Study of the feasibility of an aquifer storage and recovery system in a deep aquifer in Belgium

ALEXANDER VANDENBOHEDE[1]**, EMMANUEL VAN HOUTTE**[2] **&**
LUC LEBBE[1]

1 *Research Unit Groundwater Modelling, Department of Geology and Soil Science, Ghent University,*
Krijgslaan 281 (S8), B-9000 Gent, Belgium
alexander.vandenbohede@ugent.be

2 *Intercommunale Waterleidingsmaatschappij van Veurne-Ambacht (IWVA), Doornpannestraat 1, B-8670 Koksijde,*
Belgium

Abstract The feasibility of aquifer storage and recovery (ASR) was tested in a deep aquifer near Koksijde, Belgium. To achieve this, oxic drinking water was injected into a deep aquifer (the Tienen Formation) that contains anoxic brackish water. The hydraulic properties of the aquifer were determined using a step-drawdown test. Chemical processes caused by the injection of the water were studied by two push–pull tests. The step-drawdown test was interpreted by means of an inverse numerical model, resulting in a transmissivity of 3.38 m^2/d and a well loss coefficient of 0.00038 d^2/m^5. The push–pull tests identified mixing between the injection and pristine waters, and cation exchange, as the major processes determining the quality of the recovered water. Mobilization of DOC, aerobic respiration, denitrification and mobilization of phosphate were also observed.

Key words aquifer storage and recovery; deep aquifer; Belgium; step-drawdown test; push–pull test; cation exchange; mixing of waters

Etude de faisabilité d'un système de remplissage et de rétablissement d'aquifère dans un aquifère profond en Belgique

Résumé La faisabilité du remplissage et du rétablissement d'un aquifère a été testée pour un aquifère profond près de Koksijde en Belgique. Dans ce but, de l'eau potable oxique a été injectée dans un aquifère profond (la Formation Tienen) qui contenait de l'eau saumâtre anoxique. Les propriétés hydrauliques de l'aquifère ont été déterminées grâce à un pompage d'essai par paliers. Les processus chimiques engendrés par l'injection de l'eau ont été étudiés grâce à deux essais "push–pull". Le pompage d'essai par paliers a été interprété à l'aide d'un modèle numérique inverse, conduisant à une transmissivité de 3.38 m^2/d et à un coefficient de perte du puits de 0.00038 d^2/m^5. Les essais "push–pull" ont permis d'identifier le mélange entre les eaux injectées et originelles et l'échange cationique comme étant les processus majeurs déterminant la qualité de l'eau après rétablissement. La mobilisation du COD, la respiration aérobie, la dénitrification et la mobilisation des phosphates ont également été observées.

Mots clefs rétablissement et remplissage d'aquifère; aquifère profond; Belgique; pompage d'essai par paliers; essai "push–pull"; échange cationique; mélange d'eaux

INTRODUCTION

An aquifer storage and recovery (ASR) system consists of cyclic injection, storage and recovery of water in an aquifer (Pyne, 2005). Water, such as drinking water, can thereby be stored in a permeable zone and be recovered during times of peak demand or emergency need. The ASR system was pioneered in the 1960s in the USA, more specifically in the coastal areas of Florida and California (Pyne, 1994), and has seen many applications since. In 2005, 72 ASR systems were operational in the USA and approximately 100 systems were under study (Pyne, 2005). The ASR system has applications worldwide. Numerous examples are described in the literature, such as the implementation of ASR in the Atlantic Coastal Plain (Brown & Silvey, 1977; Castro, 1995; Johnson & Pyne, 1995), or in Charleston, South Carolina (Campbell *et al*., 1997; Mirecki *et al*., 1998).

Before an ASR system can be put into operation, the aquifer properties must be determined by the appropriate tests. Two issues are of concern: the hydraulic properties of the aquifer, and water quality changes of the stored water. The hydraulic properties determine the amount of water which can be stored and recovered. Water quality changes are determined by the mixing of pristine and injected waters and by chemical reactions. For instance, Lowry & Anderson (2006) discussed the

Open for discussion until 1 February 2009

factors determining the mixing zone geometry, whereas other authors have discussed chemical reactions in the context of ASR or injection experiments: Sniegocki (1963), Warner & Doty (1967) and Ragone & Vecchioli (1975) discussed the importance of possible dissolution of carbonate and oxyhydroxide minerals; and the dissolution of calcite, dolomite and amorphous silica was reported by Mirecki *et al*. (1998). Another important reaction is cation exchange, as illustrated by the experiment of Valocchi *et al*. (1981). Stuyfzand (1998) gives an important overview of quality changes of injection water based on 11 deep well recharge experiments in The Netherlands. Based on the number of pore flushes (PF) of the sediments, different phases were identified: displacement (0.5–1.5 PFs), cation exchange and sorption (1.5–7 PFs), redox reactions at maximum (7–20 PFs), nitrate breaking through (20–60 PFs), oxygen breaking through (60–400 PFs), pyrite consumed (400–4000 PFs), and pyrite/calcite consumed (>4000 PFs).

In this paper, ASR feasibility is investigated of a deep aquifer (the Tienen Formation) near Koksijde (Belgium). Although the Tienen Formation is an important aquifer, only limited data are available in literature. The hydraulic properties of the aquifer are determined here by the interpretation of a step-drawdown test, and chemical changes in the injection water are studied by the performance of two push–pull tests, one of which is discussed in detail. First, the geology of the site, an overview of the available literature on the hydrogeology of the Tienen Formation, and the proposed application of the ASR system are briefly discussed.

