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ORIGINAL ARTICLE

Sustainable groundwater extraction in coastal areas: a Belgian example

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Abstract Water extractions in coastal areas have to deal with salt water intrusion and lowering of hydraulic heads in valuable ecosystems. Therefore, sustainable management of fresh water resources in these areas is crucial. This is illustrated here with two water extractions in the western Belgian coastal plain which extract groundwater from a phreatic dune aquifer. One water extraction faced problems with salt water intrusion, while lowering of hydraulic heads was an issue for both. To remedy the salt water intrusion, it was found that decreasing the extraction rate was the only solution. To offset this and to increase hydraulic heads around both extractions, it was decided to artificially recharge the aquifer of the second extraction with tertiary treated wastewater. By taking these interventions, the combined production capacity of the water extractions was increased with 56% whereas 27% less water was extracted from the dune aquifer itself. Extraction history and the effects of interventions are illustrated for both water extractions with water quality data and fresh water head observations. A more detailed insight in groundwater flow and fresh–salt water distribution in the aquifer is provided by simulating the evolution of the water extractions with a 3D density dependent groundwater flow model.

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Introduction

Groundwater is an important resource in coastal areas. Groundwater resources are used for drinking water production because of their many advantages: high-quality, small-quality variations (seasonally), low-storage costs (relatively small surface facilities) and easy exploitation. About 50% of the world's population lives in coastal areas, a figure which will probably rise to 75% during this century (Finkl 1994). This growing number of inhabitants will need ever more fresh water for agricultural, industrial and domestical use which will lead to stresses on the limited fresh water supplies.

Despite the (growing) need of fresh water in coastal areas, the exploitation of it has to cope with some difficulties (Oude Essink 2001). First of all, coastal areas have a natural distribution of fresh, brackish and salt water which is the result of an evolution during recent (quaternary) geological history. This distribution can be in a dynamical equilibrium, as for instance is the case in Belgium (Van Meir and Lebbe 1999; Vandenbohede 2003), or can still be evolving, as for instance is the case in The Netherlands (Oude Essink 1996). Secondly, high extraction rates lead to lowering of the hydraulic heads influencing general groundwater flow patterns and the water balance of an area. Additionally, other problems such as land subsidence may occur (Zhang et al. 2007; Aguilar-Perez et al. 2006). Also of importance is the fact that coastal areas are in many cases valuable ecosystems in which groundwater is an important factor. Distribution between fresh and salt water, groundwater quality in general and hydraulic heads are of importance in these areas. In worst circumstances, groundwater extractions must be closed when sea water intrusion occurs and salt water reaches exploitation wells. To oppose these threats, steps must be undertaken to protect the water extraction. Artificial recharge (Asano 1992; Van Breukelen et al. 1998; Bouwer 2002; Greskowiak et al. 2005; Massmann et al. 2006) is one option. Other options are the reduction of extraction rates, deep well injection (Roosma and Stakelbeek 1990), land reclamation (Guo and Jiao 2007), building of physical barriers or working with scavenger wells (Mushtaha et al. 2000) among other methods.

On a larger timescale, sea level rise and changes in recharge rates due to global change, influence the water cycle and threaten the valuable fresh water reserves (Vandenbohede et al. 2008). In many cases, aquifers are already stressed from a quality, quantity or ecological point of view due to overexploitation and pollution and therefore both remedies and/or alternatives must be explored. In this paper, two examples of water extractions in the Belgian western coastal plain are discussed. These are both present in a phreatic dune aquifer. A short description of the extraction's history is given and it is discussed how they cope with current and future challenges of groundwater exploitation in coastal areas. First, a description of the hydrogeology of the Belgian western coastal plain and an introduction to its history of water exploitation are given. Thereafter, it is discussed how a sustainable extraction was realised. Some results of the restoration of the aquifer which are already visible are discussed. Groundwater flow, distribution between fresh and salt water and the impact of remediation actions are evaluated using the 3D density dependent finite difference groundwater flow model MOCDENS3D (Oude Essink 1998).

Belgian western coastal plain

Geology of the area

The study area is located in the western part of the Belgian coastal plain along the French–Belgian border (Fig. 1). The phreatic aquifer consists of quaternary sediments bounded below by a tertiary clay layer. The quaternary sediments in the coastal plain have been deposited due to interaction of sea level rise, palaeotopography, sediment supply and creation of accommodation space (Baeteman 1985; Baeteman et al. 1999). The two water extractions which are discussed here are situated in the dune area of the coastal plane along the French–Belgian border (Fig. 1). These dunes are part of the north-west European coastal dunes, which form a long, very narrow dune strip from Calais (France) to the north of Denmark. Seawards of the dunes is a relatively wide shore (about 500 m during low tide) with a low angle dip. A low-lying area exists landwards from the dunes. This so-called polder has a mean surface level below high tide. A dense drainage system is present in the polder to evacuate the excess of water to the sea.

Mean thickness of the quaternary phreatic aquifer under the shore, dunes and polder is 30 m. The substratum of this aquifer is formed by the clay of the Kortrijk Formation, Ieper Group. This clay is of Eocene age and is considered an impermeable boundary in this study. The lower part of the phreatic dune aquifer consists of medium to coarse medium sands of Eemian age. Fine medium sands form the larger part of the aquifer. Lenses of silty or clayey fine sand can occur. The top of the aquifer consists of medium sands. In some places, a relatively shallow (at about 0 mTAW, 0 mTAW is the Belgian reference level equal to mean low sea water level) sandy clay-to-clay layer exists.

Figure 2 shows a cross-section through the aquifer. The orientation of this cross-section is indicated in Fig. 1. The distribution between fresh, brackish and salt water as derived from log normal resistivity logs in bore holes (Lebbe and Pede 1986) is shown. In the dunes, a fresh water lens is present over the whole depth of the aquifer. The shallow water in the polder is also fresh but this becomes brackish deeper in the aquifer. Salt water is present above the tertiary base of the aquifer. Under the shore and sea, a peculiar fresh/salt water distribution can be found (Lebbe 1981,Vandenbohede and Lebbe 2007). Salt water is present above fresh water. The water quality distribution is the result of recent quaternary evolution (Vandenbohede and Lebbe 2006).

