DENSITY DEPENDENT GROUNDWATER FLOW MODEL OF THE SHORE AND DUNE AREA OF THE WESTHOEK NATURE RESERVE (BELGIUM)

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Abstract

The Westhoek nature reserve is a dune area situated along the French-Belgian border. Below the dunes a fresh-water lens is found. A particular distribution of salt-water occurring above fresh-water is found under the adjacent shore. This less known water quality distribution is in dynamic equilibrium. A 2D density dependent groundwater flow model was made using the MOCDENS3D code. First, the groundwater flow and water quality evolution under the shore and in the dunes are modelled. Then the possible impact of sea level rise is simulated for a number of different scenarios. These scenarios reflect different reactions of coastal morphology and human intervention on the sea level rise. Depending on the scenario, the extent of the shore's salt-water lens can increase, decrease of even completely disappear. Simultaneously, the extent of the dune's fresh-water lens can significantly be altered. The simulations illustrates also, besides the effects of sea level rise, that changes in boundary conditions (drainage levels, shore morphology, sea water level), either natural or human induced, can importantly alter the water quality distribution. Because of the high ecological value of the area and the dune's importance for drinking water production, these changes should be well studied beforehand.

Keywords: coastal aquifers, sea level rise, modelling, water quality distribution, Belgium

Introduction

The Westhoek nature reserve is situated on the most western point of the Belgian coast along the French-Belgian border (Figure 1). It is a dune area of about 340 ha in size and is one of the last unfragmented dune areas along the Belgian coast. The Westhoek dunes are part of the north-western European coastal dunes, which form a long, narrow dune strip from Calais (France) to the north of Denmark. Since 1957 the Westhoek dunes are designated as a state nature reserve and are currently in hands of the Nature

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Department of the Ministry of the Flemish Community. The ecological value of the nature reserve and adjacent shore is recognised to be high because of its high diversity of fauna and flora. Fresh-water is present in the phreatic dune aquifer. Therefore, the nature reserves bordering dune areas are also the primary source for drinking water production in the area.

In the south, a low laying hinterland, a polder area, bounds the dunes. Salt-water is present in the polder. The shore between the Westhoek dunes and the sea is one of the widest in Belgium (between 500 and 600 m) and has low angle dip. It is a tidal dominated sandy runnel and ridge beach. The mean tidal range is 4.08 m, which is relatively large. A salt-water lens above fresh-water, present under the shore, was observed and studied by Lebbe (1978, 1981, 1983, 1999). It was shown that a salt-water lens is present under the shore above a fresh-water tongue emanating from the dunes towards the sea. This inverse density distribution is in a dynamical equilibrium.

The lower substratum of the phreatic aquifer is formed by clay of the Kortrijk Formation, Ieper Group. It is of early Eocene age and is considered as impermeable for this study. The lower part of the aquifer consists of medium to coarse medium sands of Eemian age. The larger part of the aquifer is formed by Holocene fine-medium sands in which lenses of silty-fine sand can occur. The top of the aquifer consists of medium sands. Generally, the aquifer becomes more heterogeneous going in eastern direction from the French-Belgian border.

In this paper the development of the water quality distribution in the dunes and under the shore is modelled using the density dependent groundwater flow model MOCDENS3D. Secondly, the impact of expected sea level changes on this distribution is simulated for three different scenarios: (1) a coastal defence is present between the shore and the dunes, (2) a coastal defence is present between the shore and dunes and the shore is heightened and (3) the coastline is retreating.

Evolution to the current situation

The MOCDENS3D code (Oude Essink, 1998, 2001) is used. It is based on the three-dimensional solute transport computer code MOC3D (Konikow et al., 1996), but adapted for density differences.