SITE DESCRIPTION

Figure 1 shows the location of the test site near Koksijde, situated in the dunes of the western Belgian coastal plain. Figure 1 also shows a stratigraphic column based on deep drilling performed

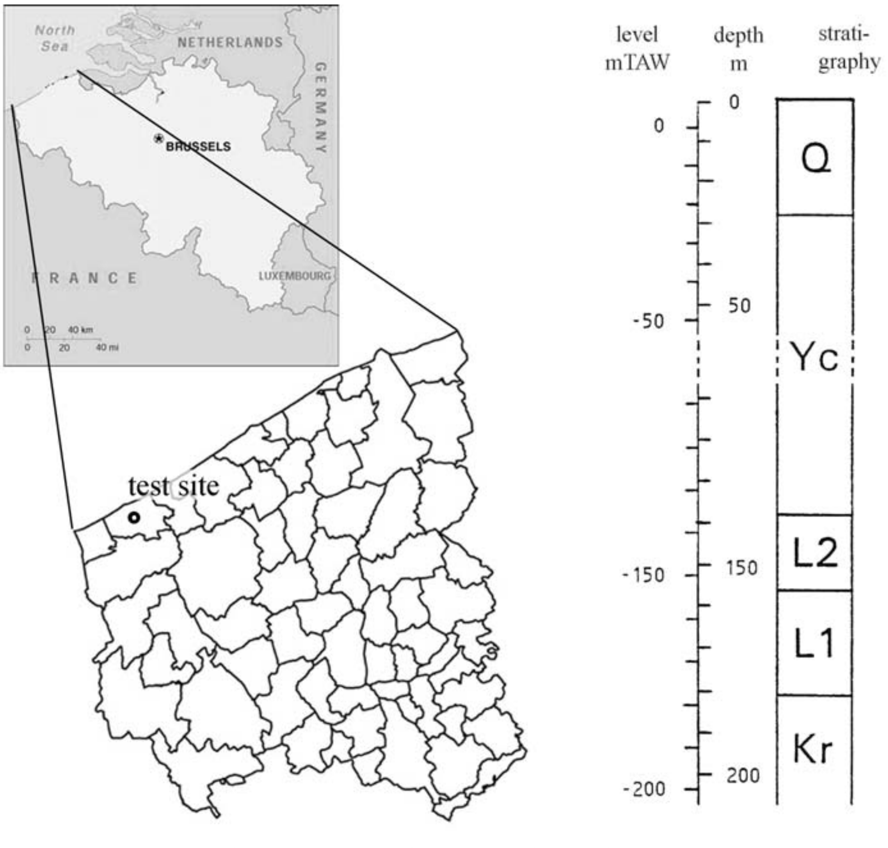

Fig. 1 Location of the test site and stratigraphic column, after Laga & Vandenberghe (1990). Q: Quaternary, Yc: Kortrijk Formation, L2 Tienen Formation, L1: Hannut Formation, Kr: Cretaceaous.

by the Belgian Geological Survey (Laga & Vandenberghe, 1990) a few hundred metres from the ASR test site. The Quaternary phreatic dune aquifer (Q) consists of medium to coarse-medium sands and is of major importance for the extraction of drinking water. It contains a freshwater lens which is exploited by the Intermunicipal Water Company of the Veurne region (IWVA). Below the Quaternary aquifer is an approx. 100-m-thick clay layer of early Eocene age belonging to the Kortrijk Formation (Yc). This acts as a semi-permeable layer of very low hydraulic conductivity. Below this are sediments of the Landen Group (L1 and L2), which are of late Paleocene age and are subdivided in two parts: the Tienen Formation (Knokke Member) (L2 on Fig. 1), consists of silty fine sands with shell fragments, glauconite and organic material and, apart from the shell fragments, contains no chalk; and the Hannut Formation (L1), which is glauconite bearing silt to silty clay. The Tienen Formation is a permeable layer, whereas the Hannut Formation is semi-permeable. Cretaceous deposits (Kr) occur below the Tienen Formation, which are also of very low permeability. The water quality of the Tienen Formation at the field site is brackish with a total dissolved solids (TDS) content of 2500 mg/L (Mertooetomo, 1995). The TDS of the pore water increases towards the north and decreases towards the south and southeast.

In addition to the phreatic dune aquifer, the Tienen Formation is an important aquifer for the exploitation of groundwater. Historically, the Tienen Formation was pumped heavily to the point that it became overexploited, resulting in a large depression cone. Nowadays, drawdowns of 60 m and more are measured in the southeastern part of West Flanders and these are still increasing. It is therefore the aim of the Flemish Community to significantly reduce the extraction. However, the Tienen Formation still has important potential for water management applications, one such example being ASR. The aim of the water company IWVA is that the ASR system will have an extra amount of water—stored in the Tienen Formation during the winter and parts of autumn and spring—available for recovery during times of peak demand, such as July–August and certain holiday periods. Daily water demand at these times can be twice as great due to the large number of tourists in the coastal area.

The water used for injection would be drinking water which is produced from the fresh dune water. An additional benefit of the ASR system is that the extraction rates in the phreatic dune aquifer will be more constant, which is of importance for groundwater-dependent dune flora. The IWVA already has three screened wells in the Tienen Formation. These were drilled for past studies and can now be recovered as ASR wells.

Relatively few data are available on the Tienen Formation. Therefore, hydraulic properties were investigated with a step-drawdown test, and the hydrochemistry was studied by means of two push–pull tests, one of which is described below in detail. These are single-well tests which were performed in a well screened over the entire thickness of the Tienen Formation (17.8 m). The well diameter is 202 mm (casing and screen) and has gravel packing (calibrated sand, 0.7–1.25 mm) surrounding the well screen. A cement grout is present above the screen.

THE STEP-DRAWDOWN TEST

Well loss

During a step-drawdown test, water is extracted from a pumping well such that the discharge rate is increased in steps over time. Drawdown is measured in the pumping well and its interpretation makes it possible to derive transmissivity of the layer and to quantify well loss. The drawdown in the pumping well, s_p (m), consists of a combination of drawdown in the aquifer, s_a (m), and an extra component in the pumping well. This extra drawdown originates from the fact that flow between the aquifer and the pumping well encounters resistance due to the construction of the well and possible clogging of the screen; it is referred to as well loss. Total drawdown in the well can be written as:

$$s_p = s_a + CQ^n \tag{1}$$

where the well loss CQ^n is a function of the well loss coefficient (C), and the discharge rate (Q), and the exponent n is assumed to be 2 in most cases (Jacob, 1947). Well loss is an important property of a well, because it is a measure of its efficiency: less water can be extracted or injected in a well with large well loss.

Calculation of discharge

A step-drawdown test was performed in one of the three screened wells in the Tienen Formation using four steps of 1.5 h. The discharge rate at the end of successive steps was: 0.90, 1.74, 3.20 and 4.12 m^3/h. A detailed evolution of the discharge rate (Qt) is given in Fig. 2. The discharge rate originating from the well storage (Qp) and the discharge rate originating from the Tienen Formation (Ql) are calculated using detailed drawdown measurements in the well, the total discharge rate and the dimensions of the well. It is necessary to make a distinction between Qp and Ql: the discharge rate of water coming from the pumped layer is important in the interpretation of the numerical model. As seen in Fig. 2, during the early part of each step, a relatively large amount of water originates from the well storage (Qp). Drawdown in the pumping well was measured at 15 s intervals using a pressure transducer. A selection of these drawdown observations is shown in Fig. 3.

