Impact of sea level rise on Dutch groundwater regimes

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Abstract

The impact of sea level rise on vulnerable coastal groundwater regimes in the Netherlands for the next millennium is investigated. For this purpose, the two-dimensional groundwater flow model MOC of Konikow & Bredehoeft [1978] is applied. It has been adapted by the author to simulate density dependent groundwater flow and solute transport in vertical profiles. The model assesses the propagation of sea level rise in the groundwater regimes. Moreover, it assesses the changes in the salinity distributions of these regimes, the changes in the volumes of freshwater lenses in sand-dunes and the changes in seepage (both quantity and quality) in low-lying polders. It appears that, independent of sea level rise, a severe (irreversible) salinisation process already occurs in the groundwater regimes along the Dutch coast. This present salinisation process is generated by human activities such as the reclamation of the (low-lying) polders during the past centuries. It is to be expected that sea level rise significantly intensifies the salinisation process. Whether or not the impact of sea level rise for a specific polder is significant in terms of seepage quantity, mean chloride concentration and chloride load, depends on the distance to the coast, the phreatic groundwater level and the subsoil parameters.

1. Introduction

Groundwater regimes in the coastal zone of the Netherlands within the zone of influence of mean sea level will be threatened by a rise in sea level even more in the future than they are already threatened today (see figure 1). Salt water intrusion in these regimes will probably accelerate. As such, the salinisation process could result in a reduction of fresh water resources. Furthermore, the seepage quantity may increase in those coastal areas which are situated below *N.A.P.*[1] The present capacity of the discharge systems (pumping stations and water courses) in several low-lying polders near the coast may be insufficient to cope with the excess of seepage water. This seepage will probably have a higher salinity than at present. A substantial increase in volumes of water required for flushing could be necessary to counteract the deterioration of the water quality of the surface water systems in the Netherlands. In addition, crops may suffer from salt damage due to the increased salinity of the soil and fertile arable land might eventually become barren land.

Though the impact of sea level rise on groundwater regimes and consequently on water management can be far-reaching, virtually all relevant literature treats this topic only very superficially. Therefore, a Ph.D. study has been set up to partly fill the gap of knowledge [Oude Essink, 1996]. In this paper, the main objective is to quantify the possible impact of sea level rise on vulnerable coastal groundwater regimes in the Netherlands during the next millennium. To arrive at a comprehensive view over the results of the simulations, a selection of only three scenarios of sea level rise has been made: one with a sea level rise of 0 metre per century (SLR=0 m/c), one with SLR=+0.6 m/c and one with SLR=-0.6 m/c (thus a sea level fall !).

Note that this paper is only a concise summary of Oude Essink's Ph.D. thesis [1996]. Obviously, innumerable cases regarding groundwater flow in coastal geohydrologic systems could be simulated. In the thesis, however, a large number of conceivable cases have been evaluated which are not treated here. For instance, the influence of land-subsidence[2] and changes in groundwater recharge[3] have been considered. Moreover, also the influence of (hypothetical) measures that counteract the negative impact

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

[2] Polders subside because of compaction, shrinkage and oxidation of peat as well as man-induced processes such as local mining activities (e.g. oil and gas) and groundwater recovery.

[3] The groundwater recharge can alter due to a change in: (a) the natural component: e.g. change in the present precipitation pattern due to climate change, and (b) the anthropogenic component: e.g. change in artificial recharge or withdrawal of groundwater from the phreatic aquifer.

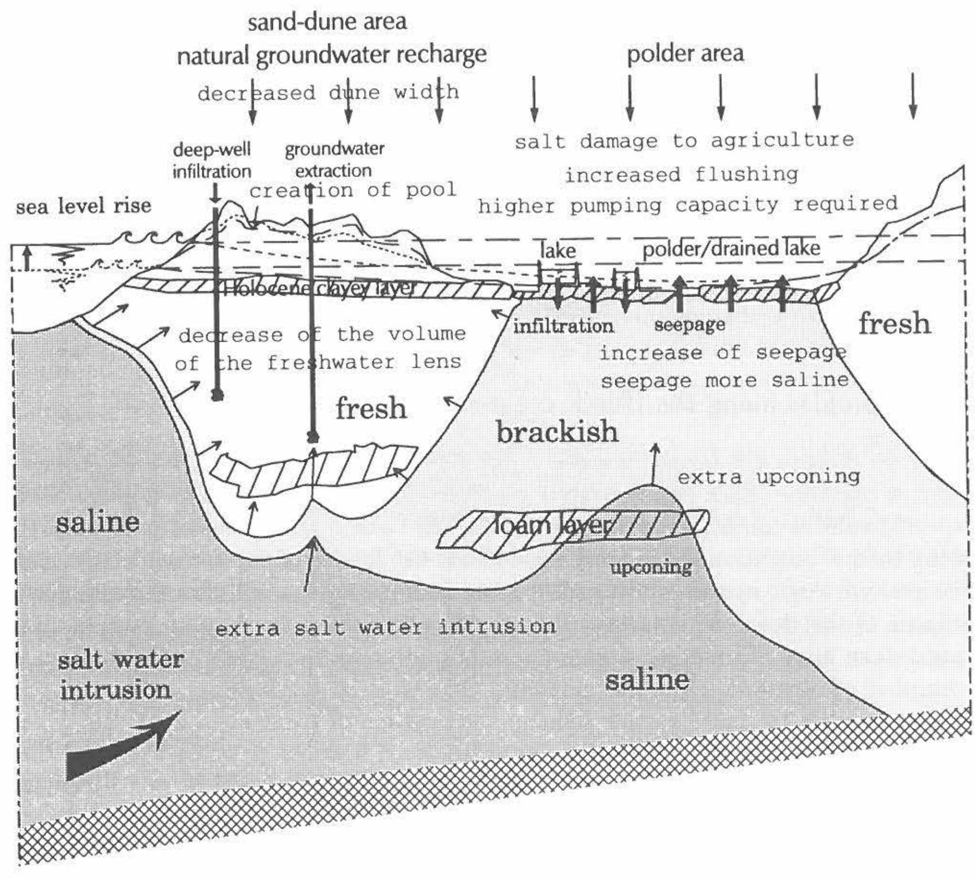

Figure 1: Possible impacts of sea level rise on the groundwater regime in the low-lying western part of the Netherlands.