Before the land reclamation, which was more or less completed in the eleventh century AD, the coastal area was a mud flat and salt marsh environment. The aquifer was mainly filled with salt water. From the seventh century AD the current dune belt started to form and this hampered the sea to enter the hinterland. The dominantly salt pore water in the aquifer became gradually replaced by fresh recharge water. In the dunes this gave rise to the fresh water lens which is present now. In the polders, whose mean surface level is below the high water mark, a dens drainage system is needed to evacuate the surplus of water towards the sea. Therefore, only a limited amount of fresh water can infiltrate in the aquifer. Only the upper part of the aquifer is freshened and older salt water is still found in the deeper part. In the dunes, fresh water can recharge the deeper part of the aquifer and this replaced the older salt water. Of importance is the dune's water divide. Water recharging south of the divide flows towards the polder and discharges along the dune–polder boundary. Water recharging north of the water divide flows towards the sea. Discharge area for this fresh water is found along the low water line. Above

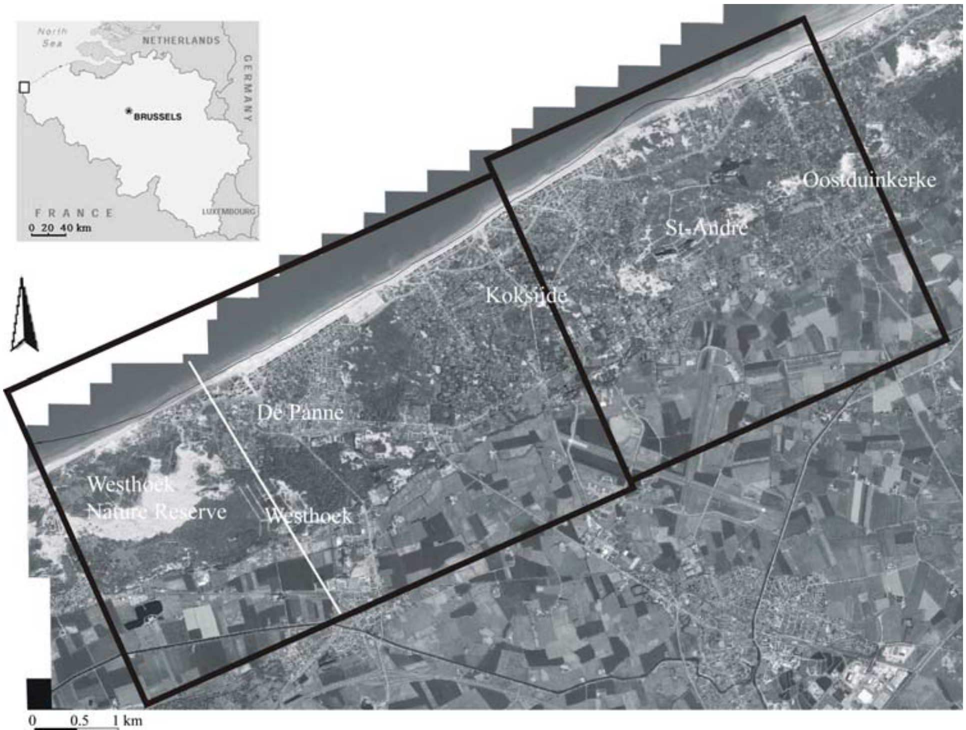


Fig. 1 Aerial photo gives an overview of the study area. The two *black boxes* show the model domain of the Westhoek extraction (*left*) and the St-André extraction model (*right*). The white line through the Westhoek extraction gives the location of the cross-section shown in Fig. 2

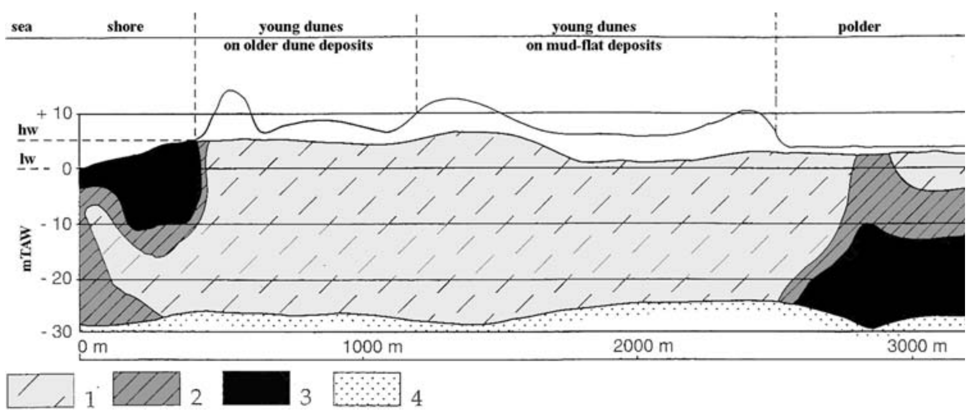


Fig. 2 Distribution of fresh (*1*), brackish (*2*) and saline (*3*) water in a cross-section perpendicular to the coast line. The location of this cross-section is shown in Fig. 1a clay layer (*4*) forms the lower boundary of the aquifer

this fresh water tongue, a salt water lens is present. This originates from the recharge of salt water on the back shore, mainly during high tide. This salt water flows towards the fore shore where it discharges, mainly during low tide. The fresh–salt water distribution reached a dynamical equilibrium after 300–400 years.

Westhoek water extraction

Two water extractions are present in the dune area. The first, called 'Westhoek extraction', is located near the French–Belgian border, west of De Panne. The second, called 'St-André extraction' is located between Koksijde and Oostduinkerke. The Westhoek extraction is active since 1967. Figure 3 gives the evolution of the discharge rate of the Westhoek extraction in function of time. During the first years, the discharge rate remained below the 1 million m^3/year whereas this increased to about 1.5 million at the end of the 1970s and to just above 2 million m^3/year during the mid 1980s. Thereafter, extraction rates declined gradually to about 1 million m^3/year in 2000. Between 1967 and 1980 well battery 1 was active with about 100 wells (Fig. 4). The centre of this well battery is located more towards the polder than towards the sea. From 1980 a second well battery, located more seawards from the first, became active with about 35 wells. Until 1994, the first well battery is responsible for approximately two-thirds of the extracted water. After 1994, an equal amount of water is extracted from both well batteries. Extraction wells have screens between 6 and 10 m or between 12 and 16 m below surface.

Figure 3 also gives the evolution of the chloride concentration of the combined extraction water of well battery

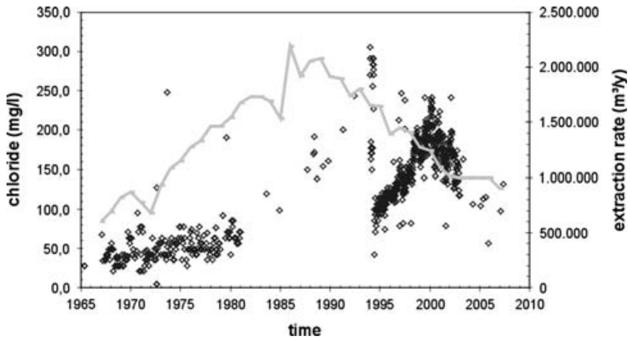


Fig. 3 Evolution of the extraction rate (–) and the chloride concentration (*opendiamond*) of the extracted water (well batteries 1 and 2) in function of time