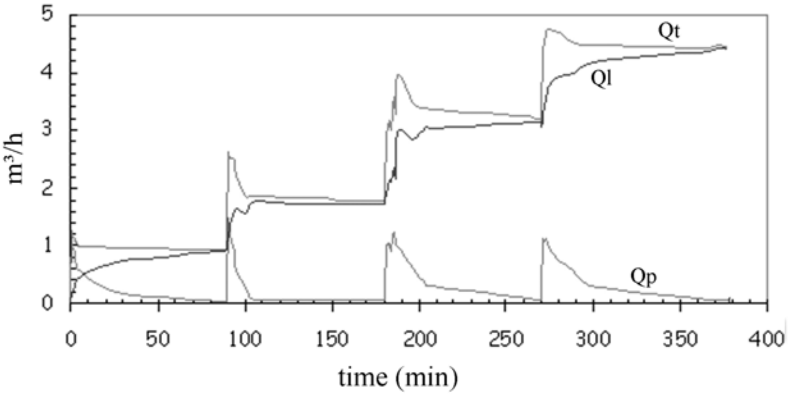

Fig. 2 Total discharge rate (Qt), discharge rate originating from the well storage (Qp) and discharge rate from the Tienen Formation (Ql) during the step-drawdown test *vs* time.

Interpretation of the test

An inverse axial–symmetric numerical model (Lebbe, 1999) is used for the interpretation of the step-drawdown test. In the model, the groundwater reservoir can be subdivided into a large number of layers. Each layer has a large lateral extension, is considered homogeneous and has a value for the horizontal and vertical hydraulic conductivity and the specific elastic storage. The top layer is bounded by the water table, or an impermeable boundary, and the lower layer by an impermeable boundary. The inner boundary is formed by the pumping well and is either a constant flux boundary (directly pumped layers) or an impermeable boundary (indirectly pumped layers). The layers are subdivided into a number of coaxial rings. Drawdown is calculated in nodal circles at different time steps. The nodal circles are situated at half heights of the rings, and their radii are equal to the geometric mean of the inner and outer radii of the rings. These inner and outer radii form a logarithmic increasing series with a factor A ($10^{0.1}$ in most cases). Time steps also form a logarithmic increasing series with this factor. The inverse model is a combination of a forward model, sensitivity analyses and a nonlinear regression (Gauss-Newton) algorithm. First, drawdown is calculated for locations and at times for which observations are available and residuals—the differences between the logarithmic values of the observed and calculated drawdown—are then derived from the observed and calculated drawdown values. The sum of squared residuals is the objective function to be minimized.

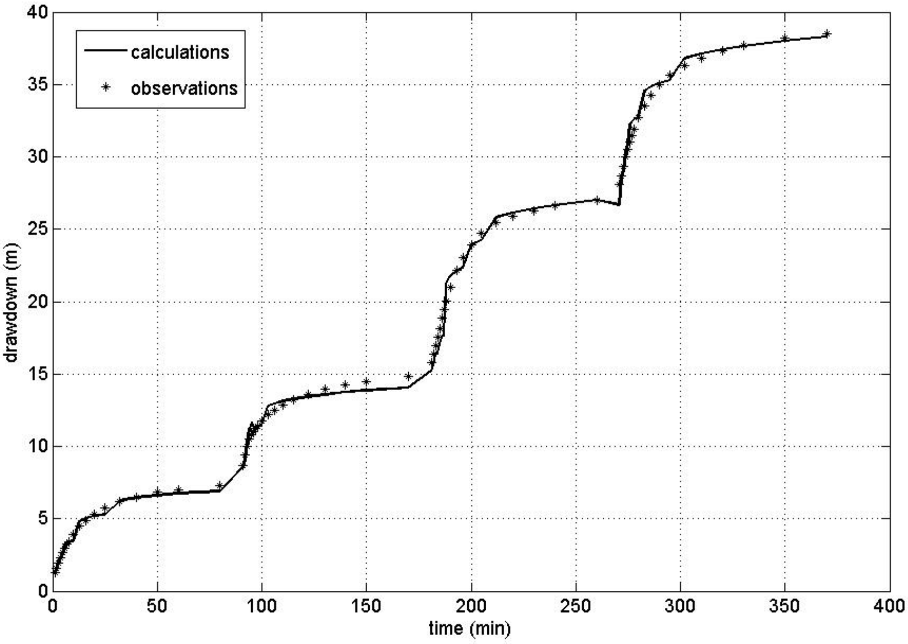

Fig. 3 Comparison between observed drawdown and the drawdown calculated with the optimized hydraulic parameters.

Next the sensitivities are calculated; these are the changes in calculated drawdown when one hydraulic parameter or one parameter group is changed. The residuals and sensitivity analyses are used to calculate adjustment factors for the most sensitive parameters, after which these parameters are adjusted to obtain better estimates for the hydraulic parameters. This algorithm is repeated until adjustment factors become very small and the objective function does not reduce further. The result is optimum values of the hydraulic parameters and their joint confidence region.

The Tienen Formation is bounded above and below by two thick semi-permeable layers with a very low hydraulic conductivity. Therefore, the aquifer was considered a confined aquifer for the duration of the test and one layer was used in the inverse numerical model. The transmissivity of the Tienen Formation and the *C* value of the well loss were to be determined. The exponent *n* of the well loss power function was fixed at 2 and specific elastic storage considered to be 5×10^{-5} m^{-1}. Table 1 shows the optimum values of the derived parameters, together with the marginal and conditional standard deviation. Table 2 shows the condition indexes and the matrix of the marginal variance-decomposition proportions.

This collinear diagnostic shows that both parameters were derived reliably. The transmissivity of the Tienen Formation is 3.38 m^2/d, which corresponds to a mean horizontal hydraulic

Table 1 Optimal values derived for the transmissivity, *T*, and the *C* value of the well loss along with the marginal (sm) and conditional standard (sc) deviation.

	Optimal value	sm	sc
T	3.38 m^2/d	0.0055	0.0026
C value	0.00038 d^2/m^{-5}	0.0882	0.0418

Table 2 The condition indexes η and the matrix of the marginal variance-decomposition proportions

Parameter η	1.0	34.2
T	0.2229	0.7771
C value	0.0000	1.0000

conductivity of 0.19 m/d. This parameter is derived with the greatest accuracy. The *C* value of the well loss is 0.00038 d^2/m^5. The marginal variance of this parameter is completely determined by the highest condition index of 34.2 and is less accurately determined. This is also partly due to the fact that the well loss is small. For instance, for the last step of the test, the drawdown due to well loss is only 3.71 m, whereas the total drawdown is 38.5 m. The exponent *n* and the specific elastic storage cannot be determined, because including one or both of these parameters in the parameter identification process leads to a very high condition number.

