DIRECT GROUNDWATER DISCHARGE TO THE NORTH SEA. A CASE STUDY FOR THE WESTERN BELGIAN COAST

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Abstract

The Belgian coastline extends for some 67 km along the North Sea. The coastal region has an almost continuos dune belt of 1 to 2 km width, separating inland lying polders from the beach slope. The North Sea itself shows strong tidal fluctuations, which also penetrate into the coastal aquifer system. This coastal aquifer is on average around 30 m thick and forms an important source for water supply in this part of the country. For this purpose it has already been used for decades. In natural conditions the dune belt acts as a groundwater divide which separates two groundwater flow systems, one to the sea and one inland to the polder region. Water catchment well fields have changed this flow pattern locally. A groundwater flow model of the western coastal region has been used to calculate groundwater fluxes from under the dune belt to the sea under different conditions: for average seasonal variations with and without pumping in the dune belt, and under increased (+10 %) and decreased (-10 %) recharge rates, and during a three decade long period (1970-2000) with real recharge rates. The results give an indication of the discharge rates to the sea and how they change from season to season, their interannual variation, and how they are affected by groundwater pumping in the dunes. The impact of small changes in average recharge rates, both increasing and decreasing, have been quantified.

Keywords: modelling, coastal aquifer, discharge, North Sea

Introduction

The considered region lies along the French-Belgian border (Figure 1) and was studied as part of the "GWEN" project (Van Camp et al., 2002a; Van Camp et al., 2002b; Walraevens et al, 2002; Hoffmann and Degezelle, 2002; Martens et al., 2002). The modelled region consists of the main dune belt (Figure 2) and part of the inland polders. In the west a second smaller, older dune belt occurs more inland. This is

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separated from the main dune belt by a landscape of old tidal flat deposits. Along the inland border of the main dune belt the occurrence of drainage canals influences the hydrodynamics; in the polders, water levels in ditches are artificially regulated.

In the main dune belt two pumping sites are active. The oldest one is located close to the French border. Abstraction rates are around 1.2 Mm^3/year. A more recent one combines groundwater extraction with artificial recharge. Netto abstraction rate (abstraction minus recharge) here is around 1.7 Mm^3/year. In the smaller, old inland dune belt a minor pumping site extracts only small amounts of groundwater.

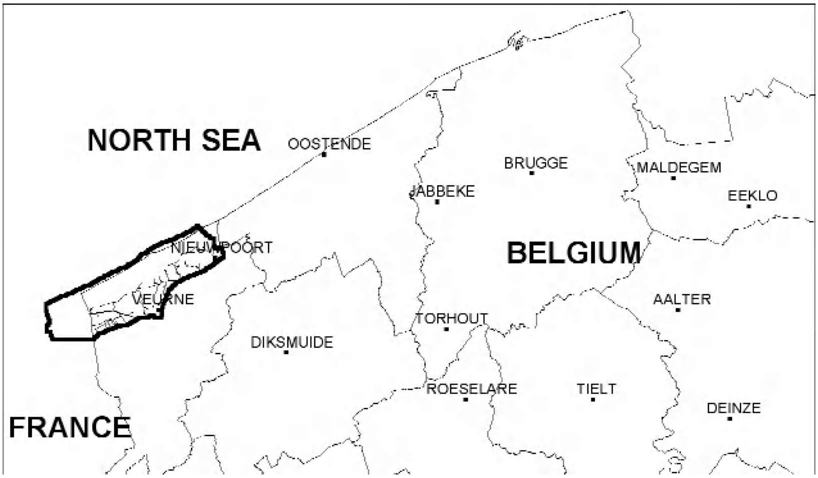

Figure 1. Localisation of the studied region in Belgium.