A 2D model is made simulating the groundwater flow in the polder, dunes and under the shore in a cross-section perpendicular on the coastline. The model consists of 30 layers and 330 columns, so the grid has 9900 cells. Every cell has a width of 10 m and the thickness of every layer is 1.0 m. So, the model grid is 3300 m in width and 30 m deep. It is divided in four parts, columns 1 to 75 represents the polder, columns 76 to 245 the dunes, columns 246 to 299 the shore and columns 300 to 330 the sea. The aquifer is bounded below by clay of the Kortrijk Formation, which is considered impermeable here. The vertical boundary in the polder is a constant salt-water head boundary recalculated to corresponding fresh-water heads. The upper boundary is located in the polder, dunes, on the shore and the sea. In the polder a recharge of 280 mm/year is used and drainage to a certain drainage level (see further). In the dunes a constant vertical flow boundary is assumed with a recharge rate of 280 mm fresh-water per year. A constant head boundary is set on the shore and the sea. The values of these fresh-water heads were deduced from measurements made on the shore (Lebbe, 1981). They range from 4.5 mTAW (mTAW is the

Belgian ordnance datum referring to mean low water level, about 2.3 m below mean sea level) on the dune/shore transition to 2.36 mTAW on the shore/sea transition. The fresh-water head further seaward corresponds with the mean sea level of 2.36 mTAW. The seaward vertical boundary is an impermeable boundary.

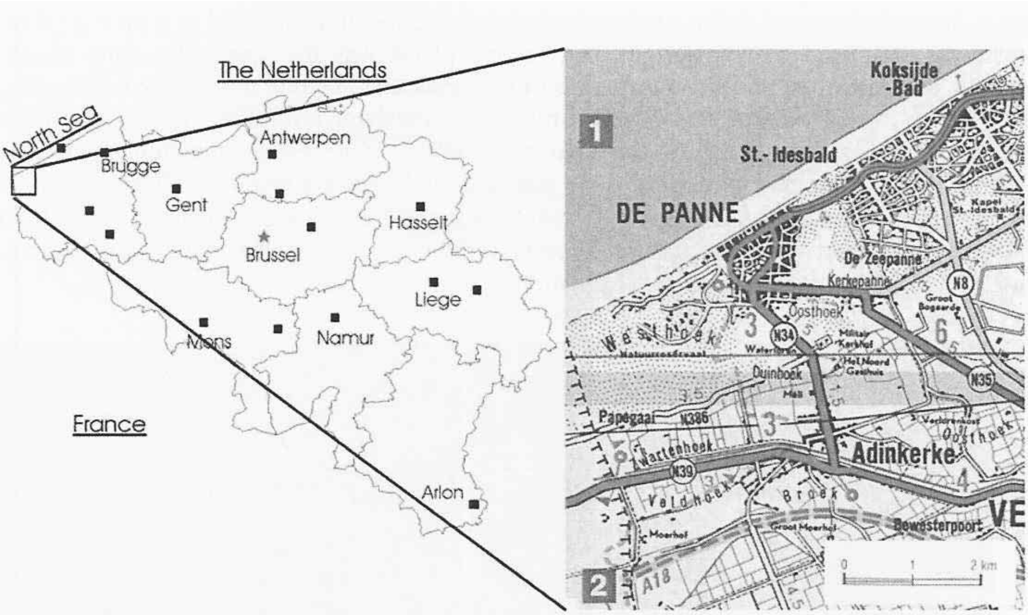

Figure 1. Localisation of the Westhoek nature reserve along the French-Belgian border.

Horizontal hydraulic conductivity of all layers in the dunes and under the shore and sea is 10.0 m/d and vertical hydraulic conductivity is 0.1 m/d. Horizontal hydraulic conductivity for layers in the polders is 6.5 m/d and its vertical hydraulic conductivity is 0.065 m/d. Longitudinal, transverse horizontal and transverse vertical dispersivity are respectively 0.2 m, 0.02 m and 0.002 m. Effective porosity is 0.38. At the beginning of the simulation, the groundwater reservoir is completely filled with salt-water. This salt-water has a TDS of 27000 mg/L and a density of 1019 kg/m^3. The fresh replacement water has a TDS of 500 mg/L and a density of 1000 kg/m^3, resulting in a buoyancy of 0.019. A time period of 700 years is simulated in one stress period divided in 5600 timesteps of 0.125 year. It is hereby considered that from 1300 AD onward the sea had no permanent access in the dunes. A general overview of the evolution of the Belgian coastal plain can be found in Vandenbohede et al. (2005). After each time step the groundwater flow is recalculated taking into account the salt-fresh-water distribution from the previous timestep. Sixteen particles are placed per cell and the fresh-water head change criterion for convergence is 0.1 mm.

