Quality evolution of the fresh and salt groundwater pumped near a drainage canal in the Western Flemish coastal plain

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INTRODUCTION

Until now, 65 % of the water supplied by the Intermunicipal Water Company of the Veurne Region (IWVA), is pumped from the fresh water lens in the dune belt of the western Flemish coastal plain. Because this extraction has reached its maximum capacity, the IWVA plans to optimize the water production by recharging water into the dunes. During winter, a large amount of fresh surface water is available in the polder area south of the dune belt. Especially the Avekapelle region is a potential intake region, because of the presence of a sandy creek ridge. This Avekapelle creek ridge is drained by two canals, the Kromme Gracht in the west and the Oude A-vaart in the east. The drainage water is of relatively good quality. Until now it is evacuated to the sea, as quickly as possible.

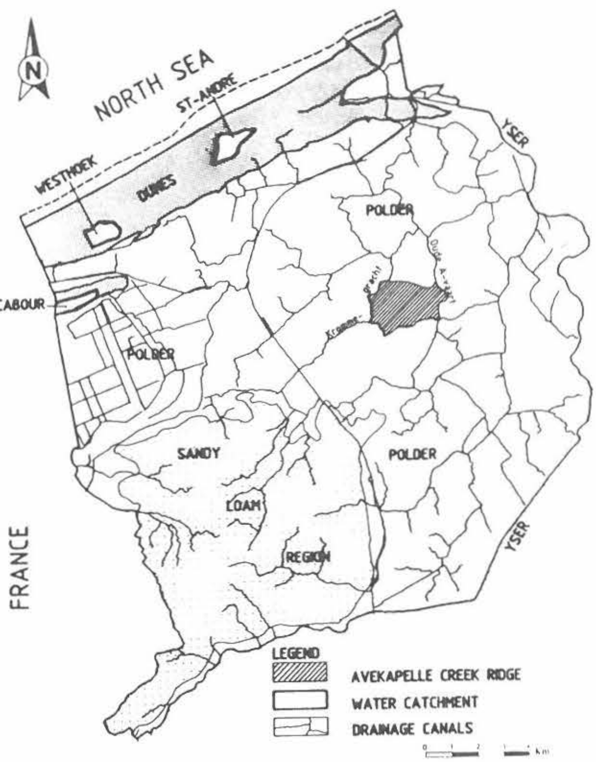

Figure 1. Location of the investigation area

DESCRIPTION OF THE PROJECT

In the dune water catchment of St-André, the IWVA plans to increase its water production by creating an infiltration basin with a capacity of 2 to 2,5 million m^3/year. To prevent propagation of the recharged water, the total amount of this water will be extracted by production wells in the vicinity of the basin. The minimum residence time of the recharged water in the phreatic aquifer will be in the order of six weeks. This is to ensure that the produced water will be bacteriologically safe.

The project will allow a total production rate of 3,5 to 4 million m^3/year in St-André, which means that the netto-groundwater production in these dunes will diminish by 0,5 million m^3/year. The production of drinking water from a combination of groundwater and surface water has a lot of advantages. The existing production system can be used. The recharge will restore natural groundwater levels and will also prevent salt water encroachment in the phreatic aquifer from the beach and from the polder area, respectively north and south of the water catchment.

The quality of the recharge water will improve so that it will approximate dune water quality. In case of pollution the recharge can be stopped while the production can still continue for a short period. Furthermore, the produced groundwater will be bacteriologically clear and no disinfection is needed (Van Houtte et al., 1995).

The recharge water could be produced in the central part of the Avekapelle creek ridge. Extraction wells alongside an intake canal, connecting the Kromme Gracht and the Oude A-vaart and crossing the creek ridge, would make it possible to capture the surface water. Because the aquifer under the creek ridge is filled with fresh water in the upper part and salt water in the lower part, it will be necessary to construct extraction well pairs. One of the wells of a pair should be screened in the upper part of the aquifer. This well will withdraw infiltrating surface water and fresh water from the aquifer. The other well of a pair should be screened in the lower part of the aquifer and will produce salt water. This system will prevent an upward flow of brackish and salt water to the fresh water wells. In order to smoothen the effect of different qualities of intake water, the well pairs must be constructed at various distances from the intake canal. After treatment, the fresh water will be pumped to the dune area. The pumped salt water will be piped to the sea.

HYDROGEOLOGY OF THE AVEKAPELLE CREEK RIDGE

The permeable Quarternary sediments form the phreatic aquifer. The thickness of this aquifer varies between 12 and 30 m. Under the central part of the Avekapelle creek ridge, the aquifer consists of a succession of fine and medium sands with shells. The top of the aquifer generally contains sandy clays. Closer to the Oude A-vaart the lower part of the Quarternary sediments become clayey. The reservoir is bounded below by Tertiary clay (Fig. 2), which can be considered as an impervious substratum.