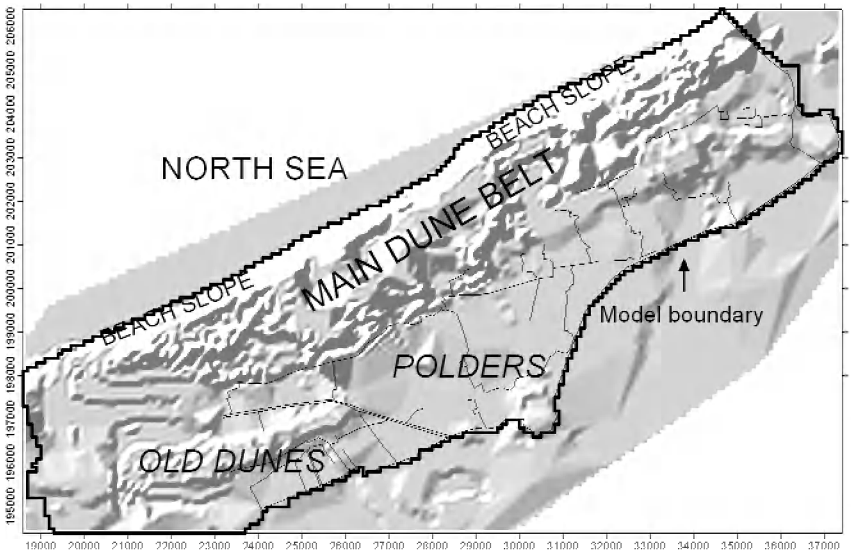

Figure 2. Physiography of the model area.

Aquifer system

The Quaternary deposits are around 30 m thick and consist of mainly sandy material. Underlying are thick tertiary clay layers. Groundwater fluxes through these clay layers are (very) small compared with the flow in the quaternary sands, and can be considered as the substratum in the flow system.

The deepest part of the Quaternary sands is coarser (medium sands) than the upper part (fine sands), and hydraulic conductivities can be quantified as around 10 m/d for the upper section and 20 m/d for the lowest section, based on different methods (pumping tests, grain size distributions). Sometimes more silty layers occur between the sands, very often between the lower medium and upper fine sands. The dunes themselves contain fine sands, while in the polders a clay layer of 1 to 2 m lies just beneath the land surface.

Locally a more complex hydrolithology is observed. Close to the French border an old inland dune belt occurs (also affecting groundwater flow) and between the main and old dune belt old tidal deposits lie near the surface, also underlying part if the main dunes. Both the polder clays and the tidal flat deposits have low hydraulic conductivities.

Hydrodynamics

Since a large number of observation wells have been used for monitoring groundwater levels over the years, the flow systems in the aquifer system are well known. A groundwater divide under the main dune belt separates two main flow systems. The first one flows northward and discharges fresh dune water into the sea; the second one brings water from the south part of the dunes into the polders where it is drained by numerous polder ditches. This study focuses onto the intensity of the first groundwater system.

Groundwater flow has changed around two important dune pumping sites. Around them the groundwater divide splits into a northern branch between the site and the sea, and a southern branch towards the polders. Piezometric levels have dropped there several meters.

Under the main dune belt no saline waters occur. In the polders they occupy the main part of the aquifer system. Locally more fresh water occurs in the upper part of the aquifer due to local flow systems and the existence of small and often temporary infiltration sites. Under the beach slope, a saltwater lens is floating on top of fresh water.

Groundwater model

Simulation code

The groundwater model uses MODFLOW as a simulation code (Mc Donald and Harbaugh, 1988).

Model boundaries

The modelled region lies mainly between the Belgian-French border and the Yser river. In the north the low tide water line on the beach slope forms the model border. The western boundary lies across the Belgian-French border and follows a streamline. The eastern boundary is formed by the Yser river which has the same tidal regime as the sea. The southern model boundary lies in the polder region and follows some polder drainage canals, in which water levels are known and kept constant. Within the model region both the dune belt and a significant part of the inland polder system are included, allowing an accurate simulation of both groundwater flow cycles originating in the dunes.