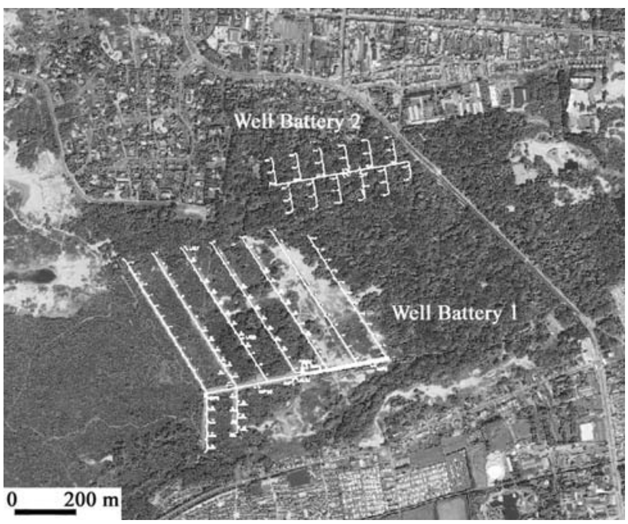


Fig. 4 Location of the *well batteries 1* and *2* of the Westhoek water extraction

1 and 2 in function of time. Background chloride concentration of the dune aquifer is 40 mg/l. Between the start of the water extraction and 1980 there was a gradual increase of the chloride concentration in the extraction water. In 1980 the chloride concentration had almost doubled the natural chloride concentration and from then on the chloride concentration increased importantly due to salt water intrusion. From the late 1980s onwards, extraction rates were lowered gradually. Since 1994 the extraction wells with the highest chloride concentration were closed. The results of these interventions can be seen during 1994 where the chloride concentration of the total extraction water decreased to approximately 80 mg/l this was; however, a temporally solution since concentrations increased again after a few years. For instance 39% of all pumping wells of well battery 1 had an enlarged chloride concentration in 2000. This shows that long-term management of water extraction in coastal aquifer is essential. Some interventions can have positive short-term effects but provide no long-term solutions. Long-term solutions necessitate a thorough understanding of groundwater flow and distribution of fresh and salt water in the aquifer. After studying and considering different options, it was decided that in 2005 1 million m^3/year would be extracted, equally distributed between each well battery. From 2006 onwards, the extraction rate in well battery 1 would be decreased by 0.1 million m^3/year. This means that well battery 1, located closest to the polders, would be closed in 2010. The decision was mainly based on the drinking water requirement of the area and the capacity of the second water extraction (St-André, see further) among other things. The sustainability for future water extraction of this intervention was checked using groundwater flow modelling (see further). The results of these decisions can already be seen in the chloride concentration of the extracted water (Fig. 3). Chloride concentrations decreased from 2000 onwards until the present day. In 2007, mean chloride concentration is about 100 mg/l. Modelling (see further) also showed that continued decrease of the extraction rate to 0.5 million m^3/year in 2010 guarantees that salinisation will no longer threaten the water extraction. The natural flow of fresh water from the dunes towards the polder is restored in a large part of the dunes. This flow pushes back the salt water intrusion leading to a sustainable water extraction.

Besides salt water intrusion, water levels in the phreatic dune aquifer are also of importance. Of importance, here is that the Westhoek extraction is located east of a nature reserve, the Westhoek Nature Reserve (Fig. 1). This nature reserve is located along the French–Belgian border and contains valuable flora and fauna which are water table dependent. Lowering hydraulic heads are thus, besides salt water intrusion, an important secondary issue connected with the Westhoek water extraction. Due to the decreasing extraction rates, the water table increased with 3 m in the vicinity of the water extraction from 1994 until 2007.

St-André water extraction

Since 1947 the St-André extraction, located between Koksijde and Oostduinkerke (Fig. 1) is active. The extraction rate rose steadily from about 0.5 million m^3/year during the 1950s to 1.75 million m^3/year during the 1960s. From then on extraction rates fluctuated around 2 million m^3/year up to the second millennium. Initially the water extraction started with one well battery with 109 wells. In 1968 a second well battery was put in use with about 54 wells. Location of the well batteries is indicated in Fig. 5. Extraction rates of both well batteries were more or less the same. Extraction wells had screens between 6 and 10 m below surface; in the 1980s new wells were drilled with screens between 12 and 16 m below surface. In 2002,

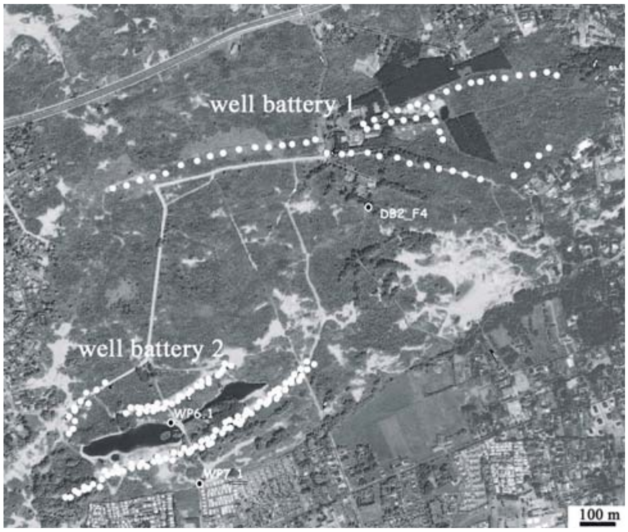


Fig. 5 Location of the *well batteries 1* and *2* in the St-André water extraction. The position of the wells is indicated with a white dot. These represent the current positions. The artificial recharge ponds can be seen between the wells of the second well battery

70 wells were active with the first well battery and 54 wells with the second well battery.

Unlike the Westhoek extraction, increase of chloride concentrations in the extracted water has never been an issue. Main issue of the St-André extraction is the lowering of the hydraulic heads. Figure 6 shows the evolution of the fresh water heads in three shallow observation wells. The location of the observation wells is indicated in Fig. 5. WP6.2 is situated between the pumping wells of well battery 2, WP7.2 is situated south of well battery 2, whereas DB2_F4 is located between well batteries 1 and 2. Fresh water head observations are present in WP6.2 and 7.2 from 1993 and from 2001 for DB2_F4. Figure 6 also shows the yearly precipitation. Groundwater levels were at their lowest between 1996 and 1997. This period corresponds with a relatively low yearly precipitation of 690 mm. Mean precipitation is 780 mm/year. Fresh water heads are 2 mTAW. Topographical level of the dunes varies between 6 and 7 mTAW for the dune slack and 9–30 m for the dune ridges. This means that the water table is between 4 and 28 m below surface level. From 1997, precipitation increased as do the groundwater levels but this remains about 1.5–2.5 m below surface level in the dune slacks.