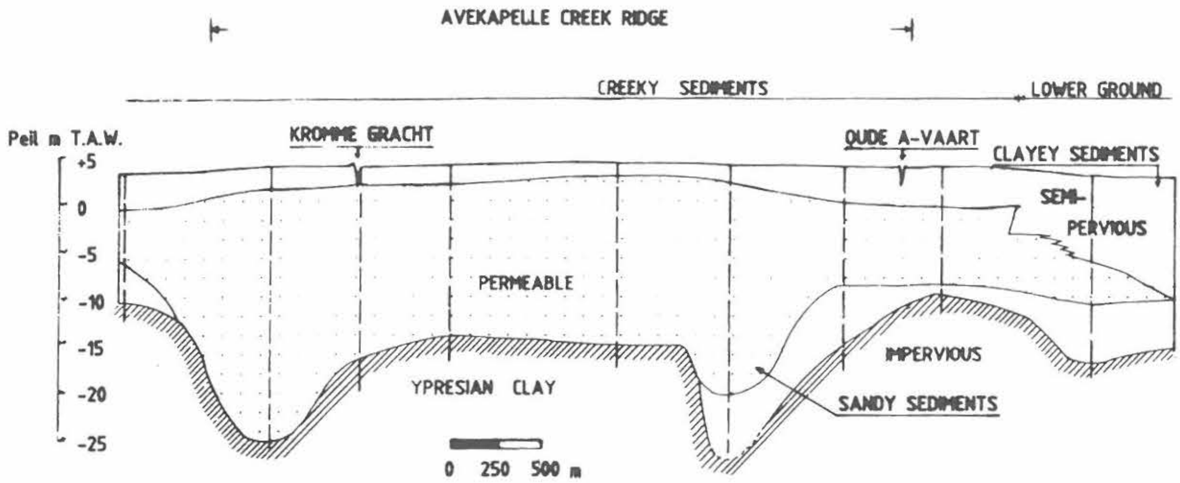

Figure 2. Lithological WE-section through the central part of the Avekapelle creek (Zeuwts, 1991)

The quality of the groundwater in the central part of the Avekapelle creek ridge varies from top to bottom (Fig. 3). According to the classification of Stuyfzand (1986), Zeuwts (1991) observed a succession of the following types of water from top to bottom : (1) fresh water of the F-$CaHCO_3$, F-CaMix and F-$CaSO_4$-types; (2) fresh-brackish water of the F_b-$CaHCO_3$ and F_b-$NaHCO_3$-types; (3) brackish water of the B-$CaHCO_3$ and B-$NaHCO_3$-types; (4) brackish water of the B-NaCl-type; (5) brackish-salt water of the B_s-NaCl-type and (6) salt water of the S-NaCl-type. In the vicinity of the Kromme Gracht and the Oude A-vaart the fresh/salt water interface rises because of the drainage activity of those canals (Zeuwts, 1991). The groundwater movement in the central part of the Avekapelle creek ridge is dominated by the drainage canals, which means that the groundwater under the creek ridge flows towards the Kromme Gracht and the Oude A-vaart.

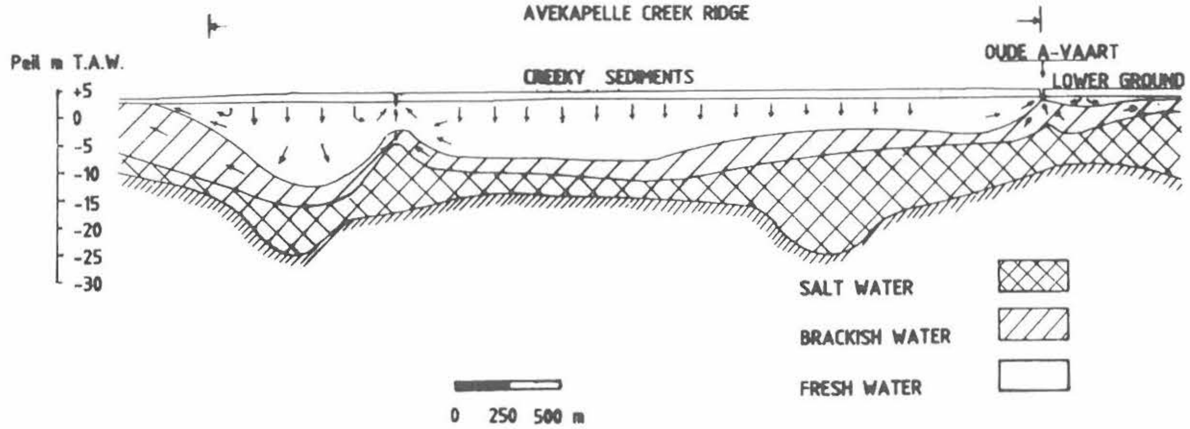

Figure 3. Fresh/salt water distribution in the aquifer of the Avekapelle creek (Zeuwts, 1991)

A double pumping test in the Avekapelle creek ridge (Lebbe et al., 1995) showed that the hydraulic resistance between the intake canal and the upper part of the aquifer is low (in the order of 9 days). During this test, the salt water from the lower part of the aquifer was discharged during 3 days at a rate of 144 m^3/day. After the first day of pumping, the fresh water from the upper part of the aquifer was extracted at a rate of 59 m^3/day. Despite the small hydraulic resistance between the upper and lower part of the aquifer (6 days), the water pumped from the upper well did not become brackish, because the hydraulic head in the lower part of the aquifer was lower than in the upper part. The sediments in the upper part of the aquifer have a horizontal hydraulic conductivity of 5,54 m/d; the sediments of the lower part 5,70 m/d. The specific elastic storage of the Quarternary sediments is 1.9 10^{-4} m^{-1}; the specific yield 0,022.