THE PUSH–PULL TEST

Performance

A push–pull test consists of two phases. First, water, marked with one or more conservative and reactive tracers, is injected into an aquifer (push phase). Thereafter, the well is pumped (pull phase) and water samples are taken from the recovered water. Two push–pull tests were performed in the Tienen Formation: the first was a short exploratory test, whereas the second was a longer test. The results of the latter test are discussed here. During the test, drinking water was injected into the brackish Tienen Formation water over a period of 21.15 days at a rate of 1.86 m^3/h. Samples of the injection water were taken once or twice a week to track its quality as a function of time. Then the well was pumped for 14.6 days at a discharge rate of 4.48 m^3/h. Daily water samples of the recovered water were taken. Redox potential, pH, temperature, conductivity and bicarbonate concentration were measured in the field. Major cation and anion concentrations, total nitrogen and dissolved organic carbon (DOC) were determined in the laboratory.

Figure 4 shows the water samples plotted on a Piper diagram together with the injection and pristine Tienen Formation water. For the samples taken during the pull phase, the time after the start of the test is given, so that these samples can be traced on the other figures. According to the

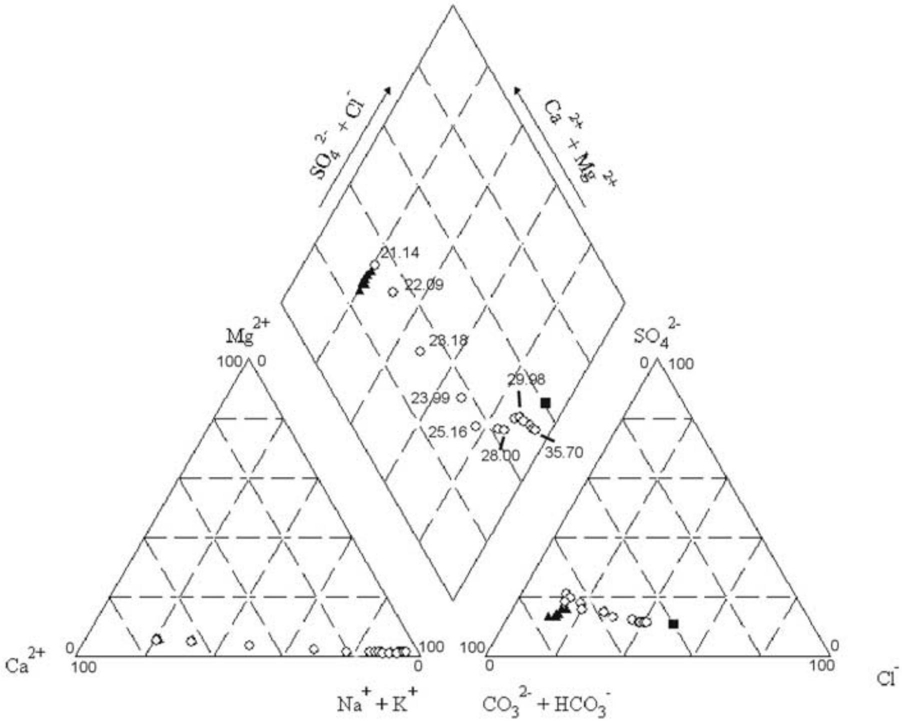

Fig. 4 Pristine Tienen Formation water (■), injection water (▲) and water samples of the recovered water (○) plotted on a Piper diagram. For the water samples of the recovered water, the time (days) after the start of the push–pull test is indicated.

classification of Stuyfzand (1993), the Tienen Formation water is a brackish B*NaMix+ water type. It contains relatively high concentrations of sodium (32.8 mmol/L), potassium (0.36 mmol/L), chloride (12.8 mmol/L), sulphate (1.82 mmol/L) and bicarbonate (14.5 mmol/L). Electrical conductivity is about 2500 μS/cm and pH is 8.3. It has low concentrations of iron, manganese, nitrogen and phosphorous. The brackish Tienen Formation water is the result of the displacement of older salt water by fresh infiltration water and the fraction of seawater is 0.025. The water quality is determined by cation exchange. Due to the flushing of the salt water by freshwater containing calcium and bicarbonate, sodium on the exchanger is replaced by calcium, forming the NaMix water type. The injection water is fresh $CaHCO_3$ water with a base exchange parameter of zero. Conductivity is approximately 280 μS/cm and pH is 7.8. The water which is injected into the anoxic Tienen Formation is oxic (about 0.034 mmol/L O_2).

Water analyses are plotted in Fig. 5, which shows the evolution of electrical conductivity (EC), chloride concentration, pH, Eh, calcium, magnesium, potassium and sodium as functions of