To remedy this situation and to compensate for the decrease in extraction rates of the Westhoek extraction, artificial recharge of water in the dunes was started in July 2002 (Van Houtte and Verbauwhede 2005). This was preceded by a thorough study to determine the best possible techniques to be applied in the context of the St-André extraction. The recharge water is produced out of effluent from a nearby wastewater treatment plant using ultrafiltration and reverse osmosis. Artificial recharge occurs via two interconnected ponds with a combined surface area of 18,200 m^2. Two rows of wells of well battery 2, situated north and south of the ponds (Fig. 5) enable reextraction of the artificially recharged water. With this system, it is permitted to recharge 2.5 m^3/year which is pumped up by well battery 2. Well battery 2 can furthermore extract an extra 1 million m^3/year (which is then native dune water). Permitted extraction rate for well battery 1 is 0.7 million m^3/year. This means that more water can be extracted than in the past but less water is extracted directly from the phreatic aquifer. The groundwater reserves of the aquifer are thus less exploited. The effect of the recharge ponds on the fresh water heads can be seen on Fig. 6. Of notice is that there was an important low precipitation from 2002 onwards. Mean precipitation from 2003 to 2006 is approximately 600 mm/year which is 180 mm/year less than the normal mean precipitation of 780 mm/year; whereas the fresh water heads in WP6.2 were between 3.5 and 4 mTAW during the wet years 2001 and 2002, these have risen to 5 mTAW after the start of the artificial recharge project. WP7.2, situated south of well battery 2 and close to the dune polder transition zone, has a mean fresh water head of 3.5 mTAW after the start of the artificial recharge project. This is more or less the same as during the wet years 2001 and 2002. Notice that fresh water heads in WP7.2 during 2003–2006 are larger than during 1995–1998, although precipitation is remarkably smaller during the former period. Fresh water heads have also increased in DB2_F4 which is located between both well batteries. The effect is not as large as for WP6.2 because DB2_F4 is situated farther from well battery 2 and relatively close to well battery 1. But the increase in fresh water heads in DB2_F4 indicates that the artificial recharge project has a positive effect on a large part of the aquifer and not only in the vicinity of the ponds. In the 5 years after the start of the infiltration project, fauna and flora has also remarkably changed. Whereas the vicinity of the recharge ponds was more or less a bare dune slack, this is now covered with vegetation.

MOCDENS3D

Fresh water heads and water quality data as some are discussed in the previous section give only a limited view on groundwater flow dynamics and fresh–salt water distribution. A more general insight can be obtained to synthesise all available information (head date, water analysis, borehole measurements, borehole descriptions, etc.) in a groundwater flow model. Therefore, two models were made, each for one of the water extractions, to illustrate general groundwater flow and water quality

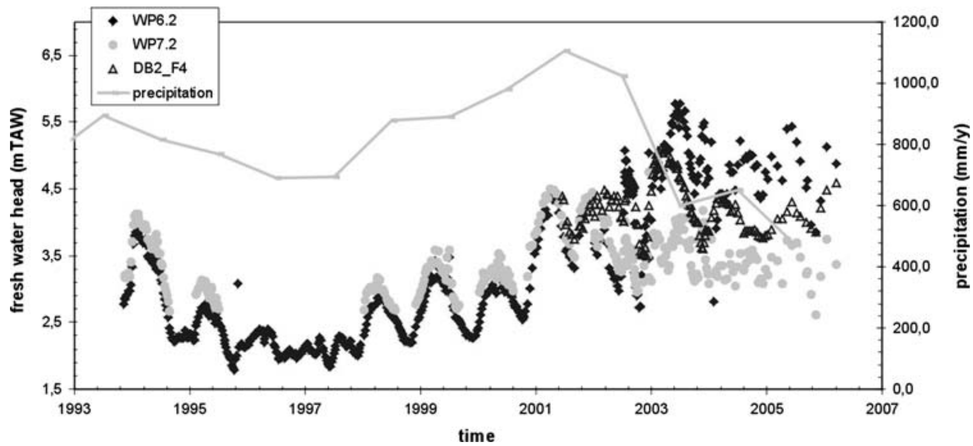


Fig. 6 Evolution of the fresh water heads in function of time in wells WP6.2, WP7.2 and DB5_F4. The *full line* gives the precipitation in mm/year for the same period. The location of the wells is indicated on Fig. 5

distribution, to evaluate the influence of the extractions and to simulate the effects of changing the extraction rate for the Westhoek extraction and the effects of the artificial recharge project for the St-André extraction. For the simulation of 3D density dependent groundwater flow and solute transport, MOCDENS3D (Oude Essink 1998) is used. MOCDENS3D is based on the 3D solute transport code MOC3D (Konikow et al. 1996), but adapted for density differences. Visual MOCDENS3D (Vandenbohede 2007) is used for visualisation of model results. Three-dimensional flow in MOCDENS3D is described by the following equation:

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} - W = S_s \frac{\partial hf}{\partial t} \tag{1}$$

where x, y and z are coordinate directions; q_x, q_y and q_z are Darcian flow velocities (m/d) in x, y and z direction; W (day^{-1}) is a flux term accounting for pumping, recharge, or other sources and sinks; h_f is the fresh water head (m);S_s is the specific elastic storage (m^{-1}) and t is time (day). The Darcy velocity components are given by

$$\begin{aligned} qx &= -K_{fx} \frac{\mu_f}{\mu_i} \frac{\partial h_f}{\partial x} \\ qy &= -K_{fy} \frac{\mu_f}{\mu_i} \frac{\partial h_f}{\partial y} \\ qz &= -K_{fz} \frac{\mu_f}{\mu_i} \left(\frac{\partial h_f}{\partial_z} + \frac{\rho_i - \rho_f}{\rho_f} \right) \end{aligned} \tag{2}$$

where μ_f and μ_i are the dynamic viscosity (kg/md) of fresh water and water at the ith point respectively; ρ_f and ρ_i are the densities (kg/m^3) respectively of fresh water and water at the same point; K_{fx} and K_{fy} are fresh water horizontal hydraulic conductivities (m/day) and K_{fz} is the fresh water vertical hydraulic conductivity (m/day).

Fresh water heads are used to cope with the different densities of waters. Groundwater flow can be simulated in an aquifer where density differences of groundwater occur and variations in hydraulic parameters within one layer and/or between different layers can be included. The groundwater flow equation is solved by the MODFLOW code taking into account density differences using a buoyancy term $[(\rho_i - \rho_f)/\rho_f]$ in the basic flow equations. This buoyancy is related to concentrations according through:

$$\frac{\rho_i - \rho_f}{\rho_f} = \frac{\rho_s - \rho_f}{\rho_f} \frac{C_{i,j,k}}{C_s} \tag{3}$$

where $C_{i,j,k}$ is the concentration (mg/l) of the ith row, jth column and kth layer of the model, C_s is the concentration (mg/l) of salt water and ρ_s is the density of salt water (kg/m^3). The advection–dispersion equation is solved by the methods of characteristics (Konikow and Bredehoeft 1978). Advection is simulated with particle tracking and dispersion with the finite-difference method.

Modelling results

Westhoek water extraction

Figure 1 shows the area which is included in the MOCDENS3D model of the Westhoek water extraction. It measures 6,450 by 3,900 m and includes the quaternary phreatic aquifer. The lower boundary of the model is the clay of the formation of Kortrijk which is considered impermeable in this study. The aquifer is subdivided in 12 layers, 86 columns and 52 rows (height 2.5 m, width and length 75 m) resulting in 53,664 finite difference cells. The quaternary aquifer is characterised by a relatively heterogeneous lithology and it is very important that the extensions of permeable and semi-permeable layers are included in the model as accurately as possible. This dictates groundwater flow and has an important influence on the distribution of fresh and salt water. The heterogeneity of the groundwater reservoir was therefore introduced in the model by means of three hydrogeological type section maps of respectively the lower, middle and upper part of the groundwater reservoir. In these maps typical successions of permeable and semi-permeable layers which occur over a wide area are distinguished. Hydrogeological type section maps were made based on numerous borehole descriptions in the study area. Five type sections are recognised in the upper part, three in the middle part and four in the lower part and these are mapped throughout the study area. The hydraulic parameters of the different type sections are based on interpretations of a number of pumping tests performed in the dunes and in the polders. By applying this approach with type sections all available hydrogeological and lithological knowledge is integrated in the best possible way.