of sea level rise have been discussed, such as (a) reclaiming land in front of the coast, thus evolving new freshwater lenses; (b) extracting (saline) groundwater, thus decreasing the seepage quantity and chloride load in the polders; (c) infiltrating of surface water (viz. *deep-well infiltration*), thus blocking the salinisation process towards the low-lying hinterland; (d) inundating low-lying polders, thus removing the driving force of the salinisation process; (e) widening existing sand-dune areas, thus generating thicker freshwater lenses; and (f) creating physical barriers, thus blocking the free entrance of saline groundwater and halting the salinisation process. Based on numerous simulations, it appears that, when the sea level rises $+0.6\ m/c$, even the most effective countermeasures cannot stop the salinisation of the subsoil on the long-term. Therefore, it is likely that human interventions can only retard the salinisation of the groundwater regimes in the long-term at the expense of major investments[4]. Finally, also cases with different subsoil parameters have been treated in order to execute a limited parameter sensitivity analysis.

The sensitivity of the groundwater regime in the Netherlands for three scenarios with different rates of sea level rise is analysed[5] by (numerical) modelling of eight representative profiles perpendicular to the Dutch coastline. For this purpose, the model MOC of Konikow & Bredehoeft [1978] is applied, which is adapted for density differences to simulate vertical profiles [Lebbe, 1983; Oude Essink, 1996]. MOC is based on the finite difference method and it uses a particle tracking technique to model (advective) solute transport. In this paper, the objective is focused on the following impacts of sea level rise:

- the propagation of sea level rise in the piezometric level distribution

[4]Whether these investments are considered feasible or not depends on the prevailing economic, environmental and political circumstances at the moment when a (political) decision is taken.

[5]Note that the methodology followed to investigate and to assess the impact of scenarios of sea level rise (and human activities) on Dutch coastal groundwater regimes could also be extended to similar vulnerable coastal groundwater regimes around the world.

- the changes in salt water intrusion in the geohydrologic system
- the changes in the volumes of freshwater lenses in sand-dune areas
- the changes in seepage (both quantity and quality) in low-lying polders

In section 2, the eight representative profiles are described. In section 3, the propagation of sea level rise in each geohydrologic system is considered. In section 4, the salt water intrusion in each geohydrologic system is described. In section 5, the evolution of the freshwater lens in four geohydrologic systems is evaluated. In section 6, the changes in seepage (both quantity and quality) is shortly discussed. Finally, some conclusions are drawn and recommendations are given.

2. Representative profiles along the Dutch coast

As MOC, adapted for density differences, is a two-dimensional model, profiles have been chosen perpendicular to the Dutch coastline. Each *representative profile* characterizes a coastal area in the Netherlands with its own specific subsoil conditions which differ from the subsoil conditions of profiles in the vicinity. The following subsoil conditions have been considered: the length of the geohydrologic system; the thickness of the geohydrologic system down to the geohydrologic base; the hydraulic conductivity; the hydraulic resistance of the Holocene aquitard; the positions and characteristics of loam aquitards; the width of the sand-dune area (if present); and the phreatic groundwater levels in the polders. Strictly speaking, the number of conceivable profiles is infinite. For reasons of simplicity, however, the number of profiles has been limited to eight. Figure 2 shows the position of these eight representative profiles perpendicular to the Dutch coastline. Note that, unfortunately, it is not possible to model the islands of Zeeland by means of a representative profile as they cannot be schematised in two dimensions[6].

Apparently, three-dimensional effects, such as groundwater flow perpendicular to the profile due to groundwater extractions or low phreatic groundwater levels in polders, are left out of consideration. In fact, these effects may be very important for the interpretation of the results, but for the applied profiles, in which subsoil parameters are averaged over areas of several hundred square kilometres, the effects are probably of minor importance.

2.1 Subsoil conditions

Figure 3 shows the schematisation of the geometry, the values of subsoil parameters and the phreatic groundwater levels in the polders of each of the eight profiles. The data of the geohydrological schematisation have mainly been borrowed from numerous sources. As can be seen, there is a great variety of subsoil conditions along the Dutch coast. The following subsoil parameters are applied in MOC: the effective porosity=0.35; the longitudinal dispersivity α_L=0.2 m; and the anisotropy factor=0.1. Sand-dune areas with freshwater lenses occur in the profiles Ber, Haa, Lei and Wad. As can be seen, the phreatic groundwater levels in the polders are below $N.A.P.$ in all profiles (except in the profile Vla). Obviously, this situation reveals that a permanent salinisation process must be taking place in the direction of the (low-lying) polders. Figure 4 shows the chloride distributions in 1990 in the eight profiles, derived from several different sources. As concentration measurements at great depths are generally rare, the chloride distribution in some places might be disputable. Specific characteristics of each profile are briefly discussed below:

1. Wie=Wieringermeer: the transmissivity of this geohydrologic system is huge, as the thickness is enormous, some 260 m, and the hydraulic conductivity high. Moreover, the hydraulic resistance of the Holocene aquitard is high. The polder (that is the Wieringermeer polder) in the reach 15,000-29,500 m has a very low phreatic groundwater level: between -4.5 and -5.5 m $N.A.P.$ At the inland boundary, the water level in the IJsselmeer is a constant piezometric level boundary. Fresh groundwater, which belongs to the freshwater body of Hoorn, is present in the central part of this profile.

[6] For instance, sand-dune areas occur in the western seaside parts of the islands, which would complicate a proper selection of the orientation of the profile. Moreover, the characteristics of these islands, such as the thickness of the geohydrologic system, the boundary conditions and the phreatic groundwater levels, differ too much from each other to join them together in one representative profile.

