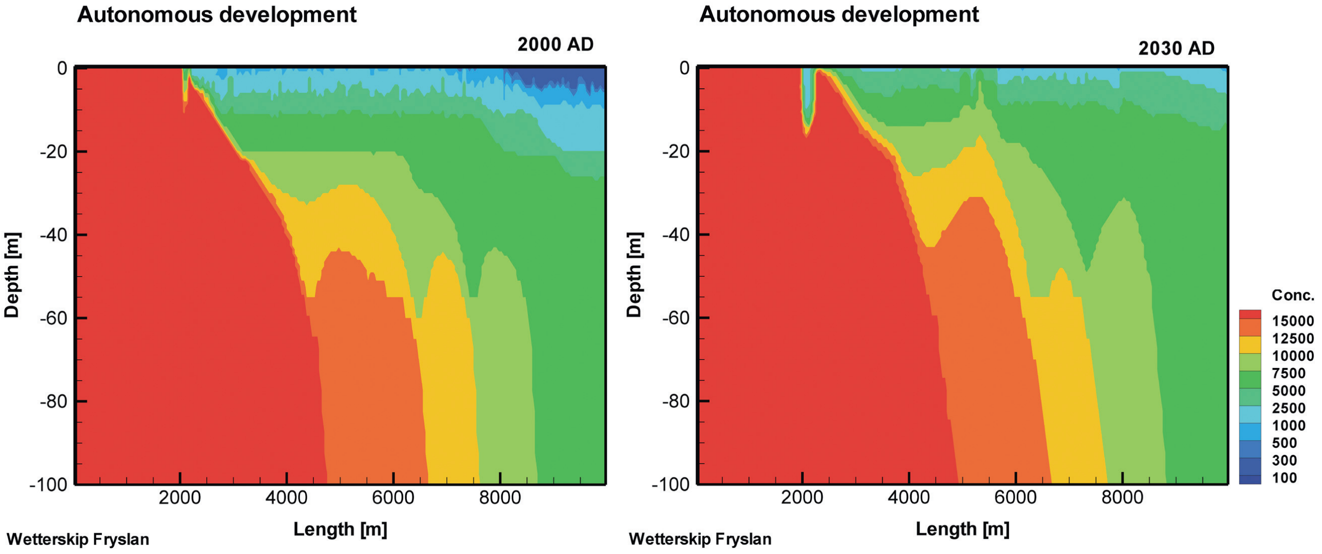

*Fig. 11. Present situation (left) and autonomous development (right) of the salinity distribution of the regional groundwater system near Barradeel.*

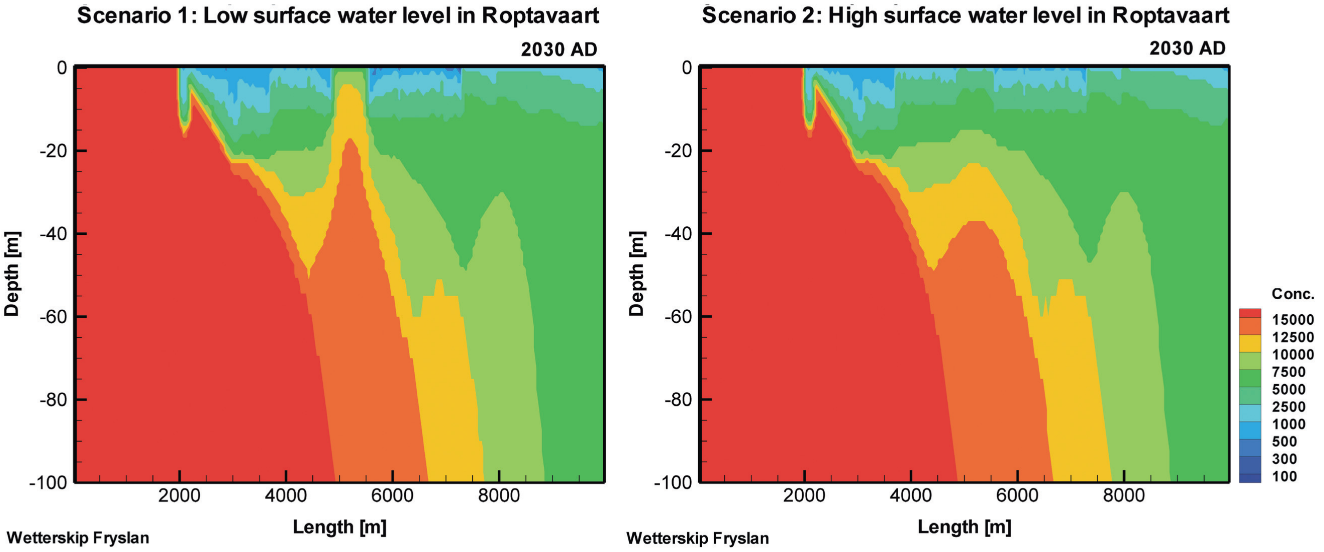

*Fig. 12. Simulated effects of two scenarios on the salinity distribution of the regional groundwater system near Barradeel.*