Reservoir schematisation and hydraulic parameterisation

The aquifer was subdivided in 6 model layers (Figure 3). The grid used a cell size of 100 m by 100 m. The deeper part of the aquifer has a higher hydraulic conductivity (Table 1). Two thin silty layers were recognized in the geophysical well loggings and borehole descriptions.

Table 1. Reservoir schematisation and hydraulic parameterisation in the model.

model layer	lithology	thickness (m)	k_h (m/d)	k_v (m/d)	storage
1	fine sands	variable	1		0.10
2	fine sands	3	10		$3\ 10^{-4}$
3	silty sands	3		0.075	$3\ 10^{-4}$
4	fine sands	10	10		$10\ 10^{-4}$
5	silty sands	2		0.1	$2\ 10^{-4}$
6	coarse sands	7	20		$7\ 10^{-4}$

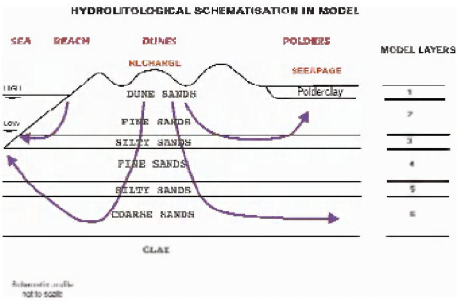

Figure 3. Hydrolithology of the aquifer system and model schematisation.

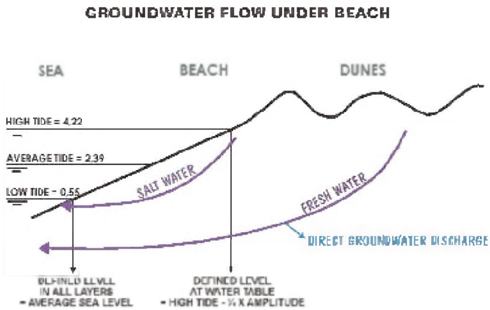

Figure 4. Superposed flow systems under the beach slope.

Boundary conditions

Different boundary conditions were defined and incorporated using different MODFLOW packages (modules). The choice of the right boundary condition is very important as it determines the mathematical formulation which is used to represent the hydrodynamic situation in the flow equation (Reilly, 2001).

Beach slope

The hydrodynamic situation under the beach slope is complex because of the highly transient flow regime created by the tidal fluctuations of the sea level. These fluctuations (Table 2) consist of two cyclic signals: a low and high tide cycle (two times a day) and spring and dead tide (half monthly). This second cyclic signal modulates the first (modifies the amplitude of the high-low tide cycle). The high tide line at the beach slope is usually located between +4 and +5 m, the low tide line between 0 and +1 m. Average sea level is +2.38 m. These data are valid for Zeebrugge, located more centrally along the Belgian coastline.

Table 2. Tidal fluctuations at Zeebrugge (in m).

Tide	High	Low	Average	Amplitude
Spring	4.61	0.27	2.44	4.34
Normal	4.22	0.55	2.39	3.67
Dead	3.72	0.90	2.31	2.82

While the low tide line can be incorporated into the model by defining constant heads at average sea level (+2.39 m), a special condition occurs at the high tide line. At high tide the whole beach slope is inundated and the water table equals that of the sea level. But as the sea retreats and the beach emerges, the local water table will start to drop, but slower than the sea level. Therefore the water table near the high tide line stays rather high. This causes the development of a small local groundwater system under the beach slope where salt sea water infiltrates at the upper beach slope and is flowing above the fresh water wedge of the main dune-sea cycle (Figure 4). This is observed at different sites along the Belgian coastline (Lebbe and Walraevens, 1988).

Aquifer recharge

The recharge of the water table was calculated from monthly meteorological data (for precipitation and potential evapotranspiration, PET) and assigned with the RCH package at the whole model region. Average recharge rates (Figure 5) range from 40-60 mm/month in winter time to zero during summer time.