A similar approach was followed for delineating recharge zones. Mean recharge is 280 mm in the dune area; however, recharge is smaller in the polder area or in a village centre. Eight different recharge zones (shore, dunes, dunes with forest, centre of villages, districts in the dunes, field in the polders, meadow in the polders and districts in the polders) were differentiated and mapped. Total dissolved solid of the recharge water is 500 mg/l. The drainage system was also mapped and is included using the drainage package of MODFLOW. The elevation of the drains is known from measurements and target levels, the hydraulic conductances of the interface between the channel and the aquifer are estimated. The history of the water extraction's discharge rate is included along with the drainage system in the polder and recharge rates in function of land use. The water extraction started in 1967. For the simulation stress periods of 3 years are used. The extraction rates are averaged over these periods.

The east and the west boundaries of the model, located perpendicular to the coast, are impermeable. The northern boundary is situated in the sea and is a constant fresh water head boundary. This is the mean sea level (2.38 mTAW) in the first layer. A constant salt water head of 2.38 mTAW is present in the first row of every layer. This value is recalculated in the corresponding fresh water heads deeper in the groundwater reservoir. Cells situated on the shore are also given a constant head being the mean groundwater level during a mean tidal cycle. The southern boundary is impermeable except in the western part due to the presence of a canal. The first two layers have therefore a fresh water head of 2.38 mTAW.

The longitudinal dispersivity is 0.30 m, the horizontal and the vertical transverse dispersivities are 0.15 m and 0.075 mm, respectively. Effective porosity is 0.38. These values were derived from the calibration of earlier models (Lebbe 1981, 1983 and 1999). The buoyancy is 0.022. Eight particles are placed per cell and the head change criterion for convergence is 1 mm. Initially, the aquifer was considered filled with salt water and the replacement of this salt water with fresh water is simulated. The resulting fresh–salt water distribution is then used to further simulate the influence of the aquifer. Observations of hydraulic heads, water quality analyses and geophysical measurements were used to calibrate the model.

Figure 7 shows four horizontal cross-sections through the aquifer along layer eight, thus in the lower part of the aquifer. Figure 8 shows vertical cross-sections which are located perpendicular to the coastline going through the centre of the water extraction. These cross-sections show the fresh water heads whereas the grey scale represents the total dissolved solids (mg/l) of the pore water. The first cross-section is of the situation right before the start of the water extraction in 1967. A water divide is present in the middle of the dunes. Water recharging north of this divide flows towards the sea, water recharging south of this divide flows towards the polder. Notice in the vertical cross-section (Fig. 8) that there is a local water divide present in the upper part of the aquifer which is positioned more towards the polder than the water divide which is present in the deeper aquifer. This is due to the presence of a shallow clay layer. Because of the larger hydraulic resistance of this clay layer, infiltration water cannot move directly vertical but has to circumvent it. Fresh water is present in the dunes whereas brackish to salt water is present under the sea and polder. The situation in 1992 shows the fresh water head configuration and salt–fresh water distribution at the time of maximum discharge rates (about 2 million m^3/year). The influence of the water extraction can be derived from the pattern of the fresh water heads. In the centre of the extraction there is a decrease of the fresh water head of more than 3.5 m with regard to the situation before the start of the pumping. Moreover, groundwater flow in a large part of the dune aquifer is influenced by the extraction. Instead of the general flow pattern with groundwater flow towards the sea or the polder, there is an important flow towards the extraction. The water divide has shifted seaward which means that less fresh water flows towards the sea. North of the water extraction, the water divide is almost located at the high water line. A change has also occurred in the distribution of fresh and salt water. There is a flow of salt water from the polder towards the water extraction. In 1992 there is already an important intrusion of salt water from the polder in the dunes. Interestingly, the salt water intrusion does not come from the sea but from the hinterland. However, the fresh–salt water distribution is also altered under the shore. Because less fresh water flows from the dunes towards the shore, the salt water lens under the shore becomes deeper and the extension of the fresh water tongue diminishes. But no salt water is flowing from the sea towards the extraction.