Figure 2 shows the results of the simulation of the water quality evolution to the current situation. Due to the recharge of fresh-water, a fresh-water lens develops under the dunes. This fresh-water lens is almost completely formed in the first 200 years. A water divide is present in the dunes whereby part of the dune's recharge water flows towards the sea and part towards the polder. Fresh-water also recharges in the

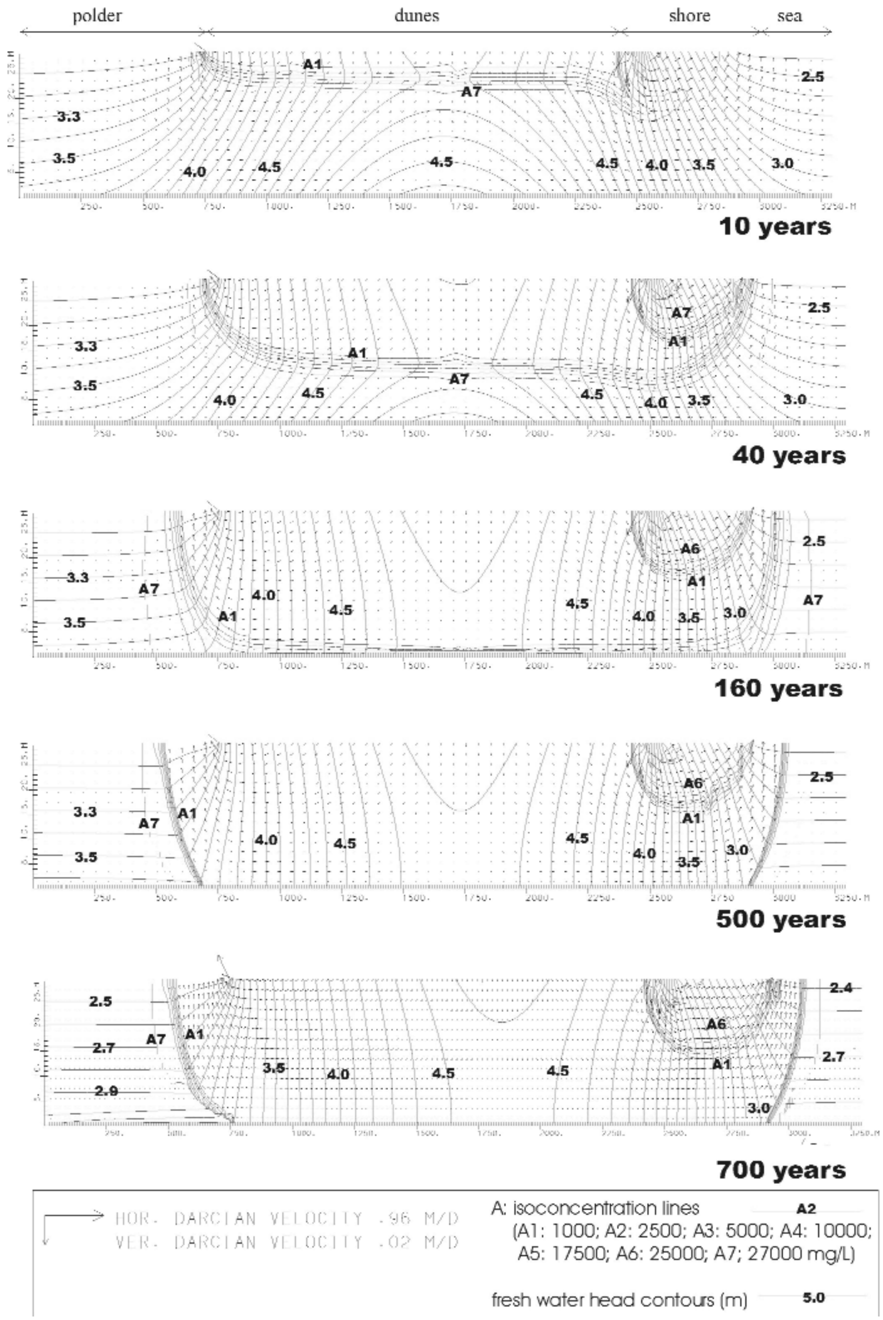

Figure 2. Evolution of water quality distribution in the polder, dunes and under the shore and sea. The simulation starts in 1300 AD and 500 year simulation time corresponds with 1800 AD, 700 years with 2000 AD or the current situation. Lines of constant fresh-water head are indicated together with isoconcentration lines and groundwater flow and its velocity using arrows.