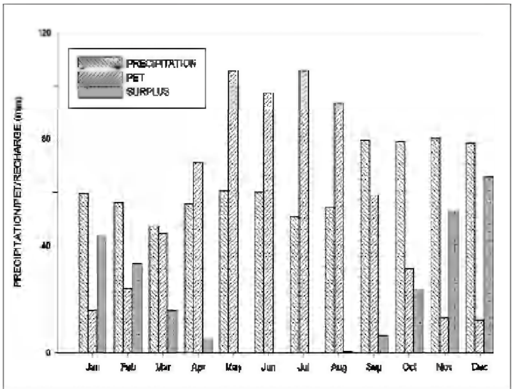

Figure 5. Long term (1970-2000) average monthly precipitation, PET and recharge (surplus) values (mm/month).

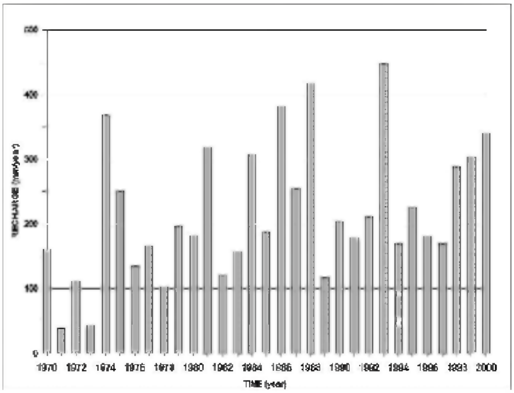

Figure 6. Yearly aquifer recharge (mm) for 1970-2000 calculated from monthly precipitation and PET values.

The long term average recharge is 248 mm/year. Total recharge used in the model is on average 22,263 m^3/day, with a maximum average in December up to 70,732 m^3/day.

Interannual variation of recharge rates (Figure 6) shows wetter conditions at the end of the 1990's.

Polder drain network

The main drainage canals were incorporated with the STR (stream) module to obtain baseflow rates, some others with the RIV (river) module. Water levels were adapted for winter and summer situation. Because it is not possible to incorporate every small polder ditch, the polder drainage was built in by using the drain module (DRN package). This allows drainage of groundwater into small ditches using wet and/or winter season, but once these dry up in summer season, no interaction with the aquifer system is sustained.

Groundwater extraction

The pumping sites were allocated by location of the individual pumping wells in the WELL package. Pumping rates are only known as yearly totals. Total groundwater extraction in the dunes is nearly 3 Mm^3/year.

Simulations

Different simulations were carried out:

- Two simulations with average seasonal flow regimes: one with and one without groundwater extraction in the dune belt; abstraction rates for the year 2000 were used.
- A simulation of the non-pumped flow regime during the period 1970-2000 with aquifer recharge rates calculated from measured meteorological data.
- Two simulations with a 10 % increase and decrease of the recharge rates and no groundwater abstraction in the dunes.

All performed simulations are transient flow calculations. Boundary conditions were updated every month (stress period size), but heads were recalculated three times every month (time step size is around ten days). The spin-up for the transient simulations was a steady state simulation with average boundary conditions.

As a result, the hydraulic head distributions and groundwater flow rates are obtained. Discharge rates to the sea were calculated from groundwater horizontal flow rates at the seaside boundary of the dune belt and give the amounts of groundwater that flows from the dune belt to the beach slope. The fluxes in all model layers were added to get the discharge for the whole aquifer. Totals were calculated by adding the values for each model column or were stored separately for investigating the lateral variation along the coastline.

Model results

Average seasonal flow regimes

Calculated piezometric levels of the water table in winter time (highest levels around March) and summer time (lowest levels around September) are mapped for the non-pumped and pumped situations.

In the non-pumped situation (figures 7 and 8) a groundwater divide follows the central part of the main dune belt from the Yser river in the north-east to the south-west model border. North of this groundwater divide, water flows towards the sea. The highest piezometric levels are found in the north-eastern part of the dune belt. A second groundwater divide is located under the second more inland dune belt in the south-west.