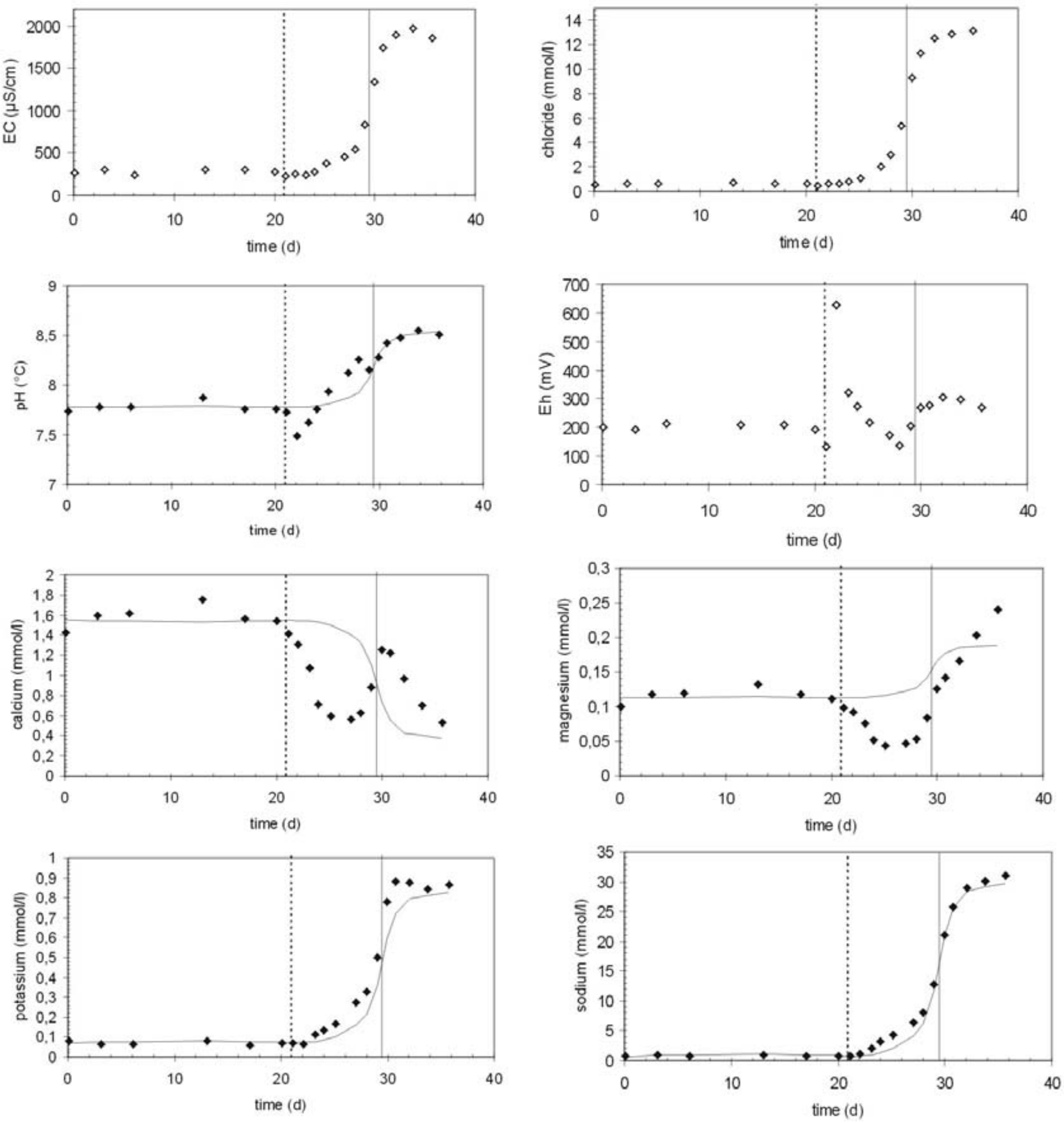

Fig. 5 Evolution of electrical conductivity (EC), pH, Eh and concentrations of chloride, calcium, magnesium, sodium and potassium during the push–pull test. Time is the duration since the start of the push–pull test. The dotted line indicates the start of the pull phase, the solid line the moment when a volume equal to the injection volume has been extracted.

time, and Fig. 6, which shows the evolution of bicarbonate, dissolved oxygen, sulphate, phosphate, nitrate, ammonia, total nitrogen and DOC as functions of time. The time origin is the start of the push–pull test, i.e. the start of the injection or push phase. On the figures, the moment of start of the pull phase, and the moment when an equal amount of injected water is recovered, are also indicated. Thus, values for the different parameters on Figs 5 and 6 before the start of the pull phase are of the injection water, and those after the start of the pull phase are of the recovered water. Water which is extracted first during the pull phase is water which was injected last during the push phase and thus has the shortest residence time. The residence time of the injection water varies between 1 h (the time needed to change between the push and pull phases during the test) and 29.5 days. For most of the parameters in Figs 5 and 6, a conservative curve is added. This gives the evolution of the parameter as if it were determined only by conservative mixing. These curves were calculated by rescaling the chloride curve. Comparison of this line with the evolution of certain parameters makes it possible to see immediately if it was determined by a process other than mixing.