Simulation of fresh and salt water extraction, respectively from the upper and lower part of the aquifer, showed that after a period of three to four years, the salt water of the lower part of the aquifer would freshen, which means that it could also be used to recharge the dunes. To investigate the relation between the quality of the produced fresh water and the quality of the surface water, it was decided that a long-term double pumping test had to be done. The results of this test are described below.

LONG-TERM DOUBLE PUMPING TEST IN THE AVEKAPELLE CREEK RIDGE

Description

Although the location of the test site is not optimal due to the vicinity of the Kromme Gracht (upconing of salt water), the existing pumping and observation wells were used. There is no suitable location available more to the centre of the creek ridge at a certain distance from the canals. The pumping wells (PP1 en PP2) are at 1 m distance from one another. The shortest distance between the Kromme Gracht and the upper pumping well (PP2) is 8 m. Four observation wells are placed in a WSW-ENE direction (Fig. 4) : two in the upper part of the aquifer (2.3 and 2.4) and two in the lower part (1.3 and 1.4). Another four observation wells, two in the upper (2.1 and 2.2) and two in the lower (1.1 and 1.2) part of the aquifer, are located on a line perpendicular to the first mentioned direction.

The pumping test started on December 11th, 1995 and lasted until April 22nd, 1996. The mean discharge rate until March 11th, 1996 was 5,09 m^3/h for PP1 and 2,64 m^3/h for PP2. On this day the discharge rate from well PP2 was reduced to 2,04 m^3/h. It remained constant until April 22nd. However, from March 11th, on the discharge rate from well PP1 gradually declined to 4,6 m^3/h and averaging 4,83 m^3/h for the period March 11th - April 22nd. The drawdown in the wells was recorded by a datalogger from December 11th until December 20th, 1995. During the rest of the time the drawdown was measured manually.

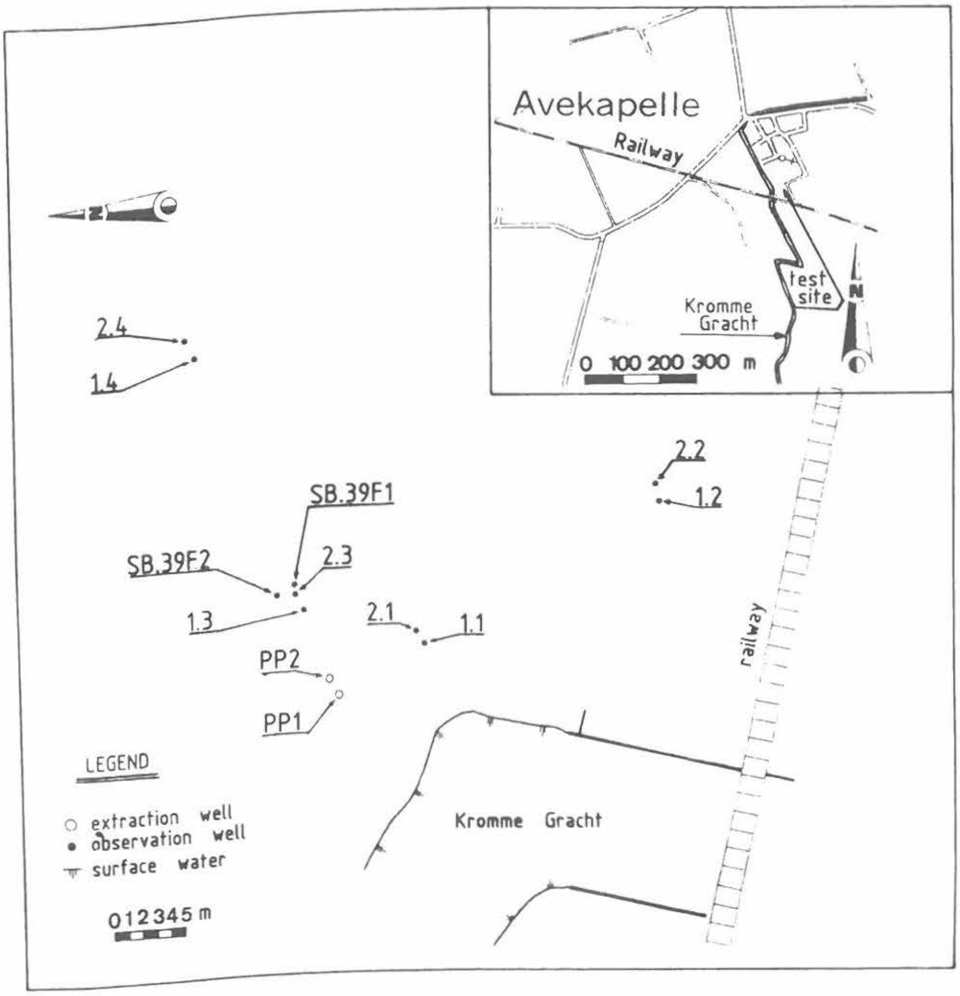

Figure 4. Configuration at the test site

The quality of the fresh groundwater (well PP2) and of the surface water was monitored by automatic registration of the electrical conductivity during the first month of the test. Also the following parameters were analysed on a regular basis (Fig. 5) : electrical conductivity, pH-value and temperature; the anions chloride, nitrate, nitrite, sulphate and bicarbonate; the cations sodium, potassium, calcium, magnesium, ammonium, total iron and total phosphorus. The bacteriological contamination was controlled by counting total coliforms.