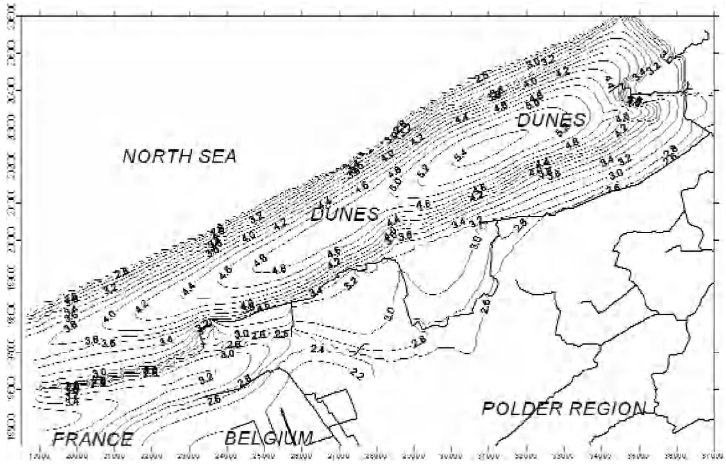

Figure 7. Calculated piezometric levels in winter time in the non-pumped situation.

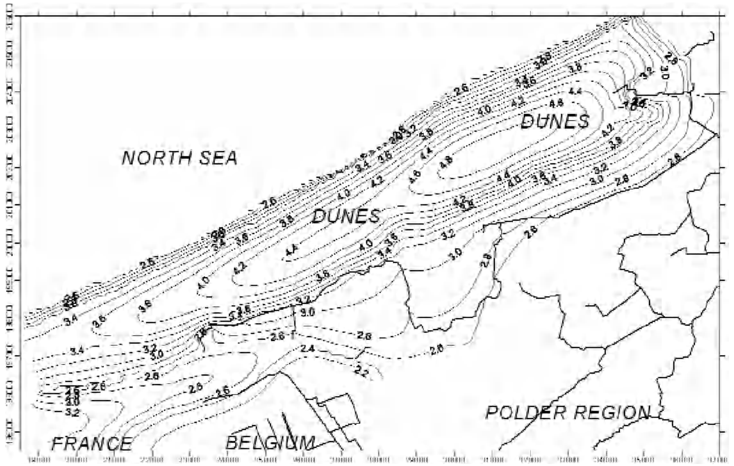

Figure 8. Calculated piezometric levels in summer time in the non-pumped situation.

In the pumped situation (figures 9 and 10), the general pattern is interrupted by the location of the two pumping sites in the main dune belt, around which piezometric levels have lowered significantly. Between the pumping sites and the sea, a groundwater divide is still present, but it is now shifted towards the sea, and is less pronounced.

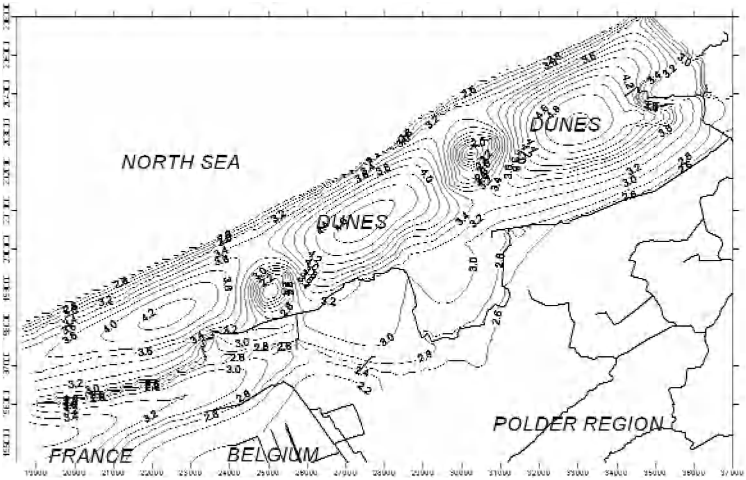

Figure 9. Calculated piezometric levels in winter time in the pumped situation.