polder. Almost all of this water is, however, drained immediately so that the groundwater reservoir remains filled with salt-water. Salt-water also recharges on the backshore during high tide. Due to the hydraulic gradient on the shore, this salt-water flows out on the foreshore and seabed, principally during low tide. Due to the hydraulic gradient between the dunes and the mean sea level, fresh-water flows from the dunes towards the sea. This, with the recharge of salt-water on the backshore, leads to the development of a salt-water lens above a fresh-water tongue under the shore. The simulations also show that this water quality distribution is present from about 200 years after the start of the simulation meaning that the nowadays-observed water quality distribution is in a dynamical equilibrium.

Drainage levels in the polders altered in recent historical times. Before 1800 AD (simulation time 500 years) this level is estimate to be 3.0 mTAW. Around 1800 AD the drainage system was ameliorated by the construction of a few larger channels and the drainage level became 2.4 mTAW (simulation time between 500 and 700 years). This has its effects on the general water quality distribution. The water dive in the dunes shifts 640 meter seawards. Therefore, less fresh dune water flows towards the sea diminishing the dimensions of the fresh-water tongue and enlarging the dimensions of the salt-water lens. So, the combination of a large shore with low relief, a relatively large tidal amplitude and a permeable groundwater reservoir makes that the observed inverse density distribution came into existence.

Sea level rise

The effects of a sea level rise of 0.4 m per century are investigated with the model. This rate of sea level rise is in line with the 'Business as Usual' scenario of the Intergovernmental Panel on Climate Change (Houghton et al., 1990). This scenario considers the effects when no active steps are taken to limit CO_2 and other greenhouse gas releases and other conditions (little is done to promote energy-saving measures, world energy supplies remain heavily dependent on fossil fuels, tropical deforestation continued…) remain the same. Three different scenarios were modelled.

In a first scenario it is assumed that a coastal defence is present, most likely a dike. Sea level will rise against this defence and the width of the shore will diminish in time. This is modelled by changing the constant head boundary of the shore and dune's first layer. Results are given in Figure 3. In time, the shore becomes less wide. Therefore the flow cycle in the salt-water lens, where salt-water infiltrates on the backshore and flows out on the foreshore, becomes smaller. Result is that the salt-water lens dimensions are diminishing. In the end, when no shore is present, a typical textbook water quality distribution and interface between fresh and salt-water evolves. Of note is also the seaward shift of the dune's water divide after 500 years because its boundary conditions are altered (the constant head on the backshore is now larger).

In a second scenario it is assumed that a coastal defence is present (for instance a dike) and that the shore is heightened with the same amount as the sea rises, for instance by sand suppletion. Thus, the width of the shore remains always the same. This is again modelled by altering the constant head boundary in the first layer on the shore and sea. Results are given in Figure 4. Because the mean sea level and the level of the shore rise in time, boundary conditions are importantly changed and the dune's water divide shifts seaward. Therefore, less fresh-water flows towards the sea and the dimensions of the fresh-water tongue