Quality of the surface water

The water of the Kromme Gracht is fresh. The mean chloride content is 236 mg/l, varying between 147 and 545 mg/l. The electrical conductivity varies from 1056 µS/cm to 1770 µS/cm, and the sodium content from 66 to 318 mg/l with an average of 146 mg Na^+/l. There is a good relationship between those parameters : high electrical conductivity corresponds with high contents of chloride and sodium (Fig. 5). The potassium content is relatively stable averaging 19,8 mg K^+/l and varying from 13 to 26 mg K^+/l. The surface water caries an important load of contaminants with mean levels for nitrate of 29,1 mg/l, nitrite of 0,43 mg/l, ammonia of 2,72 mg/l, total phosphorus of 0,84 mg/l and sulfate of 248 mg/l.

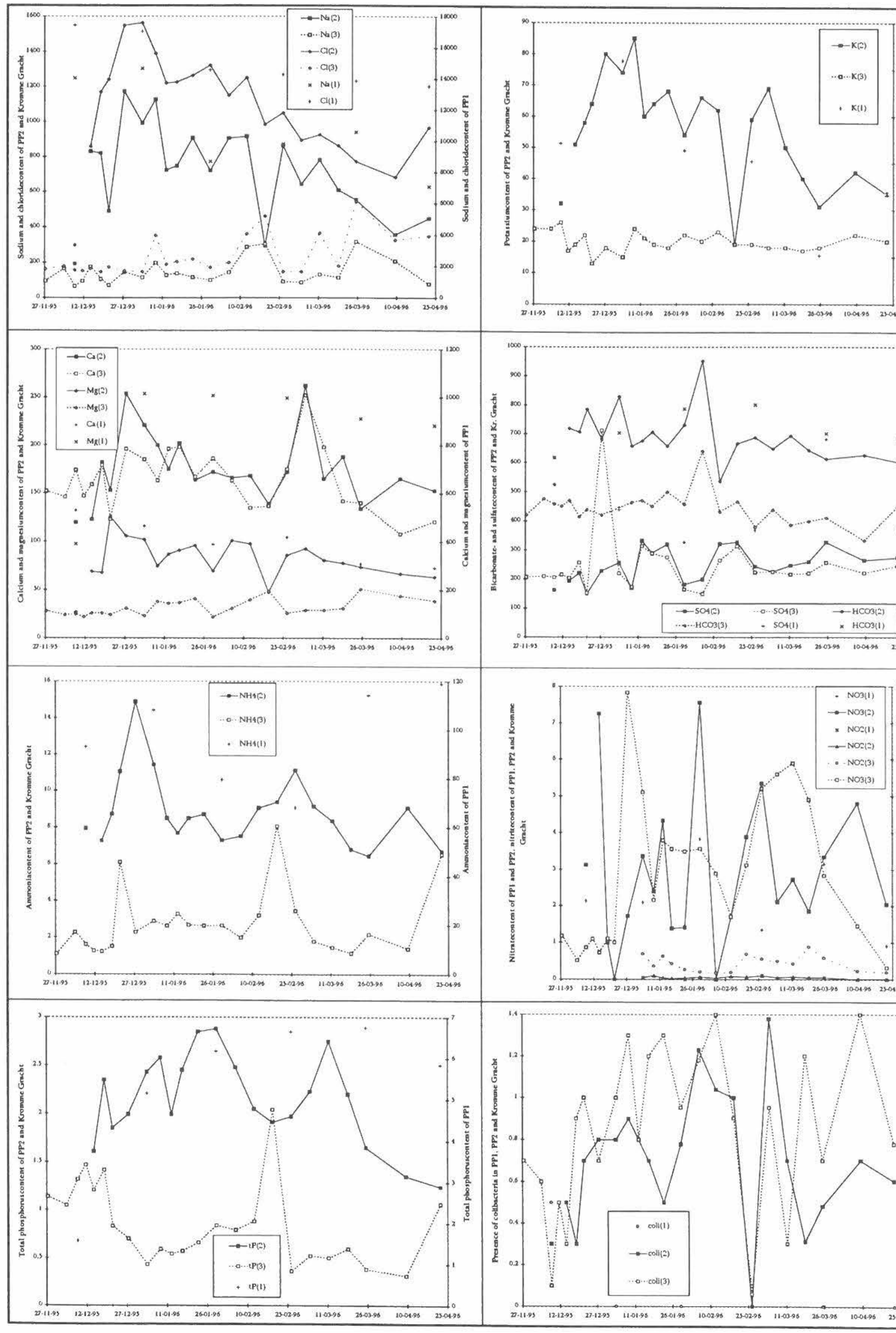

Figure 5. Chemical quality of the extracted salt (PP1, 1) and fresh (PP2, 2) groundwater and of the surface water (Kromme Gracht, 3)

The surface water is hard : the calcium content varies between between 108 and 252 mg/l with an average of 164 mg/l; the magnesium content varies between 22 and 51 mg/l with an average of 32,2 mg Mg^{2+}/l. The bicarbonate content is relatively stable and ranges between 334 and 641 mg/l with an average of 445 mg/l. The iron content of the surface water is fairly low, ranging from 0,09 mg/l to 0,73 mg/l with an average of 0,24 mg/l. The total coliform content of the surface water varies from 0,06 to 1,4 colonies/100 ml with an average of 0,84 colonies/100 ml.