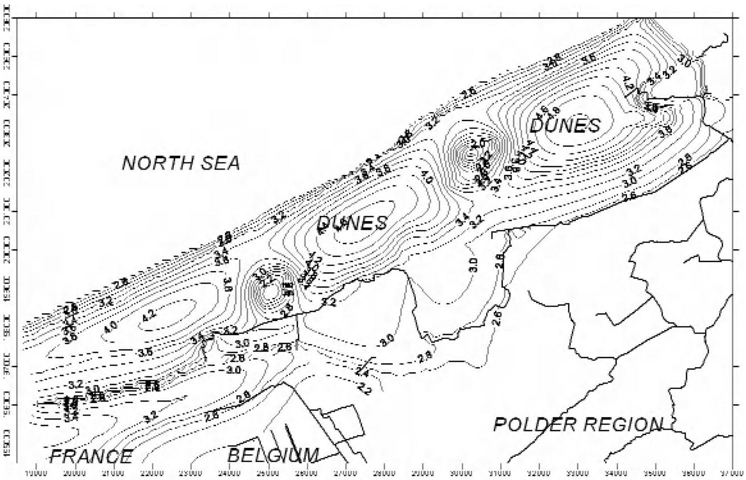

Figure 10. Calculated piezometric levels in summer time in the pumped situation.

From the horizontal fluxes, the discharge rates to the sea were calculated and are presented in a graphical way which gives the average daily discharge (in m^3/day) per m coastline as a function of time. Figure 11 gives the evolution during a representative year. We see that the highest discharge rates occur in winter time when groundwater levels are higher and the groundwater gradient towards the sea is higher. Consequently fluxes will be larger. This occurs mainly in December and January. During these months the discharge rate is nearly 0.8 m^3/day/m. In springtime, discharge is decreasing and during the summer months, when groundwater levels are near their minimum, the total discharge lowers to around 0.4 m^3/day/m near the end of September. This is recalculated to around half of the winter discharge rate. After summer time, discharge rates increase fast during October and November. Generally we can say that winter discharge rates are twice the summer values and that there is a slow decrease from the winter to summer values, but a fast increase after summer towards the high winter rates. In case of the pumped situation, discharge rates are lower. In winter time, discharge is around 0.6 m^3/day/m, decreasing in summer time to less than 0.3 m^3/day/m. Discharge rates in the pumped case are between 75 % (winter time) and 60% (summer time) of the rates in the non-pumped situation. But these numbers refer to the average for the whole model shoreline. In the sections where the two dune pumping stations are located, influence on the discharge rates will be more significant (Figure 12).

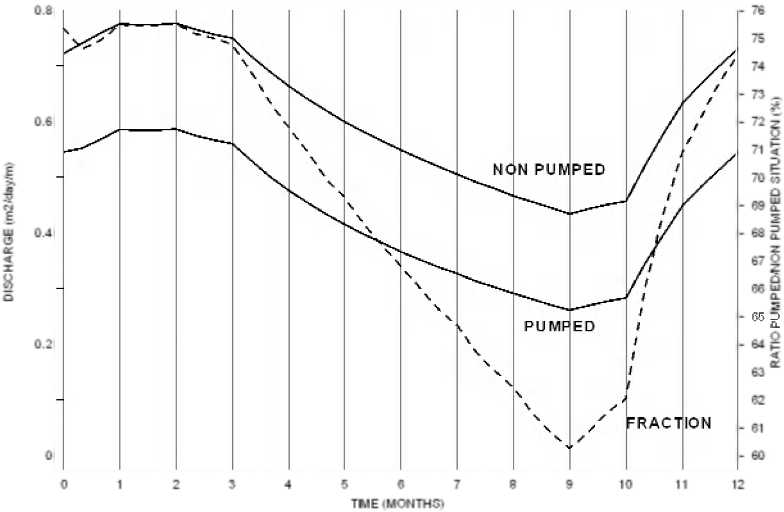

Figure 11. Monthly discharge rates to the sea for average seasonal variations in pumped and non-pumped situations and ratio of pumped vs non-pumped discharge rates (as %).