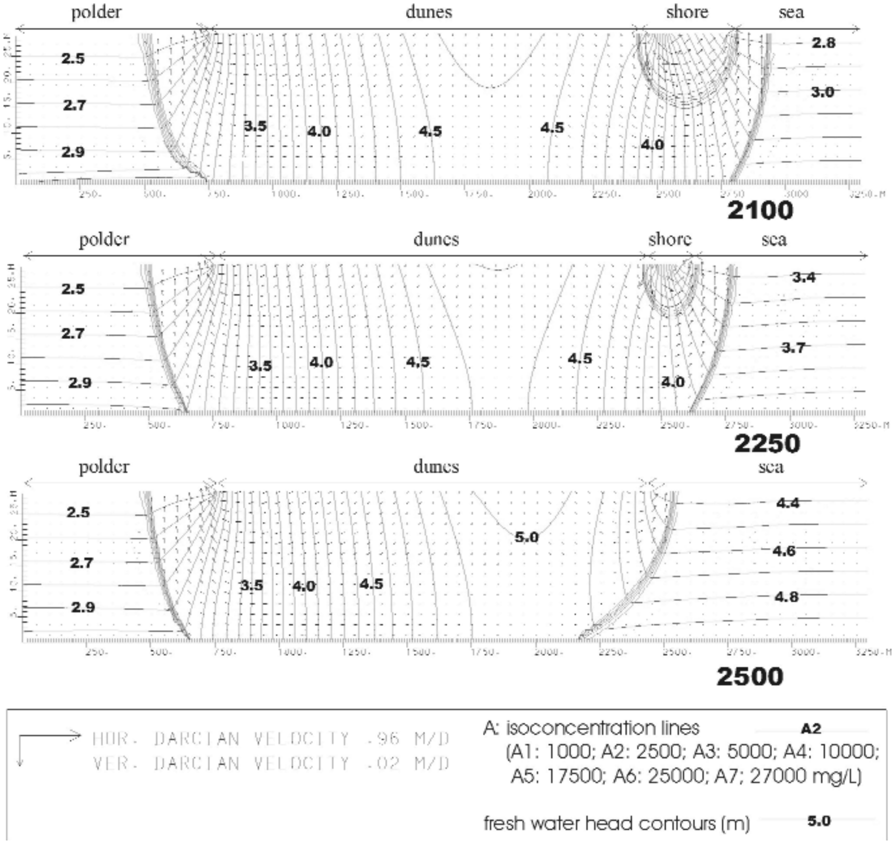

Figure 3. Water quality evolution, fresh-water head and flow under the shore, dunes and polder along the French-Belgian border with a sea level rise of 0.4 m and in the case a coastal defence is present. This is shown for 2100 AD, 2250 AD and 2500 AD. Lines of constant fresh-water head are indicated together with isoconcentration lines and groundwater flow and its velocity using arrows.

diminish. This also means that the dimensions of the salt-water lens enlarge.

In a third scenario it is assumed that the coastline is retreating: the width of the shore remains constant but it moves inland. The transition between polder and dunes does not change meaning that the width of the dune belt decreases. Additionally the shore is heightened in parallel with sea level rise. This is a simplification of the case where no coastal defence is present and the coastline has to retreat due to the sea level rise. This is again modelled by altering the boundary conditions of the first layer. The position of the dune's water divide is here again very important. This water divide moves relatively in the direction of the sea meaning that less water flows from the dunes towards the sea. As seen before, this leads to an enlargement of the salt-water lens. At a certain point in time the salt-water lens will reach the substratum of the ground water reservoir eliminating the flow of fresh-water from the dunes towards the sea. This is completed when the dune's water divide is positioned on the transition between the shore and the dunes

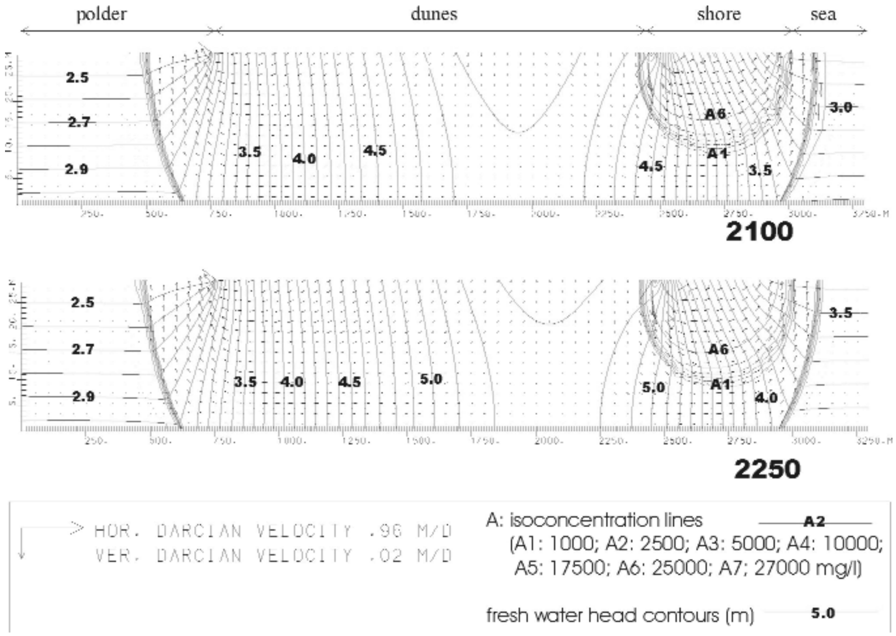

Figure 4. Water quality evolution, fresh-water head and flow under the shore, dunes and polder along the French-Belgian border with a sea level rise of 0.4 m and in the case a dike is present and the shore is heightened. This is shown for 2100 AD, and 2250 AD. Lines of constant fresh-water head are indicated together with isoconcentration lines and groundwater flow and its velocity using arrows.