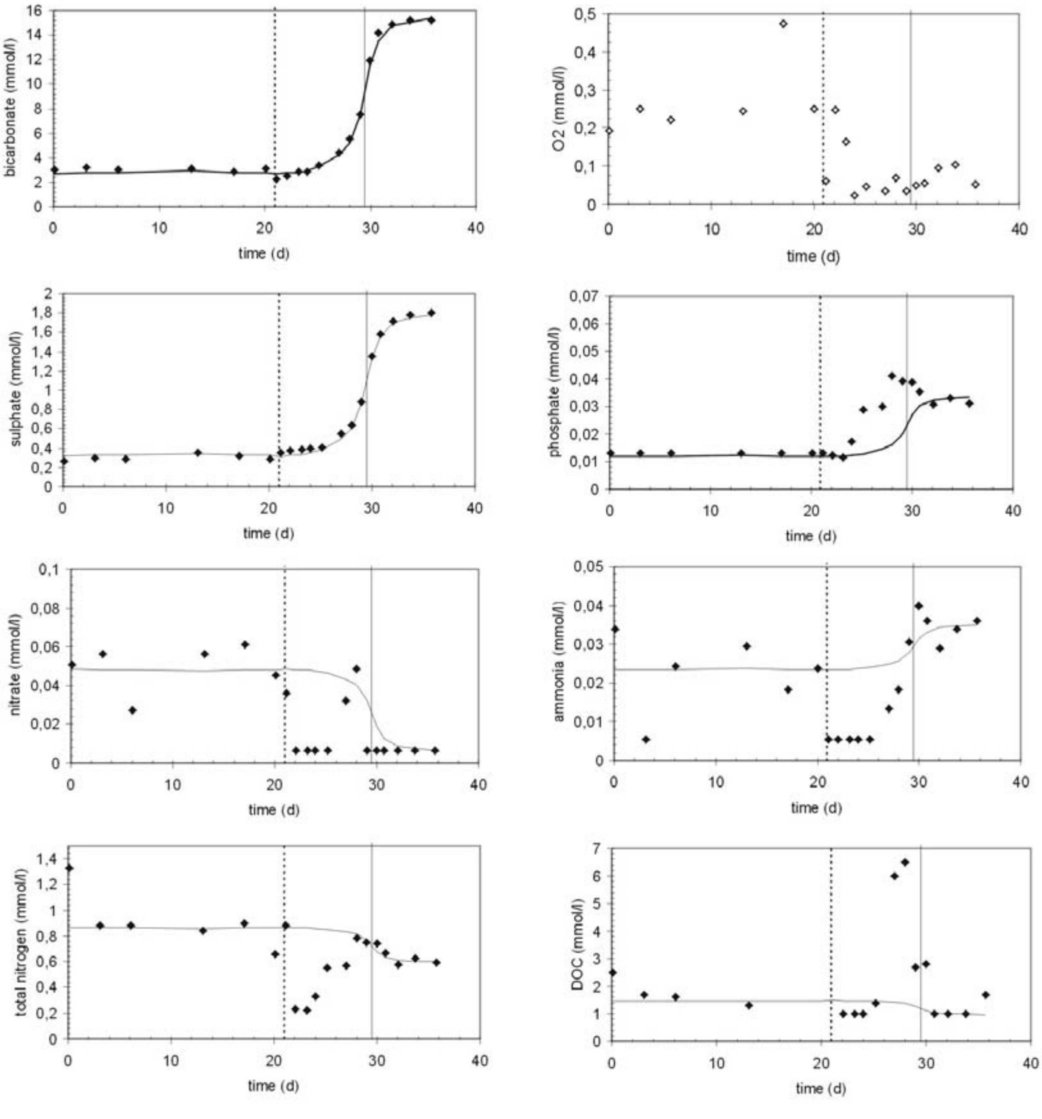

Fig. 6 Evolution of concentrations of bicarbonate dissolved oxygen, sulphate, phosphate, nitrate, ammonia, total nitrogen and DOC during the push–pull test. Time is the time since the start of the push–pull test. The dotted line indicates the start of the pull phase, the solid line the moment when a volume equal to the injection volume is extracted.

Mixing and cation exchange

The chloride concentration in the injection water (0.6 mmol/L) was much lower than in the pristine water (12.8 mmol/L). Chloride here is a conservative or non-reactive tracer. It is therefore applied to study the development of the mixing zone and for comparison of the evolution of the other parameters. In the first three days of the pull phase, chloride concentration in the extracted water was the same as that measured in the injected water; then, it increased to the value observed in the native Tienen Formation water. The transition between injected and Tienen Formation water was not instantaneous, indicating that there was an important transition or mixing zone between the two waters. This mixing zone is relatively large: of the 937.4 m^3 of water which was injected, only 34% was not affected by mixing. The same conclusion can be reached from the EC measurements.

The pH increased as a function of the residence time of the injected water, but deviated from the conservative mixing line. With increasing residence time, pH was larger than expected from mixing alone. This is the case up to the middle of the mixing zone. Also, the Eh measurements deviated from the conservative mixing line. First, the recovered water had a relatively high Eh, after which the Eh decreased.

The calcium and magnesium concentrations of the recovered water decreased as a function of time. After about 28 days of testing, concentrations were approximately the same as in the pristine water. Calcium shows a more complex evolution than magnesium, since it had a peak in the middle part of the mixing zone before decreasing to the concentration of the pristine water. Comparison with the conservative mixing line shows that calcium and magnesium were removed from the injection water in the first 10 days of the pull phase, and that calcium was added to the injection water in the centre of the mixing zone. Simultaneously with the decrease in calcium and magnesium, there was an increase in sodium and potassium. These evolutions can all be explained by cation exchange—the result of the displacement of one type of pore water with another. Concentrations in the recovered water are determined by two displacements in which cation exchange has occurred. First, there is the displacement of brackish water by freshwater during the push phase and, secondly, there is the displacement of the fresh injected water by the brackish pristine water during the pull phase.

During the push phase, the displacement of brackish water by freshwater causes sodium and potassium on the exchanger to be replaced by calcium and magnesium. The concentration of the latter two therefore decreases, while that of the former two increases. Analysis of injection experiments in The Netherlands have shown that it takes between 1.5 and 7 pore flushes before concentrations on the exchanger are in equilibrium with those in the injection water (Stuyfzand, 1998). The number of pore flushes is a function of cation exchange capacity and the concentration of the cations in the displaced and displacement water (Appelo, 1994). Three zones developed as a function of distance from the ASR well at the end of the push phase. Close to the well, where the sediments had been flushed more than 1.5–7 times, the cation concentration on the exchanger was in equilibrium with the injection water and concentrations in the water did not differ significantly from the injection water. More distally, where the sediments had been flushed between 1.5 and 7 times, cation exchange took place. The most distal zone is the pristine formation water. The reverse happens when water is extracted, due to the displacement of freshwater by the pristine brackish water. Therefore, calcium on the exchanger is desorbed. This leads to an increase in calcium concentrations and explains the temporal increase in calcium concentration in the middle part of the mixing zone. At the same time, there is also a small increase in potassium content.

On the Piper diagram (Fig. 4), the water samples plot on an s-shaped line connecting the injection and pristine waters, with two main evolutions between the two. Some water samples plot on a line parallel with the calcium-magnesium/sodium-potassium axis (until 28 h in the test), whereas others plot in the vicinity of the pristine water (from 28 h in the test). Water which was injected last during the push phase and recovered first during the pull phase is found closest to the injection water. Water with a longer residence time in the Tienen Formation plots further from the injection water and closer to the pristine Tienen Formation water. Between samples with a long residence time and those with a shorter residence time (or from 28 to 21.14 h in the test), one can see an evolution on the Piper diagram parallel to the calcium-magnesium/sodium-potassium axis. The calcium-magnesium percentage increased and the sodium-potassium percentage decreased due to the exchange. Samples with a large residence time are determined by mixing (increasing chloride concentration with time in the test) and cation exchange (replacement of freshwater by brackish water).

The number of pore flushes needed to equilibrate the concentration of the injection water with the exchanger is equal to Q_1T_1/Q_2t, where Q_1 and Q_2 are the discharge rates (m^3/d) during the pull and the push phases, respectively, T_1 is the duration (d) of the push phase and t is the time (d) between start of the pull phase and when the low calcium and magnesium concentrations are observed. This results in a number of pore flushes which is 4. This means that cation exchange takes place between 1 and 4 pore flushes and this is in good agreement with the above-mentioned results from Dutch experiments (Stuyfzand, 1998).

Other reactions

Oxygen and nitrate measurements illustrate aerobic respiration and denitrification. The injection water contains about 8 mg/L, or 0.25 mmol/L oxygen, whereas the pristine water is anoxic. The first water samples, extracted during the pull phase, contain small concentrations of oxygen until two days into the pull phase. This oxygen is consumed by the oxidation of organic matter in the Tienen Formation. The injection water is depleted of its oxygen, which is used as a terminal electron acceptor. This occurs in a zone in the immediate surroundings of the ASR well. Nitrate takes over the role of electron acceptor when oxygen is absent or at very low concentration. Nitrate concentrations in the recovered water are, therefore, very small, except during one period which will be explained later. Denitrification leads to an increase in pH and increase in the bicarbonate concentration. The latter is not observed exclusively. However, there are only small concentrations of nitrate (0.05 mmol/L) in the injection water, meaning that there will be only a small increase in bicarbonate concentration due to denitrification.