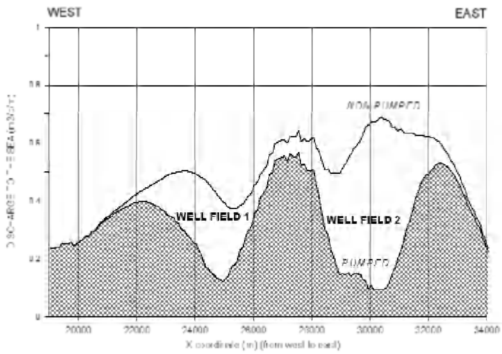

Figure 12. Variation along coastline of the average discharge rate in non-pumped and pumped cases.

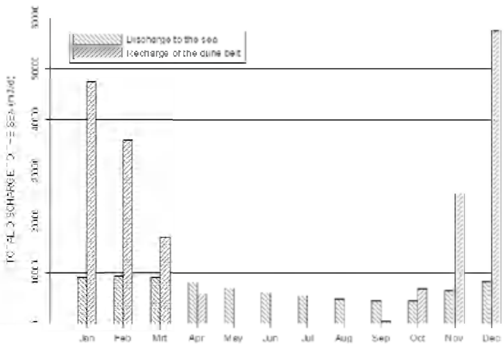

Figure 13. Comparison of total monthly recharge of the main dune belt and discharge to the sea.

Monthly comparison of the total recharge of the dune belt and the discharge to the sea for the coastline section included in the model (Figure 13) shows that recharge is much larger than the discharge in the winter season (up to five times), but during summer no recharge is occurring while discharge is continuing albeit at a lower rate. The yearly average shows that 59.8 % of the recharge of the dune belt finally flows to the sea in the non-pumped situation. In the pumped regime, this is reduced to 41.9 %.

Flow regime during 1970-2000

A three decade long simulation was carried out with the recharge rates calculated from monthly meteorological data but without pumping in the dune belt. This shows the interannual fluctuation of the discharge rates to the sea under natural conditions. Average discharge rates for the whole model are plotted versus time (Figure 14). Highest discharge fluxes have occurred in the winters of 1987-88 and 1993-94. The winter of 1974-1975 was a wet period in a decade with generally lower discharge rates and lower piezometric levels (Van Camp and Walraevens, 2001). It seems that the maximum winter fluxes show more variation than the lower summer rates.

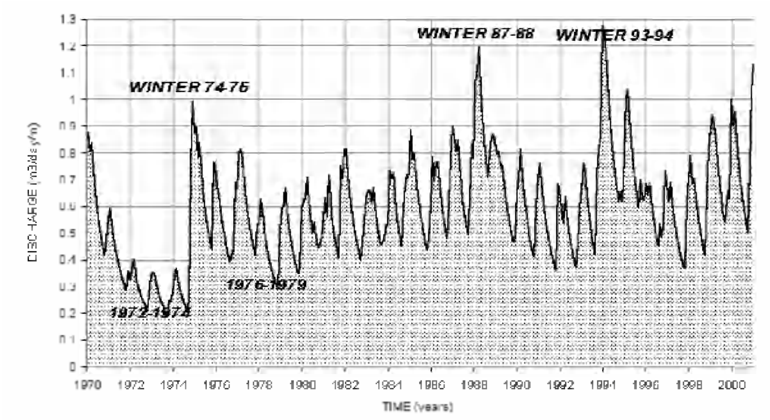

Figure 14. Calculated monthly discharge rates in the period 1970-2000 under natural conditions (no pumping).