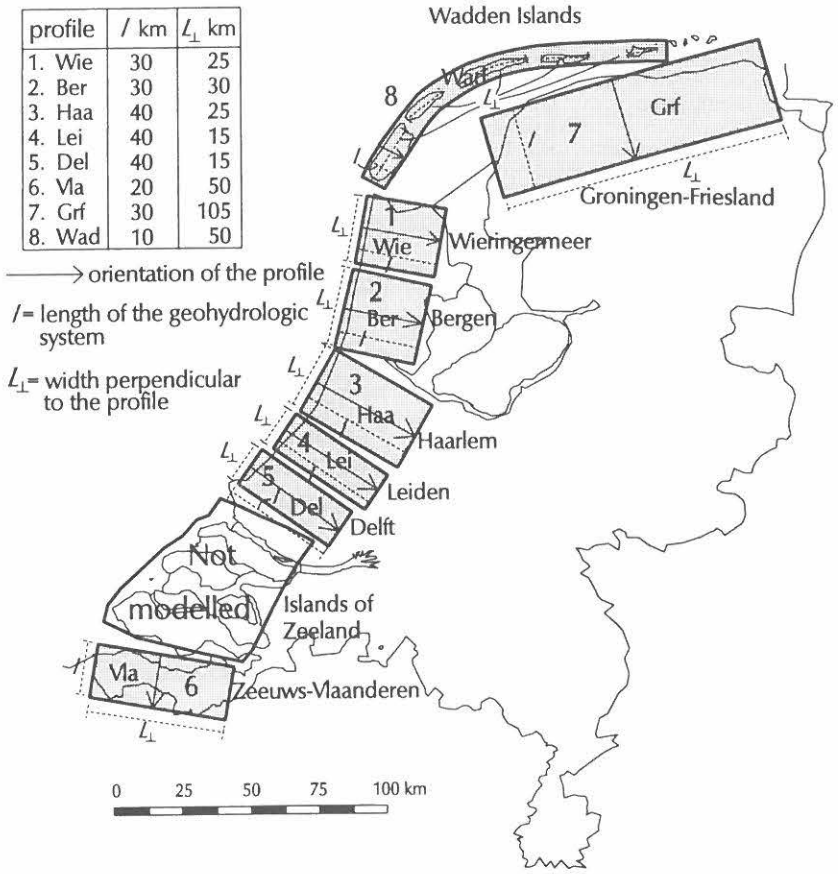

Figure 2: Location of the eight areas in which the eight representative profiles perpendicular to the Dutch coastline are defined. The names of the profiles are arbitrarily chosen: they refer to a city, region or province positioned in that profile. The islands of Zeeland are not modelled.

2. Ber=Bergen: in the central part of this profile, a low-lying polder (-4 m $N.A.P.$) occurs, which represents the areas reclaimed in the seventeenth century: the Beemster (1608-1612), the Wormer (1625-1626) and the Schermer (1633-1635). The main difference with the profile Wie in terms of chloride distribution is caused by the presence of a sand-dune area of 3000 m width under which a freshwater lens has evolved.

3. Haa=Haarlem: the hydraulic conductivity is lower than in the two profiles mentioned above. Various low-lying polders are located at a considerable distance from the coast, such as the Haarlemmermeer polder in the reach 10,000-20,000 m. From the coastline, a broad sand-dune area extends to 3500 m inland. Amsterdam Waterworks has pumped water from this area since the middle of the nineteenth century. The freshwater lens reaches to a depth of at least 80 m below $N.A.P.$ Under this lens, saline groundwater flows in the direction of the low-lying Haarlemmermeer polder.

4. Lei=Leiden: this profile resembles the profile Haa to a certain extent. The main differences, however, are that (1) the thickness of the geohydrologic system is 30 m less and (2) the phreatic groundwater level of the polders is a few metres higher. The width of the sand-dune area is 2500 m, and hence, the thickness of the freshwater lens is somewhat smaller than in the profile Haa.

5. Del=Delft: though this profile corresponds to a great extent with the profile Lei, a significant difference can be found in the hydraulic resistance of the Holocene aquitard in the reach 10,000-20,000 m: e.g. 25,000 *days* in the profile Del instead of 3000 *days* and 750 *days* in the profile Lei. The sand-dune area, present in this profile, is too small to be simulated. Relatively low polders at some kilometres inland of the coast (-2.5 m $N.A.P.$ from x=5000 m) induce a flow of saline groundwater in the geohydrologic system. Close to the city of Delft, groundwater is extracted for industrial purposes.