Quality evolution of the pumped groundwaters

Quality of the water extracted from the upper part of the aquifer (well PP2)

The quality of the water extracted from well PP2 changed significantly. It was initially a fresh/brackish and very hard water of the F_b3-NaMix type with a chloride content of 298 mg/l. After 3 days of pumping however the chloride content reached 858 mg/l, changing into brackish water of the B3-$NaCl^+$ type. According to the electrical conductivity measurements the maximum salt level was reached after 19 days of pumping. On this day no chloride analysis was available, but four days later the maximum chloride content was observed (1.564 mg/l). This water was a brackish/salt water of the B_s4-$NaCl^+$ type. Together with the salt content, the sodium-, ammonium-, potassium-, calcium- and magnesium contents increased as well. These parameters reached their maximum concentration together with the maximum level registered for the chloride content. This increase of the salt content of the water extracted from well PP2 is caused by the flux of brackish groundwater to the well.

Once the surface water had reached the pumping well, the extracted water refreshened until an equilibrium was established (chloride content of 900 to 1000 mg/l). Reduction of the discharge rate caused a gradual decline of the salt content, reaching a minimum chloride content of 684 mg/l. After approximately one month of pumping most of the parameters in the groundwater pumped from PP2 behaved as those in the Kromme Gracht.

The concentration of nitrite and nitrate, respectively averaging 0,05 and 3,23 mg/l, was low compared to the high nitrate content of the surface water. This proves that the surface water has been denitrified while passing the sediments. This denitrification may be caused by sulphur containing compounds, such as pyrite, or by organic compounds (Van Bennekom, 1991). Denitrification by pyrite is characterized by the formation of ironhydroxides, sulphate, free nitrogen and hydrogen ions. The hydrogen ions react either with chalk (shells) to form calcium and bicarbonate or with bicarbonate forming carbon dioxide. When denitrification is caused by organic compounds, the nitrate is replaced by bicarbonate and no acidification occurs. The denitrification here can be ascribed to organic compounds. The bicarbonate level in the groundwater shows the same trend as in the surface water, but with higher concentrations in the groundwater. The acidity of the groundwater remains relatively stable during the whole test period and the sulfate content of the groundwater pumped from well PP2 is in the order of the concentration of the surface water. The iron content of the groundwater is not affected by this process of denitrification and is around 1 and 1,5 mg/l. If iron hydroxides are formed they are trapped in the sediment.

The ammonia content is high, averaging 8,84 mg/l. The total phosphorus content varies between 1,24 and 2,88 mg/l, with an average of 2,1 mg/l. The fresh groundwater contains 0 to 1,23 colonies total coliforms/100 ml with an average of 0,69 colonies/100 ml. Although the counts are generally smaller than in the surface water, the water is to be considered as bacteriolically contaminated. Despite the fact that the temperature of the surface water did fluctuate substantially remaining for most of the time below 5°C, the water extracted from well PP2 has a constant temperature around 10°C.

Quality of the water extracted from the lower part of the aquifer (well PP1)

The water extracted from well PP1 was a salty and very hard water of the S6-$NaCl^+$ type with an initial chloride content of 17.434 mg/l. The salt content gradually diminished as the pumping went on, but the water was still salty and of the S6-$NaCl^-$ type. The final chloride content was 13.532 mg/l, which is 77,6 % of the initial content. Similar to the decrease of the electrical conductivity and the chloride content, a decrease of the sodium-, potassium-, calcium- and magnesium content is observed. The salt water is rich in iron and ammonia. The nitrite and nitrate content is low. The total phosphorus content increases as pumping goes on. The water extracted from well PP1 is bacteriologically safe with a constant temperature of about 11°C.

SIMULATION OF GROUNDWATER QUALITY EVOLUTION

A first attempt is made to simulate the groundwater quality evolution near a drainage canal by means of the adapted MOC model. This model of Konikow and Bredehoeft (1978) was adapted so that density differences are taken into account (Lebbe, 1981 and Lebbe, 1983). Fig. 6 shows the geometry and subsoil parameters of the cross-section. By means of a double pumping test the hydraulic conductivities of the groundwater reservoir have been determined (Lebbe et. al, 1995). Four different layers have been identified: a lower pervious layer (k^h=5.7 m/d), a middle less pervious layer (k^h=2.4 m/d), an upper pervious layer (k^h=5.4 m/d) and an upper semi-pervious layer (k^h=0.6 m/d). The ratio vertical versus horizontal conductivity is 0.4. According to the results of the modeling regression of the salt water lens on the shore of De Panne (Lebbe, 1996) the longitudinal and the transversal dispersivity have small values (α_L=0.061 m and α_T/α_L=0.25). The effective porosity n_e is 0.38. No storage changes are considered in the model.