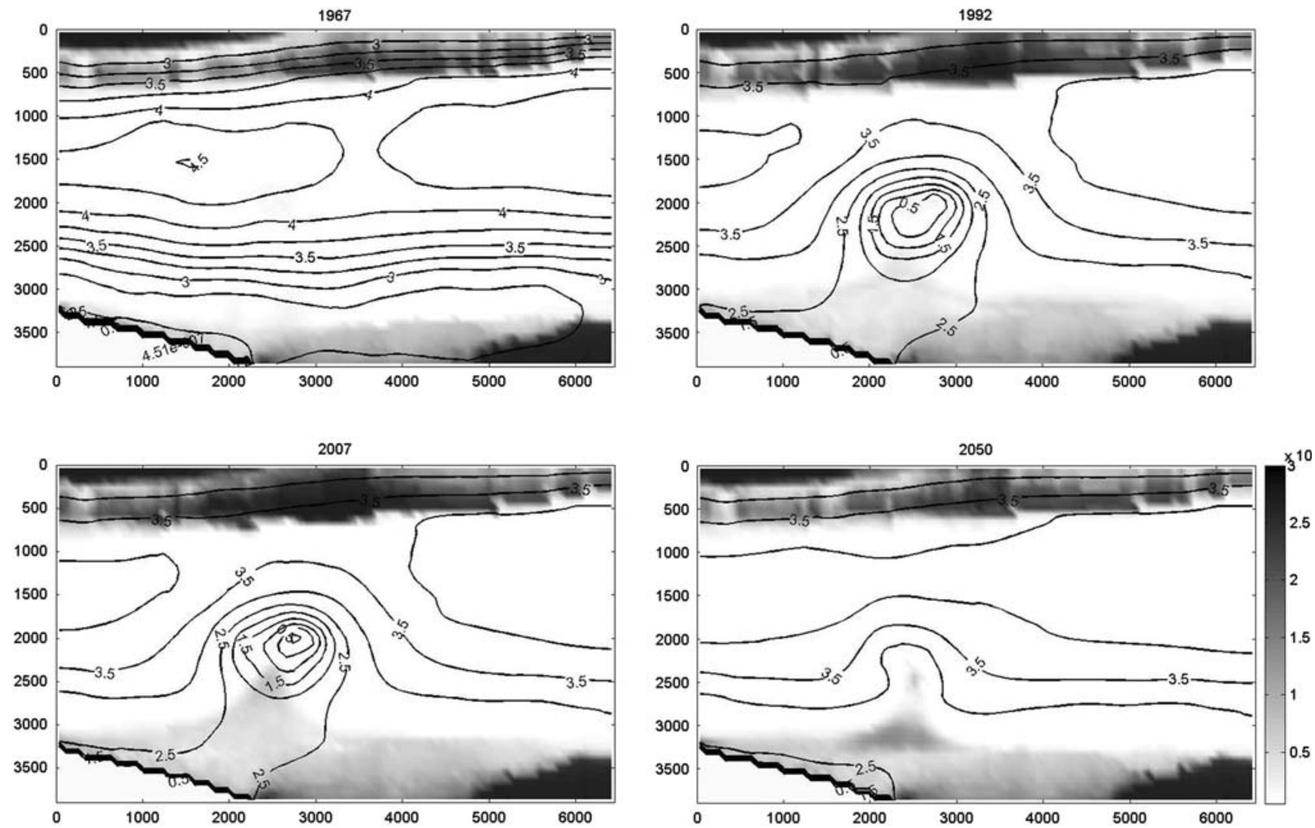


Fig. 7 Horizontal cross-sections along layer eight (20 m below surface level) of the model of the Westhoek water extraction. Lines of equal fresh water heads (mTAW) are shown; whereas, the *grey scale* represents the total dissolved solids (mg/l) of the pore water

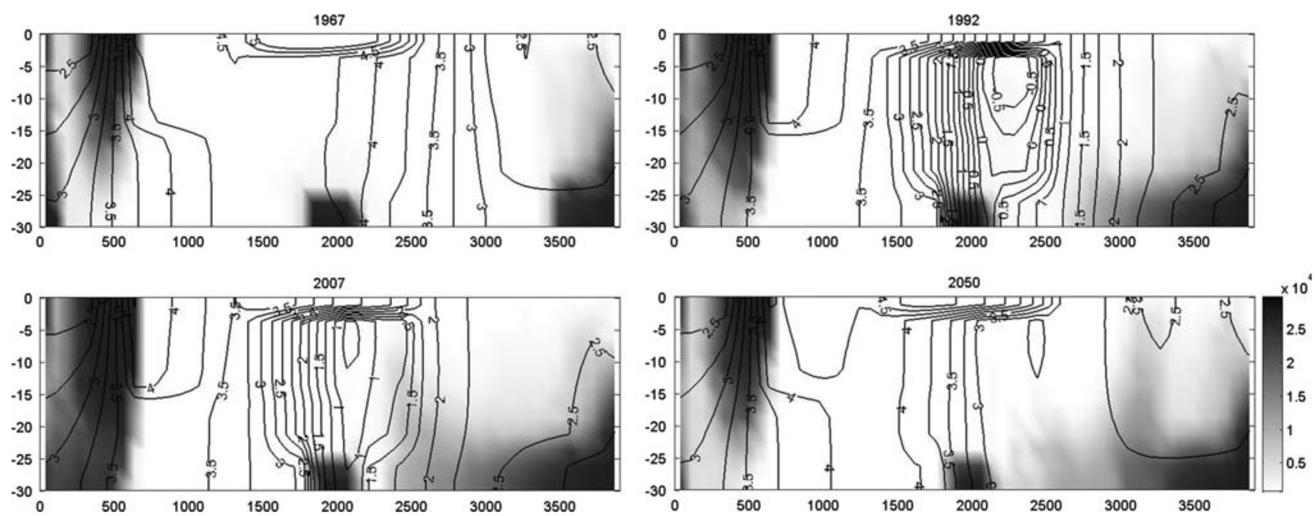


Fig. 8 Vertical cross-sections along column 33 (2,475 m from the west) of the model of the Westhoek extraction. Lines of equal fresh water heads (mTAW) are shown; whereas, the *grey scale* represents the total dissolved solids (mg/l) of the pore water

The salt water intrusion from the polders explains the increasing chloride concentration in the extracted water in function of time (Fig. 3). Initially this was remediated by closing of some extraction wells in which chloride concentrations became too large. Also, extraction rates were reduced from the late 1980s. Although this resulted in a temporally improvement, observations and model results show that this would not provide a long-term solution. Due to the high extraction rates in the 1990s salt water was pulled towards the extraction. Although the extraction rates were halved in 2005 with respect to the late 1980s, salt water remained in the wells' capture zone. This explains why closing wells resulted only in a temporally improvement. Chloride concentration in the total volume of extracted water will decrease only until salt water reaches another well. The only solution is to further lower the extraction rates so that the natural flow of fresh water from the dunes towards the polder is restored. Only in this way the salt water intrusion can be pushed back. Different scenarios to accomplish this were considered. Taking into account a relatively gradual but although decisively decrease of the extraction rates, well battery 1 will be closed in the near future. It was decided to extract 0.5 million m^3/year from each of both well batteries in 2005. From 2006 onwards, the extraction rate in well battery 1 will be decreased by 0.1 million m^3/year. This means that this well battery, located closest to the polders, will be closed in 2010. The consequence is (Figs. 7, 8) that the flow from the dunes towards the polders is partly restored. Reduction of extraction rates thus means that the salt water intrusion is pushed back towards the polder which provides a sustainable situation for future water extraction.

Beside the issue of salt water intrusion, drawdowns due to the water extraction in the dunes are also of importance. Figure 9 shows the drawdowns in 1992, when extraction rate was at its maximum, and with the extraction rate after 2010 when only well battery 2 will remain active. These drawdowns are calculated with reference to the fresh water heads before the start of the extraction in 1967. Drawdowns are calculated in layer 1, thus corresponding with the water table. In 1992 drawdown in the centre of the extraction is about 3.4 m. The zone of influence of the pumping is relatively large and also lowers the water table in the Westhoek nature reserve. Decreasing the extraction rates has also resulted in an important decline of the drawdowns. Maximum drawdowns are now in the order of 0.8 m and the zone of influence of the pumping has become much smaller.

St-André water extraction

Figure 1 shows the area which is included in the MOCDENS3D model of the St-André water extraction. It measures 4,200 by 4,500 m and includes the quaternary phreatic aquifer. The lower model of the boundary is also the clay of the formation of Kortrijk which is considered impermeable in this study. The groundwater reservoir is subdivided in 12 layers, 60 columns and 56 rows (height 2.5 m, width and length 75 m) resulting in 40,320 finite difference cells. The same approach as for the Westhoek extraction model was followed to schematise the aquifer. The heterogeneity of the aquifer was introduced in the model by means of three hydrogeological type section maps of respectively, the lower, middle and upper part of the groundwater reservoir. Three type sections are recognised in the upper part, three in the middle part and three in the lower part and these are mapped throughout the study area. The hydraulic parameters of the different type sections are based on interpretations of a number of pumping tests performed in the dunes and in the polders.