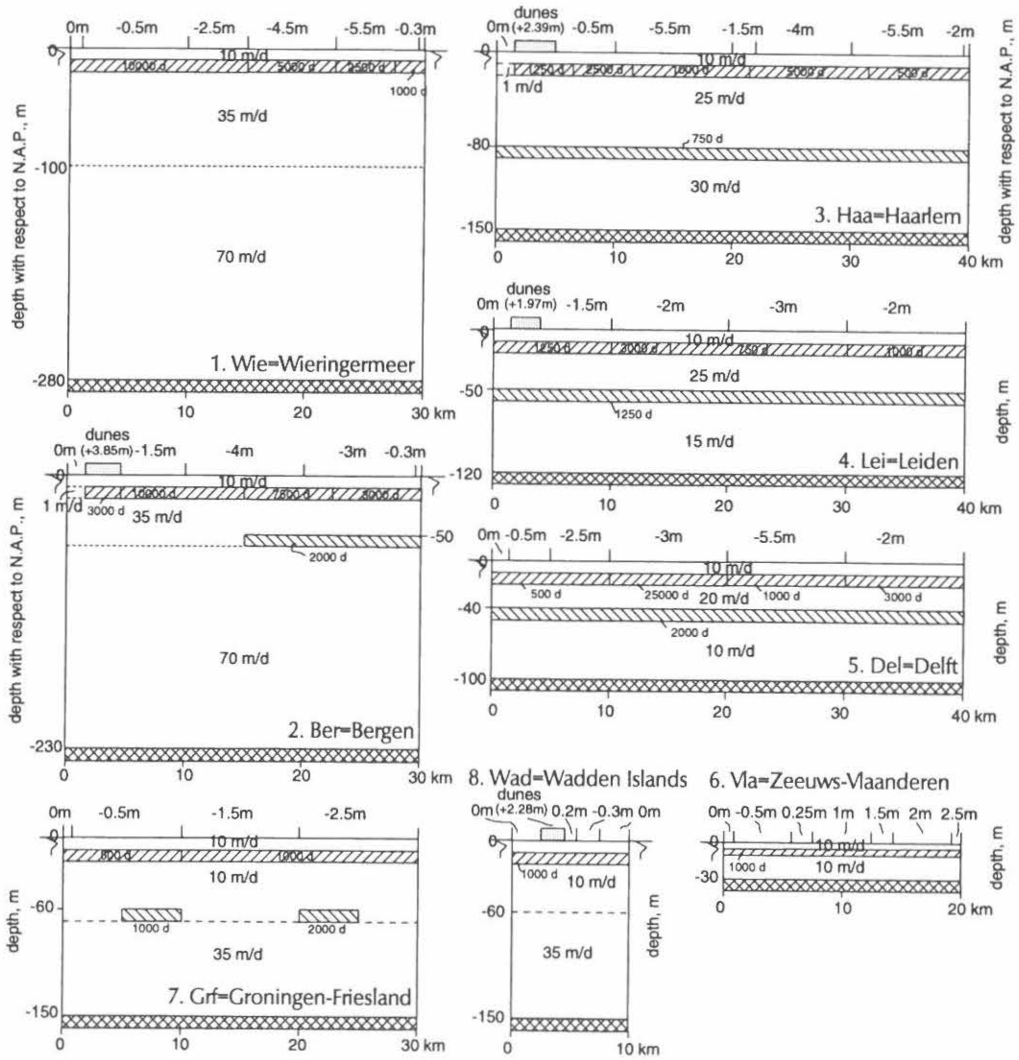

Figure 3: Schematisation of the geometry, the subsoil parameters and the phreatic groundwater levels with respect to $N.A.P.$ in the polders of the eight representative profiles. The groundwater recharge f in the sand-dune area is 360 mm/yr. The highest phreatic groundwater level in the sand-dune areas of the profiles Ber, Haa, Lei and Wad is given in brackets.

6. Vla=Zeeuws-Vlaanderen: the Belgium hinterland is also considered in this profile. The phreatic groundwater levels in the polders at some kilometres inland of the coast are above $N.A.P.$ The thickness of the geohydrologic system is the smallest of all profiles, only some 20 m. In the past, a severe salinisation process has caused high chloride concentrations in this geohydrologic system.

7. Grf=Groningen-Friesland: the phreatic groundwater levels are not very low in this profile. The length of the saline groundwater tongue is limited to some kilometres. More inland of the tongue, brackish groundwater is present in the entire geohydrologic system.

8. Wad=Wadden Islands: at both boundaries, a sea condition is present. At the Waddenzee side, polders are present with phreatic groundwater levels around $N.A.P.$ At the North Sea side, the width of the sand-dune area is 2000 m, under which a freshwater lens has evolved with a thickness of about 80 m. Note that this profile closely corresponds with that of Texel.

2.2 Model parameters in MOC

The following model parameters are applied in the adapted MOC model (see also Oude Essink [1996]). Each grid cell has a length Δx of 250 m and a height Δz of 10 m (only for the profile Vla, the height Δz is equal to 5 m). Each grid cell contains five particles. The convergence criterion TOL is 10^{-5} ft. The flow time step Δt equals 1 $year$. During this step, the velocity field remains constant. The maximum

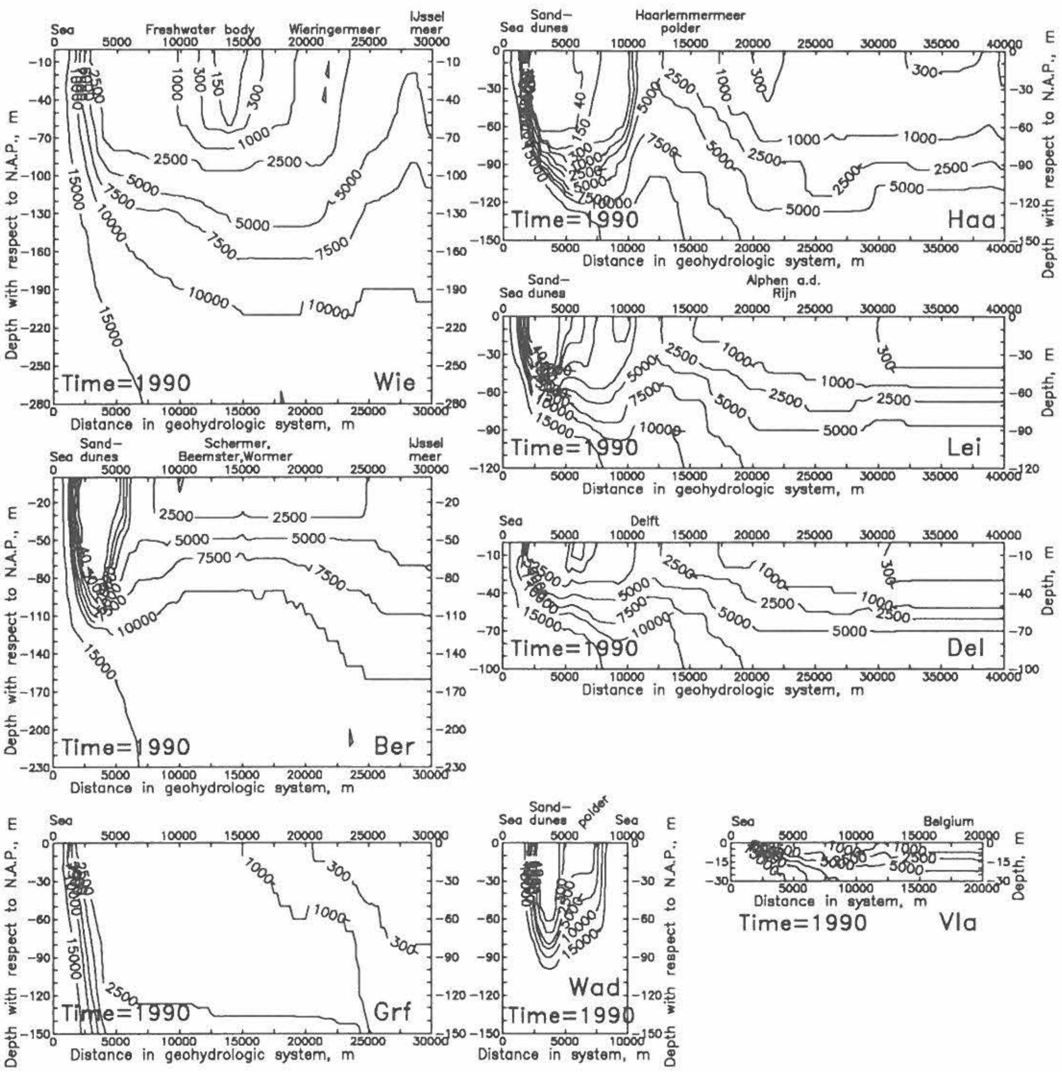

Figure 4: Present fresh-saline distributions (in $mg\ Cl^{-}/l$) in 1990 in the eight representative profiles.

relative distance in a grid cell is set to 0.9.