the transect significant salinisation takes place. In scenario two, upconing of saline groundwater in polder Roptavaart still occurs although salinisation is much less here. Freshening only takes place in the areas within 1.5 km from the coast, whereas the rest of the transect is subjected to salinisation. Salinisation along the most southeastern 2.5 km of the transect is similar as in scenario one.

In addition to this qualitative analysis, the results have been analysed quantitatively by computing the average chloride load to the surface water system at the end of the simulation period for all four cases. At the starting time, the average chloride load is 600 kg/ha/year. In the reference scenario, the average chloride load increases with 1070 kg/ha/year compared to starting time, to an average chloride load of 1670 kg/ha/yr. In scenario one, the average chloride load to the surface water system amounts 2270 kg/ha/yr. The extreme low surface water levels at Polder Roptavaart cause these high average chloride loads. The advantage is, however, that the salt load is concentrated at one point, whereby the salt load to other areas is reduced. Scenario two will reduce the chloride loads to the surface water to an average value of 284 kg/ha/yr, compared to the starting time. This scenario seems like an effective measure to mitigate salinisation. Due to the increased groundwater levels, however, conventional agriculture is no longer possible.

## Conclusions

The two case studies illustrate groundwater and surface water salinisation in the subsurface of the Wadden Sea area by autonomous development of the groundwater flow system, sea-level rise, land subsidence and anthropogenic measures. The Wadden Sea area is a typical low lying deltaic area, so similar effects can be expected in other deltaic areas in the world.

The Texel case study indicates that the autonomous development of the groundwater flow system already leads to significant salinisation of the groundwater and surface water system in polder areas. Because the polders on the island of Texel are close to the sea, sea-level rise has a strong impact on salinisation. Salt loads are expected to double here within approximately two centuries. The influence of sea-level rise on the seepage quantity is relatively strong compared to the deep polder areas in the western part of the Netherlands. This might force water managers to increase the capacity of the pumping stations. Similar effects can be expected on the other Wadden Sea islands, as they have comparable hydrogeological settings.

For the Texel case study, an initialisation simulation was needed to smooth out unwanted, unrealistic density-dependent groundwater flow due to an inaccurate initial groundwater salinity distribution. A promising data source that may circumvent the need of a long initialisation period are airborne electromagnetic (AEM) geophysical methods. These methods can be used to cover large areas in a relatively short time span. They are especially suitable for detecting the salinity of groundwater, as the electromagnetic signal is related to subsurface conductivity and therefore depends on the salinity of the groundwater. Complicating factors include the effect of electrically conductive infrastructure (e.g., power lines, railways, etc.) and the effects of the equivalence problems in the inversion procedure of the electromagnetic signal. In the northern Netherlands, Sky-TEM time domain data (Aarhus University) as well as HEM frequency domain data (The Federal Institute for Geosciences and Natural Resources; BGR) were used within the CliWat project to construct a three-dimensional groundwater salinity distribution. (e.g., Steuer et al., 2007) The results of these surveys and an analysis of their added value to density dependent groundwater flow and solute transport modeling will be published in the summer of 2012 (Faneca et al., 2012).

The Barradeel case shows that enhanced land subsidence by salt exploitation will accelerate salinisation in the surrounding area. Within a period of 30 years the chloride loads to the surface water are expected to be almost three times the present loads. An increase of the surface water level as a counter measure leads to a reduction, and in some areas even freshening of the shallow groundwater and surface water system. If a polder area is designated as a (saline) groundwater collection area by maintaining a very low controlled water level, the salinisation in the nearby areas can be reduced considerably. Similar effects and counter measures can be expected in other areas of northern Friesland because the hydrogeological features near Barradeel are comparable with the rest of the area. In addition, the extraction of natural gas in northern Friesland may induce similar accelerated land subsidence and hence, accelerated salinisation.

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