The history of the water extraction's discharge rate is included along with the drainage system in the polder and recharge rates in function of land use. The water extraction started in 1947. For the simulation stress periods of 3 years are used. The extraction rates are averaged over these periods. The east and the west boundaries of the model, located perpendicular to the sea, are impermeable. The northern boundary is situated in the sea and is a constant fresh water head boundary. This is the mean sea level (2.38 mTAW) in the first layer. A constant salt water head of 2.38 mTAW is present in the first row of every layer. This value is recalculated in corresponding fresh water heads deeper in the groundwater reservoir. Cells situated on the shore are also given a constant head being the mean groundwater level during a mean tidal cycle. The southern boundary is impermeable. The longitudinal, the horizontal

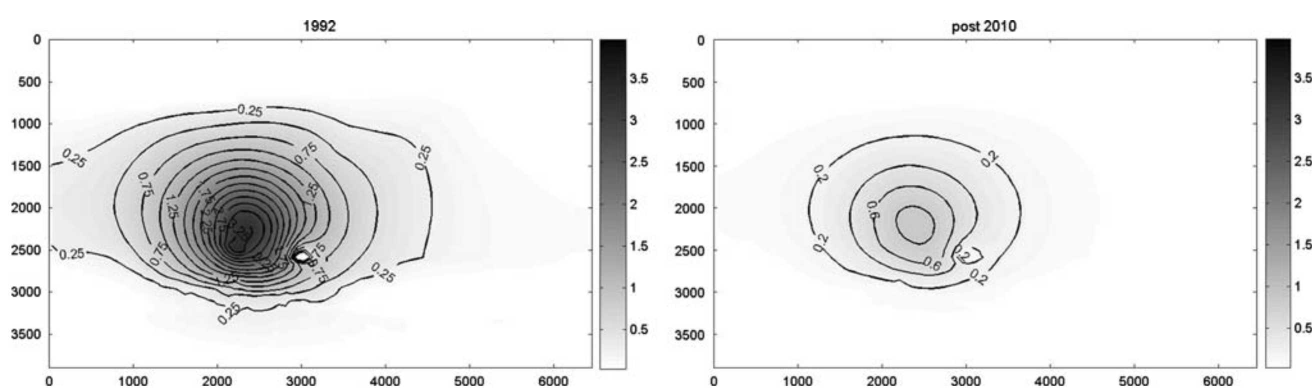


Fig. 9 Drawdown in the first layer (water table) for the situations in 1992 and after 2010. Reference situation are the fresh water heads before the start of the water extraction

and the vertical transverse dispersivities are 0.30 m, 0.15 m and 0.075 m, respectively. Effective porosity is 0.38. These values were derived from the calibration of earlier models (Lebbe 1981, 1983 and 1999). The buoyancy is 0.022. Eight particles are placed per cell and the head change criterion for convergence is 1 mm. Also the replacement of the older salt by fresh infiltration water was first simulated. Observations of hydraulic heads, water quality analyses and geophysical measurements were used to calibrate the model.

Figure 10 shows horizontal cross-sections through the aquifer for the situation before the start of the water extraction (1947), 2000 and 2007. These show the fresh water heads for the first layer (water table) and salt-fresh water distribution in layer five (level of the extraction) for 2000. Figure 11 shows north–south oriented cross-section situated through the water extraction. Fresh water heads are indicated whereas the grey scale represents the total dissolved solids content (mg/l). The situation before the start of the water extraction (1947) is more or less equal to that described for the Westhoek extraction. In the dunes, a water divide is present. Fresh water recharging north of this divide flows towards the sea, water recharging south of it flows

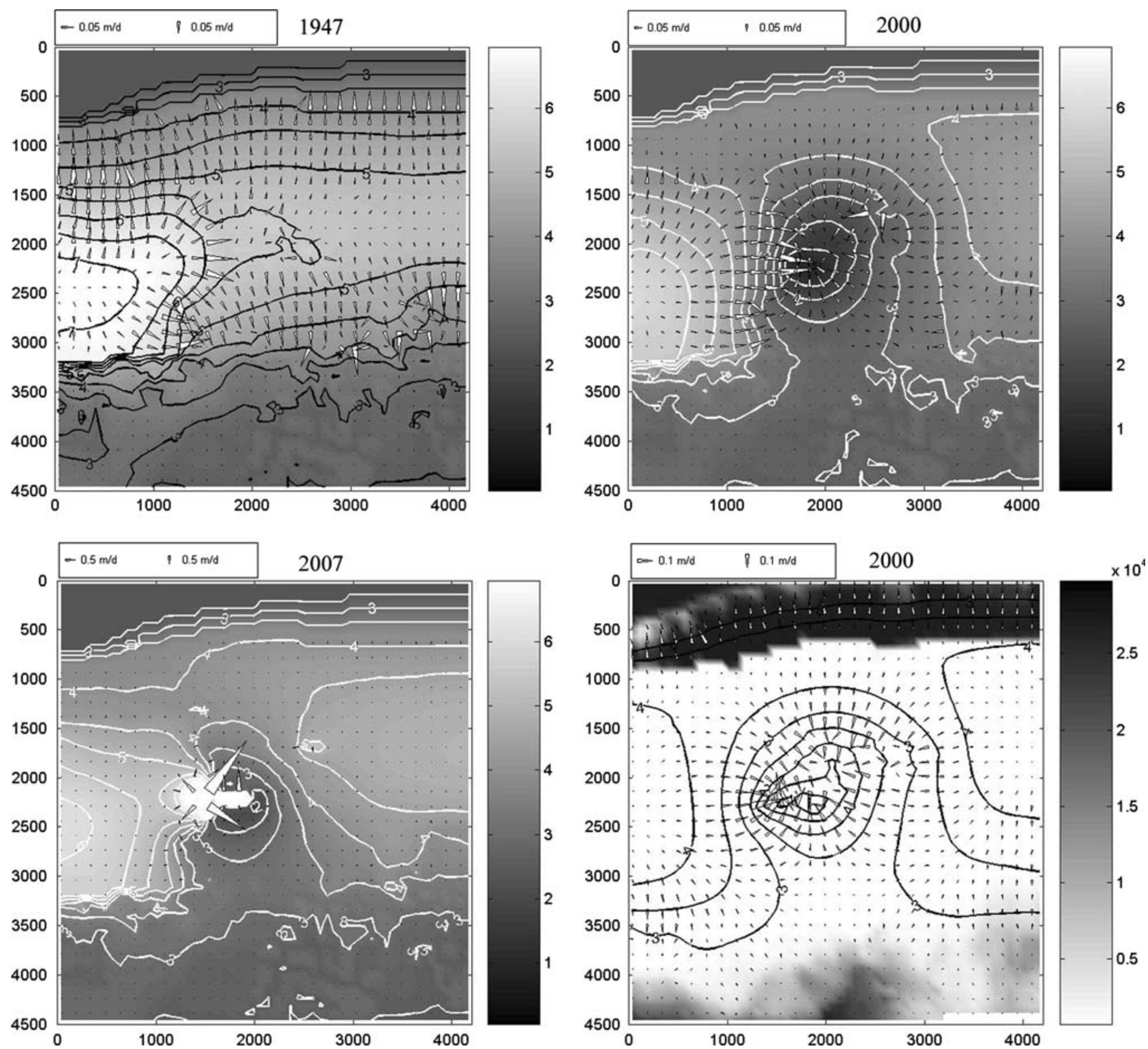


Fig. 10 *Upper* figures and *lower left* figure show the fresh water head (mTAW) in the first layer of the model for 1947, 2000 and 2007. This corresponds with the position of the water table in the model domain. *Lower right* figure gives the fresh water heads at the level of the water extraction (layer 5) whereas the *gray scale* corresponds with the total dissolved solids content (mg/l). *Arrows* give the direction and magnitude of effective flow velocities