and fresh-water is no longer allowed to flow to the sea. With a further sea level rise salt-water infiltrates on the backshore. There is flow of salt-water towards the sea and towards the polder. This diminishes the dune's fresh-water lens importantly.

Conclusions

Under the shore of the western Belgian coastal plain, an interesting inverse density distribution is found. A salt-water lens occurs above a fresh-water tongue. This is the combined effect of a permeable groundwater reservoir, a wide shore with low dip and an important tidal amplitude whereby salt-water infiltrates on the backshore during high tide and flows out on the foreshore, principally during low tide. A fresh-water lens is present in the dunes and salt-water is found in the bordering polder. With the simulations it was shown that sea level rise has an important impact on the groundwater flow and water quality distribution in the dunes and under the shore. The shore's salt-water lens can enlarge, diminish or even completely disappear. The same can be said about the outflow of the dune's fresh-water on the sea floor. In the dunes, the water divide can shift landwards or seawards and the dimensions of the fresh-water lens can alter.

Sea level rise is, speaking in terms of policy and management, considered as a long-term issue. The calculations can, however, also been seen as simulations of changes to the systems boundary condition.

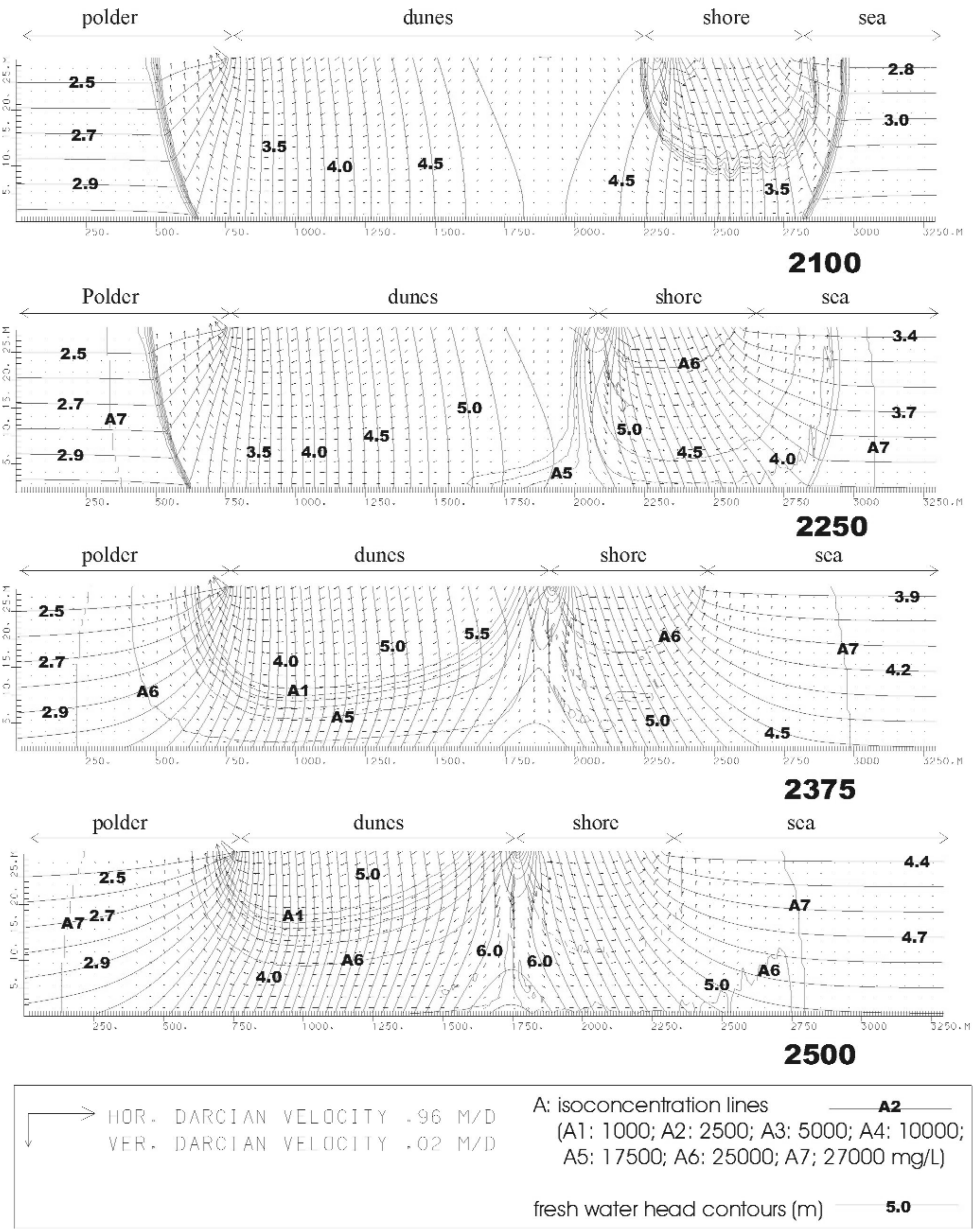

Figure 5. Water quality evolution, fresh-water head and flow under the shore, dunes and polder along the French-Belgian border with a sea level rise of 0.4 m and in the case the coastline is retreating. This is shown for 2100 AD, 2250 AD, 2375 AD and 2500 AD. Lines of constant fresh-water head are indicated together with isoconcentration lines and groundwater flow and its velocity using arrows.