2.3 Three scenarios with different rates of sea level rise

The scenario with no sea level rise (SLR=0 m/c) is applied as the so-called *reference case* for all cases. The present situation concerning boundary and initial conditions, phreatic groundwater levels in the polders and groundwater extraction rates is maintained during this scenario. Accordingly, many processes[7] that may affect the geohydrologic system are left out of consideration. The results of this scenario may clarify the effect of (past) human activities, such as land reclamation which has created low-lying polders. Furthermore, the time lag has been determined before a state of dynamic equilibrium regarding the salinity distribution will be reached.

A sea level rise of +0.6 m/c and a sea level fall of -0.6 m/c are considered for a simulation time of one millennium. The change in sea level is added to the freshwater head in the grid cells at the seaside boundary before each calculation time step of 1 *year*. The time lag, in which the freshwater head in the geohydrologic system rises to a new state of dynamic equilibrium due to sea level rise, can be neglected with respect to the time lag in which the salinity distribution changes. Therefore, it

[7] These processes are of a hydrological nature (e.g. less precipitation, more evapotranspiration due to climate change), a morphological nature (e.g. shoreline retreat) or a man-induced nature (e.g. sand-suppletion at the coastal zone to counteract shoreline retreat).

is allowed to change the freshwater head in the geohydrologic system instantaneously by setting the specific storativity equal to zero. Bear in mind that a sea level rise with a rate of e.g. +0.6 m/c means a sea level elevation of 6 m after a simulation time of one millennium. This rise in sea level induces an elevation in phreatic groundwater level in the sand-dune area. In fact, the rise in phreatic groundwater level could be impeded if the position of the land surface is fixed. In order to assure that the phreatic groundwater level can rise freely, sand-suppletion is supposed to nullify the possible impediment.

3. Propagation of sea level rise

In straightforward terms, the so-called characteristic length λ of a formation[8] indicates the zone over which a sea level rise at the seaside boundary influences the geohydrologic system: that is the so-called *zone of influence*. As the geometry of the profiles is complex, the zone of influence is determined by calculating the difference in piezometric level, expressed in freshwater, in 2090 for the scenario SLR=+0.6 m/c with respect to the scenario SLR=0 m/c (see figure 5). Three types of sensitivity for sea level rise can be perceived:

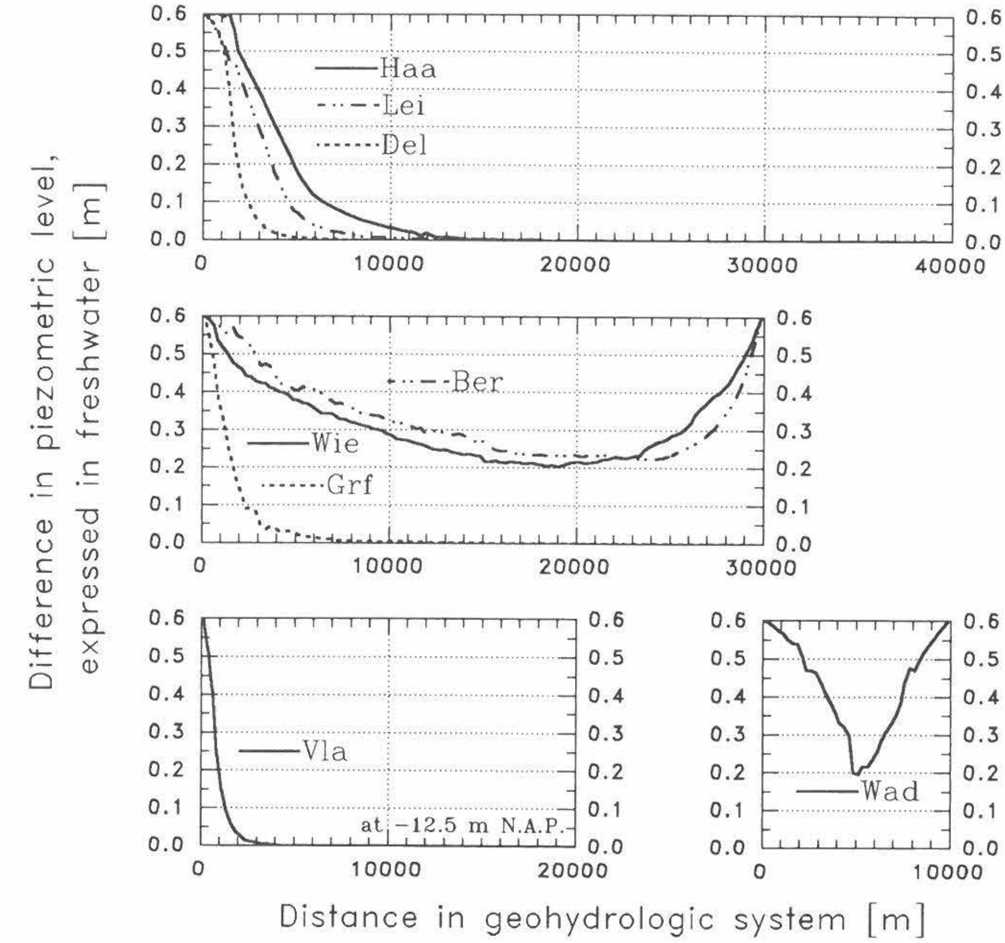

Figure 5: The propagation of a sea level rise in the geohydrologic system: differences in piezometric level, expressed in freshwater, at -25 m $N.A.P.$ (in the profile Vla at -12.5 m $N.A.P.$) in 2090 for the scenario SLR=+0.6 m/c with respect to the scenario SLR=0 m/c.