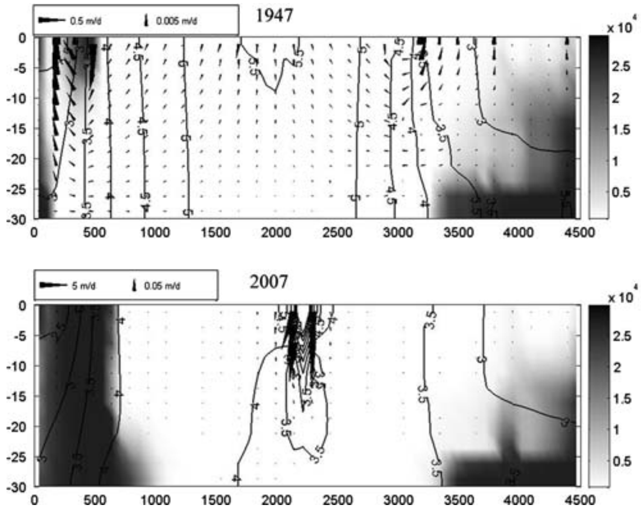
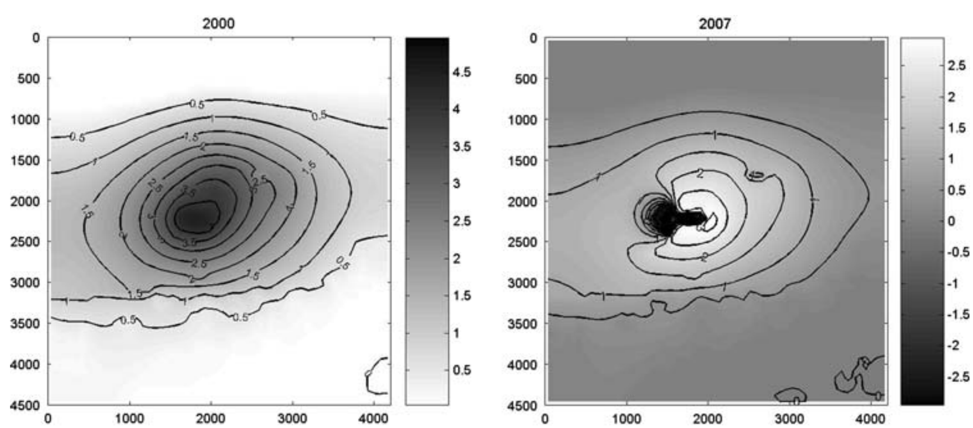


Fig. 11 Vertical north–south cross-sections through the water extraction for 1947, 2000 and 2007. *Lines* show the fresh water heads (in mTAW) whereas *gray scale* indicates total dissolved solids of the pore water (mg/l). *Arrows* give the direction and magnitude of effective flow velocities

towards the polder. This results also in a fresh water lens in the dunes. Brackish and salt water are present in the polder whereas a salt water lens is present below a fresh water tongue under the shore. Fresh water heads are higher in the western part of the area than in the eastern part due to the presence of a shallow clay layer. This raises the fresh water head in the western part. From the late 1960s until 2002, extraction rates remained almost constant, about 2 million m^3/year. Water levels have dropped to about 1.5 mTAW in the centre of the extraction in 2002. In large parts of the dunes groundwater flow direction is towards the extraction instead of towards the sea or the polder. Unlike the Westhoek extraction, there are no current problems with salt water intrusion although the influence of the extraction can be seen, most notably under the shore. The water quality distribution consisting of a salt water lens floating above a fresh water tongue has disappeared. As explained for the Westhoek extraction, this is due to the decreased flow of fresh water from the dunes towards the sea.

To remedy falling hydraulic heads, the infiltration project started in June 2002. The implication of this project on the general flow can be seen in Figs. 10 and 11. First of all, there has been a general increase in fresh water heads corresponding to the situation in 2002. Figure 12 shows the drawdown of the water table in 2000 and in 2007. These drawdowns are calculated with reference to the fresh water heads before the start of the water extraction in 1947. In 2000, a maximum drawdown of about 4 m is calculated in the centre of the water extraction. In the current situation (2007), drawdowns are maximum about 2–2.5 m. In the vicinity of the infiltration pond there is an important increase of the fresh water heads. Besides an increase in the fresh water heads with reference to the 2000 situation, it is also of importance that the natural flow of fresh water from the dunes towards the sea or the polder is restored in large parts of the aquifer. This also means that any future risk on salt water intrusion from the sea or from the polder is averted.

Fig. 12 Drawdown in the first layer due to the water extraction for 2000 and 2007. Reference situation are the fresh water heads before the start of the water extraction



Conclusions

Groundwater reserves in coastal aquifers have specific issues of concern and must be well managed to be sustainable on the long-term. This is illustrated here by two water extractions in the western Belgian coastal plain. Main issue of the Westhoek extraction was the intrusion of salt water from the polder in the dunes which resulted in increasing chloride concentrations in the extraction wells. Additional issue was the lowering of fresh water heads in the dune aquifer. Decrease of extraction rates and the closure in the near future (2010) of well battery 1 which is located closest to the polder, proved to be the best solution. The Westhoek extraction illustrates very well that once salt water has entered the capture zone of the extraction, only long-term planning results in sustainable solutions. Relatively small interventions such as the closure of individual wells and restricted decrease of extraction rates results in temporally solutions. This is evident from the chloride data of the extracted water and from the modelling results.

Main issue of the St-André extraction was the decreasing hydraulic heads in the dune area. This was remedied by starting an artificial recharge project in July 2002 whereby additionally treated effluent of a wastewater treatment plant is infiltrated in the dune aquifer. Doing so, capacity of the St-André extraction increased from 2 to 4.2 million m^3/year which is more than a doubling. Moreover, this is realised by a decrease from 2 to 1.7 million m^3/year of water which comes directly from the aquifer. The remainder of the water (2.5 million m^3/year) is artificially recharged water.

Obviously, the Westhoek and St-André extractions must be evaluated together. Before the start of the artificial recharge project, total water production was 3 million m^3/year in 2001: 1 million m^3/year from the Westhoek extraction and 2 million m^3/year from the St-André extraction. In 2010 this will be 4.7 million m^3/year: 0.5 million m^3/year from the Westhoek extraction and 4.2 million m^3/year from the St-André extraction. This means an increase of 57%. From these 4.7 million m^3/year, only 2.2 million m^3/year is originating from the aquifer. The remaining 2.5 million m^3/year is recharged water. This means a decrease of 27% of water which is originating from the phreatic aquifer in the dunes. Consequently it can be concluded that a sustainable water extraction is developed in the western Belgian coastal plain.

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