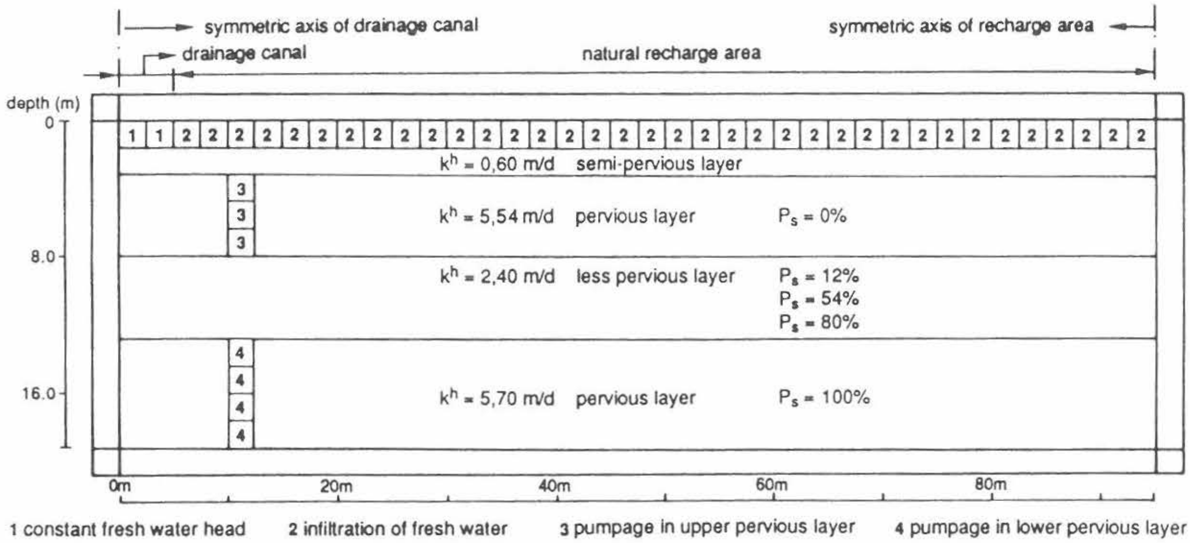

Figure 6. Geometry and subsoil parameters of the modeled cross-section

The modeled cross-section is subdivided in 12 layers and 38 columns. All columns have the same width (2.5 m) and all the layers the same thickness (1.6m). The lower boundary of the modeled cross-section coincides with the top of the 100 m thick Tertiary clay layer and is impervious in the model. The two vertical boundaries of the cross section are supposed to be impervious because they coincide with water divides. One vertical boundary is located under the middle of the drainage canal, the other vertical boundary in the middle of the recharge area. The upper boundary is a constant flux boundary under the natural recharge area and a constant head boundary (fresh water head is 1.9 mTAW).

The initial salt water distribution is first calculated by means of a first simulation. During this first simulation a constant infiltration of 0.069 m^3/d of pure fresh water per meter of drainage canal (280 mm/year) is assumed whereas the head in the drainage canal is constant. Because of this boundary condition a groundwater flow arises which deforms the transition zone which was here initially assumed to be horizontal (see salt water percentages in Fig. 6). After 20 years of simulation the transition zone reaches a new dynamic equilibrium and consequently, a new stable position. Under the drainage canal is an upconing of salt water and the transition zone has the largest thickness. Under the centre of the recharge area the transition zone is situated on the largest depth. In figure 7 the salt water distribution is represented along with the fresh water head configuration and the flow velocity field. This salt water distribution is now used as initial distribution in the second simulation.

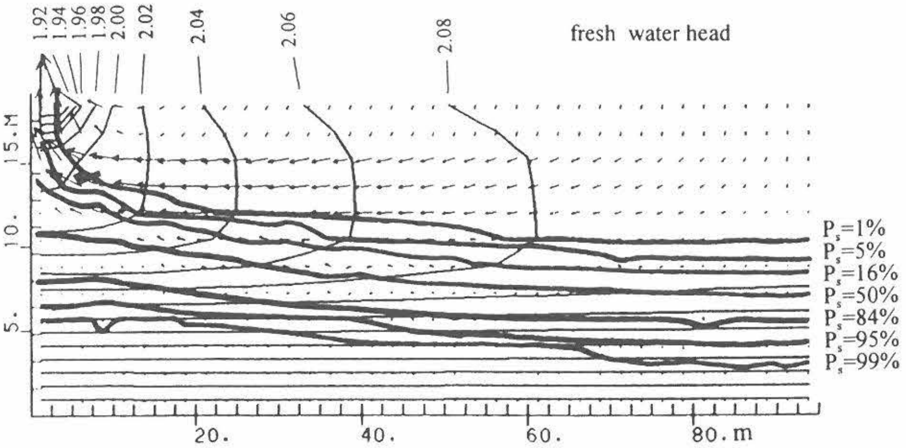

Figure 7. Salt water distribution along with the fresh water head configuration and flow velocity for the dynamic equilibrium reached after the simulation of 20 years of steady-state