Variation of the seaward discharge along the coastline over the years is visualized in the form of a graph (Figure 15) which gives the flux as a function of the distance along the coast on the vertical axis and as a function of time on the horizontal axis. Periods with high seaward discharge are easily recognized as darker vertical strips, each corresponding with a wet winter season. The winter periods of 1987-88 and 1993-94 show the highest discharge rates, while rates were not pronounced in the first half of the seventies.

Flow regimes with altered recharge rates

Two simulations were done with altered recharge rate of the aquifer system: a 10 % increase and a 10 % decrease of the monthly recharge rates. Summer months without recharge were not affected.

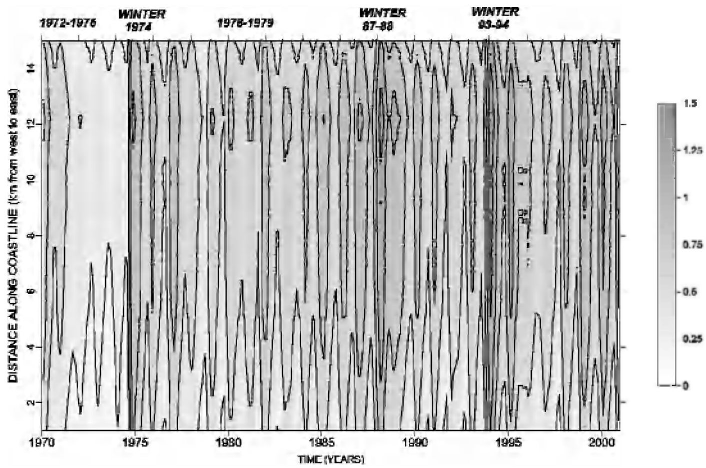

Figure 15. Variation along the coastline of the discharge flux to the sea during the last three decades in the non-pumped case (in m^3/d/m).

Comparison of these simulations with normal seasonal flow regimes (Figure 16), shows that an increase and decrease of the discharge rates with +8.8 % and –8.8 % is to be expected which do not differ much from the forced changes in the recharge rates. Therefore the 59.8 % ratio of total discharged water from the dune belt recharge is changed only to 59.3 % for the 10 % increase and 60.6 % for the 10 % decrease scenario.

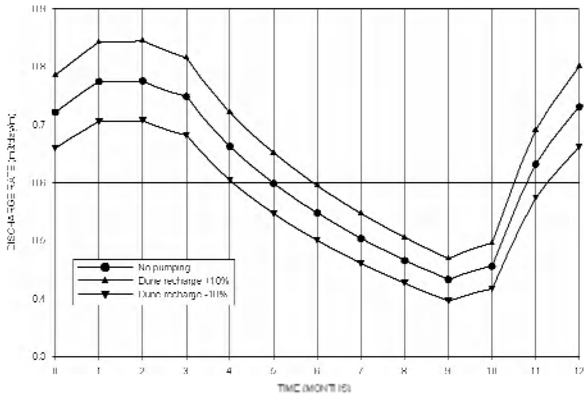

Figure 16. Calculated monthly discharge rates with increased and decreased aquifer recharge rates (no pumping).

Summary and conclusions

With a groundwater flow model which covers around one third of the Belgian North-Sea coastline, the amount of dune recharge water discharging to the sea was calculated. Different flow regimes were investigated.

In the average seasonal, the flow regime with no groundwater abstraction in the dunes, around 60 % of the water recharging the coastal dune belt flows to the sea. Discharge rates are in winter time nearly twice as large as in summer time. After winter, a long slow decrease in the discharge rates occurs, while after summer they increase quite fast. In the case with two pumping stations in the dunes, only 42 % of the dune recharge water is still flowing to the sea.

During the last three decades, the highest discharge rates have occurred in the winters of 1987-88 and 1993-94. During the seventies, discharge rates were generally lower due to meteorological constraints.

Changes of the recharge rates with 10 % of the actual long-term average will alter the discharge rates with around 9 %.

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