[8] In a simple geohydrological schematisation, which consists of a Pleistocene sandy aquifer overlain by a Holocene (clayey) aquitard, also named the *Holland profile*, the characteristic length λ equals $\sqrt{kDc}$, where k is the hydraulic conductivity of the semi-confined aquifer ($L\,T^{-1}$), D is the saturated thickness of the aquifer (L), and c is the hydraulic resistance of the aquitard (T).

I. **High sensitivity to sea level rise**: the profile **Wad**. The zone of influence is very long because: (1) the level of the sea rises at both boundaries of the geohydrologic system; (2) the length of the geohydrologic system is small; and (3) the transmissivity is relatively high.

II. **Moderate sensitivity to sea level rise**: the profiles **Wie** and **Ber**. The zone of influence of sea level rise is significant. Consequently, piezometric levels in the geohydrologic system elevate significantly due to sea level rise. The two causes for this substantial rise in piezometric level are: (1) the transmissivities of the aquifers and the hydraulic resistance of the Holocene aquitard are very high; and (2) the piezometric level at the IJsselmeer side boundary also rises at the same rate as the sea level[9].

III. **Low sensitivity to sea level rise**: the profiles **Haa**, **Lei**, **Del**, **Vla** and **Grf**. The zone of influence of sea level rise is only a few kilometres. Thus, the attenuation of sea level rise is great in these profiles. For instance, the distance in the geohydrologic system, over which a freshwater head elevation of 6 cm (10% of the sea level rise) can still be noticed, is as follows: in **Haa** 8000 m; in **Lei** 5300 m; in **Del** 2800 m; in **Vla** 1600 m; and in **Grf** 3000 m.

4. Salt water intrusion in the geohydrologic system

Salt water intrusion in each geohydrologic system is discussed through analysing the chloride distribution in 2990 for the scenario SLR=+0.6 m/c and the time lag before a state of dynamic equilibrium in the salinisation process is reached.

4.1 Chloride distribution in 2990 for the scenario SLR=+0.6 m/c

Figure 6 shows the chloride distributions in 2990 in the eight profiles for the scenario SLR=+0.6 m/c. Through comparison with figure 4 (the situation in 1990), one can deduce the following:

1. **Wie=Wieringermeer**: two main causes for the severe salt water intrusion of the geohydrologic system are the high transmissivities and the low-lying Wieringermeer polder in the reach 15,000-29,500 m. The entire system will be saline in 2990.

2. **Ber=Bergen**: also in this profile, a severe salt water intrusion occurs. The freshwater lens remains, though the volume obviously decreases due to sea level rise. The aquifer, which underlies the low-lying polder in the central part of the profile, contains much more saline groundwater in the future than in 1990.

3. **Haa=Haarlem**: the freshwater lens decreases in such a way that salt water intrusion in the geohydrologic system in the center the low-lying polder (e.g. the Haarlemmermeer polder) will be severe.

4. **Lei=Leiden**: salt water intrusion is rather limited for several reasons: (1) the thickness of the geohydrologic system is 'only' 120 m; (2) as such, the freshwater lens is obstructing the inflow of saline groundwater to the hinterland; and (3) the phreatic groundwater levels of the polders are not as low as in the profile **Haa**. Saline groundwater will eventually reach the polder which is located directly behind the decreasing freshwater lens.

5. **Del=Delft**: the results correspond to some extent with those in the profile **Lei**. In the first kilometres inland of the coast, a severe salt water intrusion is taking place. Saline seepage occurs in the polder in the reach 5000-7500 m, because there the phreatic groundwater level is relatively low (-2.5 m $N.A.P.$) and the hydraulic resistance is low (500 $days$). Industrial groundwater extractions in the vicinity of Delft cause upconing of brackish groundwater. Meanwhile, surface water infiltrates in the geohydrologic system in the reach 8000-20,000 m, as the extractions create a low piezometric level in the aquifer. From about 10,000 m inland of the coast, the impact of sea level rise is very limited due to the high hydraulic resistance of the Holocene aquitard.

[9] As such, the geohydrologic system is influenced at the seaside as well as at the IJsselmeer side, and consequently, the piezometric level in between rises due to both these rises.