Sulphate concentrations are close to the conservative line, indicating that no, or negligibly small, amounts of sulphate react. This means that pyrite oxidation, which proved to be important in the Dutch injection experiments (Stuyfzand, 1998; de Ruiter & Stuyfzand, 1998), is not important here. Pyrite oxidation would also lead to a decrease in pH, which is not the case here. Phosphate concentrations are larger than the conservative curve and the difference increases with residence time. Notice that large phosphate concentrations coincide with small calcium concentrations. This is due to simultaneous desorption of the phosphate. Also, oxidation of organic material can lead to increased phosphate concentrations. A peak in ammonia concentrations coincides with the peak in calcium and also results from the displacement of freshwater by brackish water during the pull phase.

The DOC concentration in the injected and pristine waters is small, about 1.5 mg/L. However, DOC concentrations increased to 6.5 mg/L for a short period in the pull phase. The water had a more brownish colour, whereas otherwise it was clear. Related to the increase in DOC is an increase in nitrate concentration. Large concentrations of DOC coincide with small concentrations of calcium. Because of the small calcium concentrations, the calcium–DOC complex is mobilized, leading to an increase in the DOC. As can be seen in Figs 5 and 6, the peak in DOC occurs in the distal part of the zone of cation exchange, more specifically, between 1 and 1.5 pore flushes.

DISCUSSION AND CONCLUSIONS

Using a step-drawdown test and push–pull tests, basic data were obtained to study the possibility for an ASR system using the Tienen Formation in the western Belgian coastal plain. The step-drawdown test resulted in a transmissivity of 3.38 m^3/d. This means that maximum discharge rates are of the order of 7–8 m^3/h leading to drawdowns of 70–80 m in the ASR well. On the IWVA site, three screened wells in the Tienen Formation are present from past studies, meaning that a

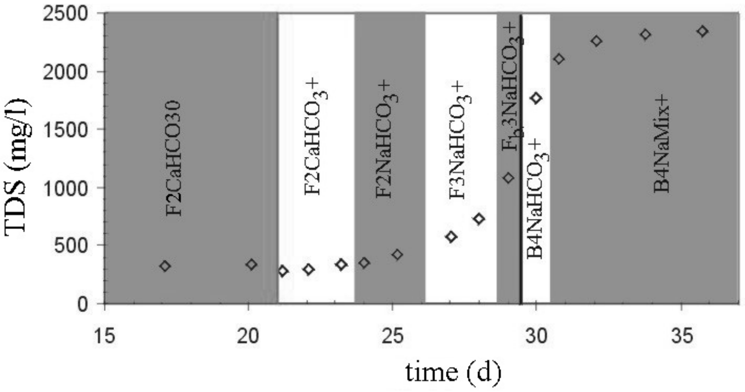

Fig. 7 Evolution of the total dissolved solids (TDS, mg/L) during the push–pull test with an indication of the water types according to Stuyfzand (1993). Time is the duration since the start of the push–pull test. The water types reflect both mixing and cation exchange.

maximum of 576 m^3/d can be recovered from the three ASR wells. Although this is a relatively small amount of water, it would serve the purpose of the ASR system, to provide an extra amount of water during periods of peak demand.

The quality of the stored water is mainly determined by mixing and cation exchange. Figure 7 shows a summary of the water types which succeed each other during the pull phase, according to Stuyfzand (1993). Mixing results in a transition zone between the fresh injection water and brackish pristine water. Water types evolve from fresh (F) to brackish (B). Alkalinity also increases from moderate (2) to high (4). The width of this mixing zone is important for the further use of the recovered water (Lowry & Anderson, 2006), since the TDS content can be a constraint. When, for instance, the same amount of water as was injected is extracted, a TDS content of about 1400 mg/L is expected. Although this is relatively high, in the case of the application described here, this is less of a problem as the water will be mixed with freshwater from the Quaternary aquifer (in a ratio of less than 1:9) and the TDS of the resulting water will thus increase only marginally.

Cation exchange was identified by comparing the observed calcium, magnesium, sodium and potassium concentrations with a conservative curve. Evolution of water types in Fig. 7 illustrates cation exchange as one of the most important reactions determining water quality. Pristine water is a NaMix water type with a positive base exchange index. This water is the result of a historic replacement of seawater by fresh recharge water. The injection water is a $CaHCO_3$ water with a neutral base exchange index. Intermediate water types are $NaHCO_3$ waters with a positive base exchange index, thus reflecting surplus marine cations, or the displacement of salt (or brackish) water by freshwater. However, the observations here are somewhat more complex, because two stages of cation exchange must be considered. There is a displacement of brackish water by freshwater during the push phase, and a displacement of freshwater by brackish water during the pull phase. Due to the former process, calcium and magnesium are exchanged for sodium and potassium. The latter process results in an important temporary increase in calcium concentration in the transition zone during the pull phase. It was further determined that it takes about four pore flushes before complete equilibrium of calcium, magnesium, potassium and sodium concentrations is reached.

Other important reactions are the mobilization of phosphate, aerobic respiration and denitrification. Cation exchange is also responsible for some significant secondary reactions. Most important here is the mobilization of DOC due to the small calcium concentrations. The DOC concentrations increased to about 6.5 mg/L and gave the water a slightly brownish colour. It was determined that the increased DOC levels occurred before 1.5 pore flushes. These higher DOC concentrations are less of a problem when the recovered water is mixed with the Quaternary dune water. A way to avoid extracting in this zone is to inject an extra amount of water which will not be recovered during the first ASR cycle. Therefore this zone with increased DOC concentrations is never recovered and stays as a buffer zone between the injection and pristine waters.

An important aspect of an ASR system is the natural groundwater flow. This influences the geometry of the volume of injected water and the recovery efficiency. The hydraulic gradient at the site is of the order of 6.8×10^{-4}, which results in an effective flow velocity of 3.3×10^{-4} m/d, or a groundwater movement of 12 cm per year (Lebbe *et al*., 1987). This means that the effect of natural groundwater flow is minimal.