During the second simulation the evolution of the groundwater quality is calculated for an intermitted pumping on the two pervious layers near the drainage canal during a period of four years. The finite-difference cells where water is pumped are indicated by the number 3 and 4 in figure 6. During the seven months with the largest infiltration rate, water is pumped with a constant discharge rate. During the first period of seven months, the total discharge rate in the upper pervious layer is equal to 0.8 m^3/d per meter of drainage canal, whereas the total discharge rate in the lower pervious layer is 2.0 m^3/d per meter of drainage canal. During the second period of seven months the total discharge rate in the upper pervious layer is 1.2 m^3/d per meter of drainage canal and 2,0 m^3/d per meter of drainage canal for the lower pervious layer. During the third and fourth period of seven months the discharge rates are the same in the upper and lower pervious layer : 1.5 m^3/d per meter of drainage canal. The lower boundary and the vertical boundary of the modeled cross-section are all impervious as in the first simulation. The drainage canal is held at the same constant level as in the first simulation, whereas the salt water percentage of the canal water is augmented from 0% in the first simulation to 1.6% in the second simulation. The object of this salt augmentation is meant as a tracer of the canal water in the modeling problem. In the recharge area the infiltration rate is in this second simulation time-dependent. For each month of the year the average infiltration rates are as estimated by Lebbe (1978). The ratio of the monthly average infiltration rates to the yearly average infiltration rate (280 mm/year) is given in table 1. During each month of pumping the total amount of infiltration is only a fraction of the total pumping amount. The largest part of the pumped water is provided by artificial recharge through the canal bottom.

Table 1. Ratio of the monthly average recharge rate versus the yearly average recharge rate.

April	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar
.1429	.0951	.0563	.0346	.1487	.4241	1.292	3.063	2.445	1.884	1.744	.6827

In figure 8 the calculated salt water percentage fluctuations are represented for the different pumped cells. One can see that the fluctuation of the salt water percentage is strongly level dependent in the lower pervious layer. Already after the first seven months of pumping the salt water percentage at the top of the lower pervious layer reaches the salt concentration of the drainage canal while the salt water percentage at the base only shows a slight decrease. During the first pumping period the salt water percentage in the pumped cells of the upper pervious layer is also level dependent. In this first pumping period the salt at the base of this layer is pumped away. The salt water content in the upper part of the upper pervious layer is initially lower than at its base. After somewhat less than two months of pumping the salt content in the upper pervious layer reaches its lowest value. After three and a half months of pumping the salt water percentage of the three pumped cells in the upper pervious layer reaches 1.6 %, the assumed salt percentage of the canal. After the first pumping period the salt content stays in these cells approximately at the same salt content of the canal. At the start of the second, third and fourth pumping period the salt content changes only slightly after which it reaches again the salt content of the canal.

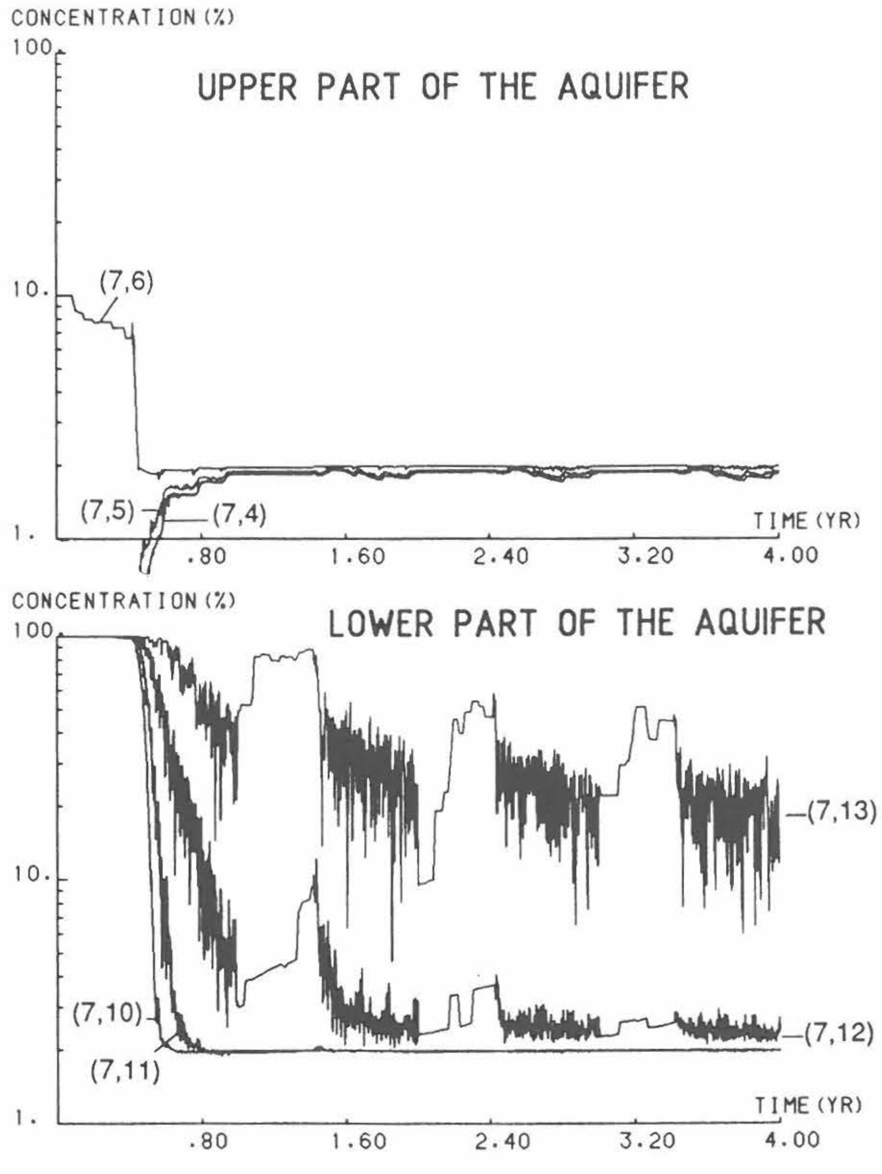

Figure 8. Salt water percentage fluctuation for the pumped cells

CONCLUSION

Due to the location of the test site at only 8 m distance from the Kromme Gracht, the quality of the water extracted from the upper part of the aquifer was influenced by the upconing of salt water near this drainage canal. Reduction of the volume extracted from the upper pumping well reduced the salt content in a significant way.