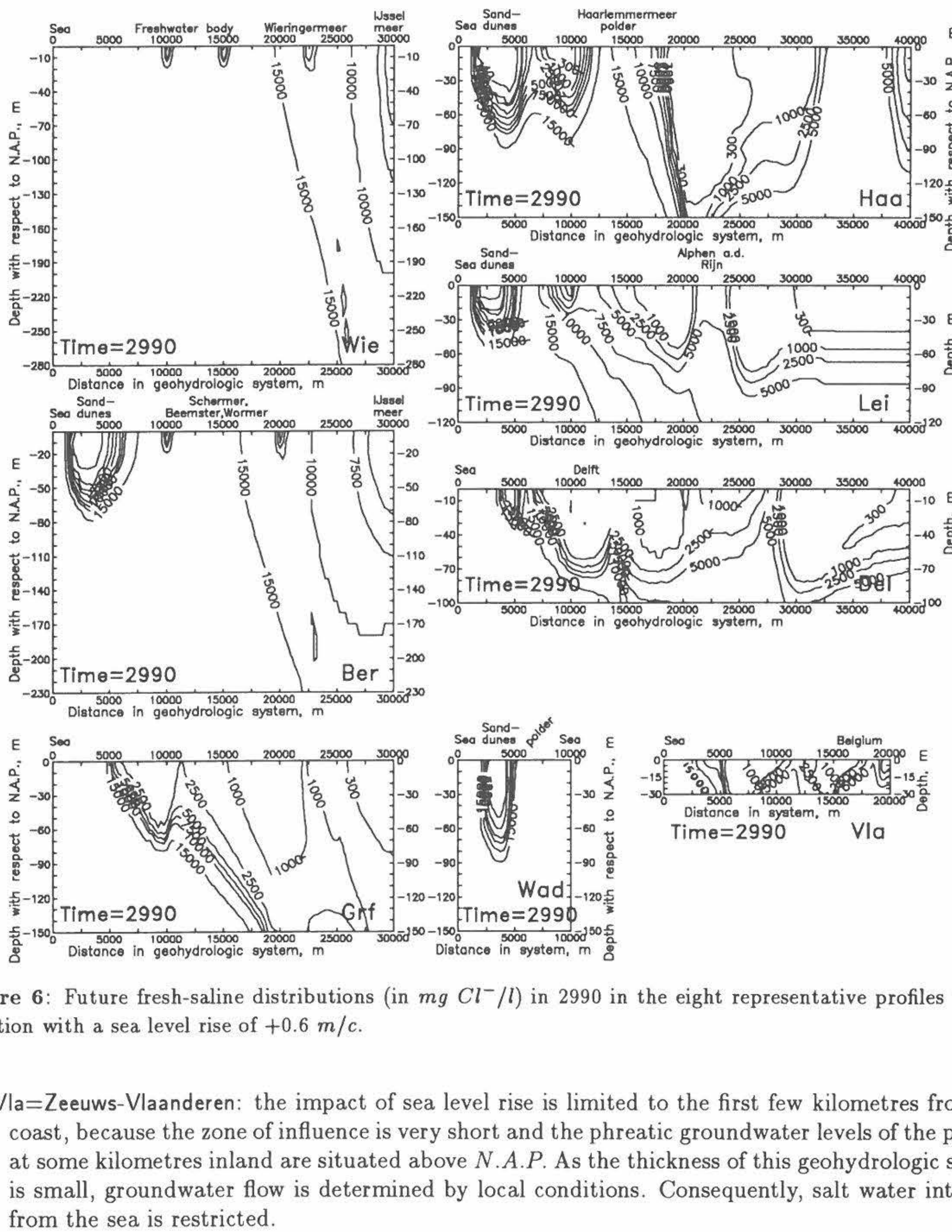

Figure 6: Future fresh-saline distributions (in $mg\ Cl^-/l$) in 2990 in the eight representative profiles for the situation with a sea level rise of $+0.6\ m/c$.

6. Vla=Zeeuws-Vlaanderen: the impact of sea level rise is limited to the first few kilometres from the coast, because the zone of influence is very short and the phreatic groundwater levels of the polders at some kilometres inland are situated above *N.A.P.* As the thickness of this geohydrologic system is small, groundwater flow is determined by local conditions. Consequently, salt water intrusion from the sea is restricted.

7. Grf=Groningen-Friesland: eventually, the geohydrologic system will be completely saline in the first kilometres inland of the coast.

8. Wad=Wadden Islands: the geohydrologic system underneath the polder becomes more saline at great pace. However, the freshwater lens remains though its volume decreases. Note that the phreatic groundwater level in the sand-dune area is supposed to rise with sea level rise. Sand can be supplied where necessary in order to assure that the phreatic groundwater level can rise freely.

4.2 Time lag before a state of dynamic equilibrium is reached

Based on analyses of the changes in volume distribution of fresh, brackish and saline groundwater in the geohydrologic system for the scenario SLR=0 m/c as a function of 10,000 years[10] [Oude Essink, 1996],

[10] As the state of dynamic equilibrium will not be reached within one millennium in several profiles, the simulation time has been extended to 10,000 years.

it appears that most of the geohydrologic systems along the Dutch coast have at present not yet reached a state of dynamic equilibrium as far as the salinity distribution in the subsoil is concerned. The time lag of a geohydrologic system between the cause of changes and the ultimate effect on the salinisation process is mainly determined by three causes: (a) the driving force of the salinisation process, that is the phreatic groundwater levels in the polders and/or groundwater extractions; (b) the transmissivity and porosity of the geohydrologic system, that is the velocity with which groundwater can pass through the geohydrologic system; and (c) the geometry (size) of the geohydrologic system under consideration. Based on the causes mentioned above, four durations of time lags can be classified:

I. A time lag of several centuries: geohydrologic systems with small geometries: the profiles Vla and Wad.

II. A time lag of a large number of centuries: geohydrologic systems with high transmissivities and low-lying polder areas: the profiles Wie and Ber.

III. A time lag of a few millennia: geohydrologic systems with moderate transmissivities and polder areas with high phreatic groundwater levels: the profiles Haa and Grf.

IV. A time lag of several millennia: geohydrologic systems with low transmissivities and polder areas with high phreatic groundwater levels: the profiles Lei and Del.

Considering the absolute change in the volume of saline groundwater, the salinisation appears to be greatest in the northern part of the Netherlands in the profiles Wie, Ber and Grf. Salt water intrusion is still substantial in the profiles Haa, Lei and Del. The salinisation is limited in the profiles Wad and especially Vla, which is obvious as the geohydrologic system of the profile Vla is small.

5. Freshwater lenses in sand-dune areas

Figure 7 shows the volume of fresh groundwater in the sand-dune areas as a function of time in the four profiles Ber, Haa, Lei and Wad. During the next century, the impact of sea level rise on the fresh groundwater resources along the coast appears to be of minor importance, at most a few percents. After a millennium, however, the changes are (obviously) significant.