Thereby, they show what can happen if for instance the shore's morphology is changed, drainage levels in the polder relative to the mean sea level are altered or the dune's water divide is displaced. These are short-term operations. Simulation show that important changes to the groundwater flow and water quality distribution can be the result of that. The area of and surrounding the Westhoek nature reserve has a high ecological value and rich diversity of fauna and flora partially originating from the underlying hydrogeology. Moreover the dunes are the only source for drinking water production in the area. Therefore generally human interference in coastal plains must be carefully studied and planned beforehand.

References

HOUGHTON, J.T.; JENKINS, G.J. and EPHRAUMS, J.J. (eds) (1990). *Climate Change. The IPCC Scientific Assessment*. Intergovernmental Panel on Climate Change (IPCC), Science Working Group (I). Cambridge University Press.

KONIKOW, L.F.; GOODE, D.J. and HORNBERGER, G.Z. (1996). A three-dimensional method-of- characteristics solute-transport model (MOC3D). *U.S.G.S. Water Resources Investigation Report* 69-4267.

LEBBE, L. (1978). *Hydrogeologie van het duingebied ten westen van De Panne.* Ph.D. Thesis, Geological Institute, Ghent University. (Hydrogeology of the dune area west of De Panne; in Dutch). (Unpublished).

LEBBE, L. (1981). The subterranean flow of fresh and salt-water underneath the western Belgian beach. 7th Salt-water Intrusion Meeting, Uppsala. *Sver. Geol. Unders. Rap. Meddel*. 27: 193-219.

LEBBE, L. (1983). Mathematical model of the evolution of the fresh-water lens under the dunes and beach with semi-diurnal tides. 8th Salt-water Intrusion Meeting, Bari. *Geologia Applicata e Idrogeologia*, XVIII(II): 211-226.

LEBBE, L. (1999). Parameter identification in fresh-salt-water flow based on borehole resistivities and freshwater head data. *Advances in Water Resources*, 22(8): 791-806.

OUDE ESSINK, G.P. (1998). MOC3D adapted to simulate 3D density-dependent groundwater flow. In: *Proc. of MODFLOW '98* Conference, October, 4-8, 1998, Golden, Colorado, USA, I: 291-303.

OUDE ESSINK, G.H.P. (2001). Salt-water Intrusion in a Three-Dimensional Groundwater System in The Netherlands: A Numerical Study. *Transport in Porous Media*, 43(1): 137-158.

VANDENBOHEDE, A.; LINSTER, T. and LEBBE, L. (2005). Modelling of density dependent groundwater flow in the southwestern Belgian coastal plain. *This volume*.