The water in the Kromme Gracht is fresh and hard. The mean chloride content was 236 mg/l, the mean sodium content 146 mg/l. However the water is nutrient-rich with mean levels for nitrate of 29,1 mg/l, ammonia of 2,72 mg/l, sulfate of 248 mg/l and total phosphorus of 0,84 mg/l. Although the nitrate content in the surface water is important, the content in the groundwater extracted from the upper part of the phreatic aquifer (PP2) is fairly low averaging 3,23 mg/l. This is caused by denitrification into the sediments by organic compounds. The salt content of the water extracted from the lower part of the aquifer gradually decreases, reaching 77,6 % of the initial content.

As a result from the evaluation of the quality of the waters, the extraction wells in the upper part of the aquifer will have to be located at some distance from the existing drainage canals. Each fresh water well must be coupled to a salt water well in the lower part of the aquifer. Varying the distance between the extraction wells and the intake canal will smoothen the effect of different qualities of intake water. In order to prevent an upward flow of brackish and salt water to the fresh water wells, the proportion of extraction between the lower and upper part of the aquifer must be initially in the order of 5 to 2. According to the prolongation of the extraction process, this ratio can decrease in time.

From the first attempt to simulate the groundwater quality evolution near the drainage canal by means of the adapted MOC model one can conclude that the pumped water from the upper pervious layer will reach the average salt content of the drainage canal over a relatively short period. In the lower pervious layer the fluctuation of the salt water depends from the depth in the aquifer. The upper half of the lower aquifer freshens already after one extraction period while the groundwater in the lower half freshens only slightly.

The chemical analysis of the waters during the long-term double pumping test, together with the simulation of the groundwater quality evolution, show that surface water in the Avekapelle creek ridge can be captured by extraction wells alongside an intake canal. The groundwater extracted from the upper part of the aquifer can be treated by membrane filtration processes. In this way more than 80 % of the salts will be reduced, what means that the produced water will be of good quality (according to the Dutch standards) to artificially recharge the dunes. The groundwater extracted from the lower part of the aquifer will freshen as pumping goes on.

The whole project fits in a broader perspective : integrated management of the available surface water in the polder area and sustainable management of the fresh water lens in the dune belt by artificial recharge of the phreatic aquifer.

REFERENCES

KONIKOW, L.F. and BREDEHOEFT, J.D. 1978. Computer model of two-dimensional solute transport and dispersion in groundwater. U.S.G.S. Techniques of Water-Resources Investigations, Book 7, Chapter C2, 90 p.

LEBBE, L., 1978. Hydrogeologie van het duingebied ten westen van De Panne. Geological Institute, Ghent University, Ph. D. dissertation, 164 p.

LEBBE, L., 1981. The subterranean flow of fresh and salt water underneath the western Belgian beach. Proceedings 7th Salt Water Intrusion Meeting, Uppsala. Sveriges geologiska undersökning, Rapporten och meddelanden, 27, pp. 193-218.

LEBBE, L., 1983. Mathematical model of the evolution of the fresh water lens under the dunes and beach with semi-diurnal tides. Proceedings 8th Salt Water Intrusion Meeting, Bari. Geologica Applicata e Idrogeologia, Volume 18, parte 2, pp. 211-216.

LEBBE, L., TARHOUNI, J., VAN HOUTTE, E. and DE BREUCK, W., 1995. Recharge of an artificial recharge test and a double pumping test as preliminary studies for optimizing water supply in the Western Belgian coastal plain. Hydrogeology Journal, volume 3, Number 3, 1995, pp. 53-63.

LEBBE, L., 1996. Regression modelling of fresh and salt water heads and borehole resistivities observed on the shore. Proceedings of ModelCARE '96, Golden, Colorado, IAHS Publication (in print).

STUYFZAND, P.J., 1986. A new hydrochemical classification of water types : principles and application to the dunes aquifer system of the Netherlands. Proceedings 9th Salt Water Intrusion Meeting, Delft. pp. 641-655.

VAN BENNEKOM, C.A., 1991. Beïnvloeding grondwaterwinning- en zuivering door uitspoeling van stikstofverbindingen. H_2O 1991, nr. 25, pp. 619-622.

VAN HOUTTE, E., VANLERBERGHE, F., LEBBE, L. and DE BREUCK, W., 1995. Optimization of the drinking-water production in the dune area of the western Flemish coastal plain. International Symposium on Environmental Impact Assessment in Water Management, Bruges, pp. 302-309.

ZEUWTS, L., 1991. Hydrogeologie en hydrochemie van de IJzervlakte tussen de Frans-Belgische grens en Avekapelle-Pervijze (Westelijke kustvlakte). Geological Institute, Ghent University, Ph. D. dissertation, 389 p.