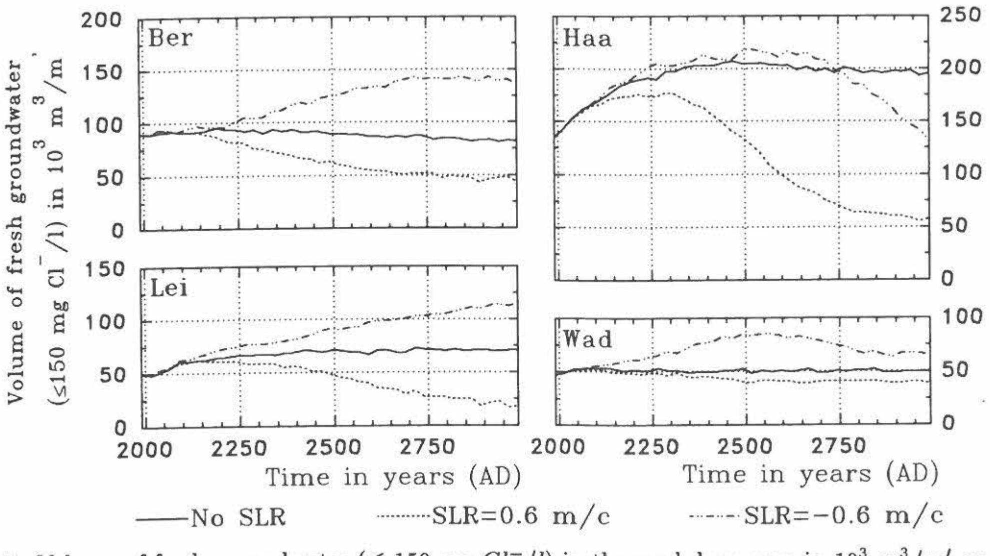

Figure 7: Volume of fresh groundwater ($\leq 150\ mg\ Cl^{-}/l$) in the sand-dune area in $10^3\ m^3/m'$ as a function of time for the three scenarios of sea level rise.

Two phenomena occur in the profile Haa. Firstly, for the scenario SLR=-0.6 m/c, the volume of the freshwater lens drops below the volume for the scenario SLR=0 m/c after some seven centuries. The reason for this phenomenon is that, after some centuries, the groundwater flow in the sand-dune area alters in the direction of the sea, as the sea level is falling. The shape of the freshwater lens also changes, which results in a decreasing volume of fresh groundwater. Secondly, for the scenario SLR=0 m/c, the volume of fresh groundwater increases significantly (e.g. +23.4 % in 2090 with respect to 1990) because of two reasons: (a) the groundwater extraction rate has been decreased since 1956 and (b) the freshwater lens evolves towards the low-lying polder in the reach 10,000-20,000 m, and as a result, the volume increases. In the profile Wad, the volume of fresh groundwater decreases during the second half of the next millennium for the scenario SLR=-0.6 m/c. The reason is that, from then on, sea level fall causes fresh surface water, which originates from the polder adjacent to the sand-dune area, to infiltrate in the geohydrologic system. This water, which contains a higher chloride concentration than 150 $mg\ Cl^-/l$, supersedes the fresh groundwater that recharges the sand-dune area.

6. Seepage in low-lying polders

The impact of sea level rise in a specific polder can be significant in terms of seepage quantity, mean chloride concentration and chloride load if the following situations occur: the polder is situated directly inland of the coast; the phreatic groundwater level in the polder is low, namely several metres below *N.A.P.*; and/or the zone of influence of sea level rise in the geohydrologic system is long as a result of high transmissivities of aquifers. In this section, the changes in seepage through the Holocene aquitard in low-lying polders are shortly discussed for the three topics: (6.1) seepage quantity; (6.2) mean chloride concentration; and (6.3) chloride load.

6.1 Seepage quantity

The propagation of the sea level rise (see figure 5) already indicates the possible changes in seepage quantity due to sea level rise. Obviously, if the sea level rise is attenuated considerably in the geohydrologic system, the changes in seepage quantity are limited. In general, for Dutch polders at a great distance from the coast, the increase in seepage due to sea level rise appears to be of minor importance with respect to the already existing seepage quantities in those polders. For the scenario SLR=0 m/c, the decrease in seepage quantity through the Holocene aquitard due to changes in density distribution (caused by the salinisation of the geohydrologic system) is not insignificant, and thus remarkable. The impact of a sea level rise of +0.6 m (during the next century) on the change in seepage quantity is considerable (up to several tens of percents) in polders in the first kilometres from the coast, whereas it is marginal (mostly up to only a few percents) in polders located further inland.

6.2 Mean chloride concentration

In general, it takes several decades or even centuries before brackish and saline groundwater reach polders that are located several kilometres inland of the coast. It is clear that the nearer the polder is to the seaside boundary, the earlier the impact of sea level rise on the chloride distribution can be noticed. During the next century, the mean chloride concentration of the subsoil will probably increase with several hundreds of $mg\ Cl^-/l$ in many low-lying polders along the Dutch coast due to the combined effect of a sea level rise of +0.6 m and the non-equilibrium state of the present salinisation process as a result of the delayed effect of previous human activities. After several centuries, the impact of sea level rise on the mean chloride concentration becomes substantial in almost all polders, and accordingly, a considerable increase in the salinity of seepage can be expected in the distant future.

6.3 Chloride load

During the next century, the increase in chloride load is drastic in nearly all polders in the low-lying regions of the Netherlands. Even those polders beyond the zone of influence of sea level rise are affected. It appears that the changes in chloride load are much greater than the changes in seepage quantity. As an indicative estimate: the chloride load through the Holocene aquitard in the low-lying coastal regions of the Netherlands will be doubled in 2090, three fifths of which is caused by a sea level rise of 0.6 m and two fifths by the delayed effect of previous human activities (namely the reclamation of lakes or parts of the sea) on the future salinisation process.

Conclusions

- groundwater flow and solute transport are flow processes,
- most of the groundwater regimes of the eight studied profiles along the Dutch coast have not yet reached a state of dynamic equilibrium as far as the salinity distribution in the subsoil is concerned,
- sea level rise significantly accelerates the salinisation,
- many groundwater regimes will eventually become completely saline due to: (1) the future sea level rise; and (2) the present difference in polder level and sea level caused by previous human activities, such as the reclamation of lakes or parts of the sea.
- when the sea level rises +0.6 m during the next century, the volumes of the freshwater lenses in the four profiles with existing sand-dune areas hardly decrease. However, a few centuries later, the decrease in volume may reach several tens of percents,
- when the sea level rises +0.6 m during the next century, the chloride load increases substantially in nearly all polders in the low-lying regions of the Netherlands.

Recommendations

- as the impact of sea level rise could be significant in the coastal groundwater regimes in Zeeland, it is recommended to consider these islands through three-dimensional numerical modelling. For this purpose, a promising three-dimensional model could be an interconnected model of MODFLOW [McDonald & Harbaugh, 1984] (made suitable for simulating density dependent groundwater flow) and the (solute) transport model MT3D [Zheng, 1990],
- to increase the reliability of numerical groundwater modelling, groundwater regimes should be calibrated more accurately through intensifying the data collection of subsoil parameters and time series of hydrochemical constituents.

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