Finally, clogging of the ASR well is considered. Possible causes for clogging are entrapment of gases, blocking of pore spaces by suspended solids, biological growth, particle rearrangement, swelling of clays or clogging due to chemical reactions (Pyne, 2005). The injection water is of high quality and the concentration of suspended solids is minimal. Because the Tienen Formation contains an important silt and clay fraction, swelling of clay minerals by the injection water is a possibility. Transmissivity of the aquifer would then decrease and less water could be injected. The sodium adsorption ratio (SAR) is a measure to quantify this. The SAR of the injection water in the present case is 0.65, which is well below the critical value of 10. Despite this, it is important to identify a possible clogging risk in time. This can be done by monitoring drawdowns during the injection phase of an ASR cycle. The step-drawdown test provides data to determine whether drawdown values for a certain discharge rate are becoming lower with each cycle. If this is the case, possible clogging problems are developing. Then a new step-drawdown test can be performed to compare the well loss with that determined before the start of the ASR system.

From these first tests, it is concluded that an ASR system using the Tienen Formation is a possibility. However, further testing, for instance a fully monitored first ASR cycle, is advisable to achieve an operational system.

Acknowledgements This research was done as part of a research project funded by the Institute for the Promotion of Innovation by Science and Technology in Flanders (IWT-Flanders), grant IWT/OZM/050342. The first author is also supported by the IWT-Flanders. The authors also would like to thank Prof. Dr Pieter Jan Stuyfzand (Free University Amsterdam) for his helpful discussions on the results of the push–pull tests.

REFERENCES

Appelo, C. A. J. (1994) Some calculations on multicomponent transport with cation exchange in aquifers. *Ground Water* **32**(6), 968–975.

Brown, D. L. & Silvy, W. D. (1977) Artificial recharge to a freshwater sensitive brackish-water sand aquifer, Norfolk, Virginia. *US Geol. Survey Prof. Paper 939.*

Campbell, B. G., Conlon, K. J., Mirecki, J. E. & Petkewich, M. D. (1997) Evaluation of aquifer storage recovery in the Santee Limestone/Black Mingo Aquifer near Charleston, South Carolina, 1993–1995. *US Geol. Survey Water Resour. Report 96-4283.*

Castro, J. E. (1995) Aquifer storage and recovery Myrtle Beach, South Carolina; Phase II: A hydrologic, geochemical, and economic investigation. Report 7, South Carolina Dept of Natural Resour. Water Resources Division, Columbia, South Carolina, USA..

de Ruiter, H. & Stuyfzand, P. J. (1998) An experiment on well recharge of oxic water into an anoxic aquifer. In: *Artificial Recharge of Groundwater* (ed. by J. H. Peters *et al*.), 229–304. Balkema, Rotterdam, The Netherlands.

Jacob, C. E. (1947) Drawdown test to determine effective radius of artesian well. *Trans. Am. Soc. Civil Engrs* **112**, 1047–1070.

Johnson, A. I. & Pyne, R. D. G. (eds) (1995) *Artificial Recharge of Ground Water*, vol. 2. (Proc. Second Int. Symp. on Artificial Recharge of Ground Water, New York) Am. Soc. Civil Engineers.

Laga, P. & Vandenberghe, N. (1990) The Knokke well (11E/138) with a description of the Den Haan (22W/276) and Oostduinkerke (35E/142) wells, Toel. Verh. Geol. Mijnk. Belg. 29 / Belg. Geol. Dienst, Brussels, Belgium.

Lebbe, L. (1999) *Hydraulic Parameter Identification. Generalized Interpretation Method for Single and Multiple Pumping Tests*, 359. Springer-Verlag, Berlin, Germany.

Lebbe, L., Van Camp, M., De Ceukelaire, M. & Van Burm, P. (1987) Hydrogeologisch mathematisch model van de grondwaterstroming in de gedeeltelijk afgesloten watervoerende lagen onder West-, Oost-, Zeeuws-, en Frans-Vlaanderen (Hydrogeological mathematical model of groundwaterflow in the deep semi-confined aquifers in west-, east-, Zeeuws- and French-Flanders, in Dutch). Ghent University, Geological Institute, Ghent, Belgium.

Lowry, C. S. & Anderson, M. P. (2006) An assessment of aquifer storage recovery using ground water flow models. *Ground Water* **44**(5), 661–667.

Mertooetomo, M. (1995) Modellering van een grondwaterwinning op basis van de hydrogeologische kenmerken van het veellagig grondwaterreservoir te Koksijde-Oostduinkerke (België) (Modelling of groundwater extraction based on the hydrogeological characteristics of the groundwater reservoir, Koksijde-Oostduinkerke, Belgium, in Dutch). PhD. dissertation, Ghent University, Belgium.

Mirecki, J. E., Campbell, B. G., Conlon, K. J. & Petkewich, M. D. (1998) Solute changes during aquifer storage recovery testing in a limestone/clastic aquifer. *Ground Water* **36**(3), 394–403.

Pyne, R. D. G. (1994) *Groundwater Recharge and Wells* (first edn). Lewis Publishers, Boca Raton, Florida, USA.

Pyne, R. D. G. (2005) *Aquifer Storage and Recovery: A Guide to Groundwater Recharge Through Wells* (second edn). ASR Systems LLC, Florida, USA.

Ragone, S. E. & Vecchioli, J. (1975) Chemical interaction during deep well recharge, Bay Park, New York. *Ground Water* **13**, 17–24.

Sniegocki, R. T. (1963) Problems in artificial recharge through wells in the Grand Prairie Region, Arkansas. *US Geol. Survey Water-Supply Paper 1615-F.*

Stuyfzand, P. J. (1993) Hydrochemistry and hydrology of the coastal dune area of the western Netherlands. PhD Thesis, Nieuwegein, KIWA, Afd. Onderzoek & Advies, The Netherlands.

Stuyfzand, P. J. (1998) Quality changes upon injection into anoxic aquifers in The Netherlands: evaluation of 11 experiments. In: *Artificial Recharge of Groundwater* (ed. by J. H. Peters *et al.*), 283–291. Balkema, Rotterdam, The Netherlands.

Valocchi, A. J., Street, R. L. & Roberts P. V. (1981) Transport of ion-exchanging solutes in groundwater: chromatographic theory and field simulation. *Water Resour. Res.* **17**(5), 1517–1527.

Warner, D. L. & Doty, L. F. (1967) Chemical reaction between recharge water and aquifer water. In: *Proc. IASH-UNESCO Symp. on Artificial Recharge and Management of Aquifers* (Haifa, Israel, March 1967), 278–288. IAHS Publ. 72. IAHS Press, Wallingford, UK (http://iahs.info/redbooks/a072/07228.pdf).

Received 7 February 2007; accepted 19 March 2008