MODELLING OF THE SODIUM CHLORIDE TRANSPORT IN ALNARPSSTRÖMMEN IN SOUTH-WESTERN SCANIA, SOUTH SWEDEN

Anna JÄRVEGREN MEIJER (a), **Kenneth M. PERSSON** (b) and **Bo LEANDER** (b)

(a) Department of Water Resources Engineering, Lund University, Box 118, 21 00 LUND, SWEDEN
(b) SWECO VBB VIAK, Geijersgatan 8, SE-216 18 MALMÖ, SWEDEN

ABSTRACT

For approximately 20 years, the main groundwater resource in southwestern Scania, south Sweden, Alnarpsströmmen has recovered from subsea groundwater levels, due to less extraction. A great number of observations of the water quality and water levels have been collected, partly due to the work of "Samarbetskommittén för Alnarpsströmmen", a regional water organization that has controlled the water quality and water levels in the aquifer since 1965. Some wells have been monitored by the cities of Malmö and Lund since 1900. The observations have been used in this study to compare observed chloride concentrations due to changes in groundwater tables, with modelled chloride concentrations due to an assessed freshening process, where rainwater, low in chloride, has rinsed the aquifer for 100 years.

Although the groundwater levels overall have recovered with 4-6 m in the entire aquifer, virtually no specific changes have been observed with regard to chloride concentration during the period of observation of the wells. The simulations of a freshening process used PHREEQC2 of USGS. The simulations showed a very slow rinsing effect. The modelled chloride content in the well Prästberga was reduced from ca 160 mg/L down to ca 110 mg/L after 100 years of freshening. In another well, Bennikan, lying closer to the sea, the chloride content went modestly down from 200 mg/L to 170 mg/L after 100 years. That the processes are very slow is supported by the observations during the last century. Some mechanisms, which might explain why the process is slow, are discussed in the article.

Keywords

Regional study, freshening, chloride transport, Scania, Sweden

INTRODUCTION

The purpose of this paper is to study the changes in Chloride-concentration in the groundwater of the confined aquifers of Alnarpsströmmen in south-western Scania, south Sweden. See figure 1 for location. Evaluating water analysis and water pressures from 1930 up to today as well as a section of modelling the retraction of saltwater using PHREEQC2.0, a geochemical model developed by USGS, have carried out the study. The situation in Alnarpsströmmen is unique as we have a large aquifer with recovering groundwater levels due to less extraction of water in the last 30 years. This makes it possible to look at the changes in concentrations of Chloride in an aquifer allowed to recover. Three wells have been chosen for the study because of their characteristics and geographic location, see figure 1 for location. Bennikan lies closest to the sound Öresund and has the highest concentration of chloride out of the three. Prästberga lies a couple of kilometres east and Källby even further inland. Källby has the lowest concentrations of chloride. Bennikan and Prästberga lie in an area where the water pressure has been below zero but now recovered.

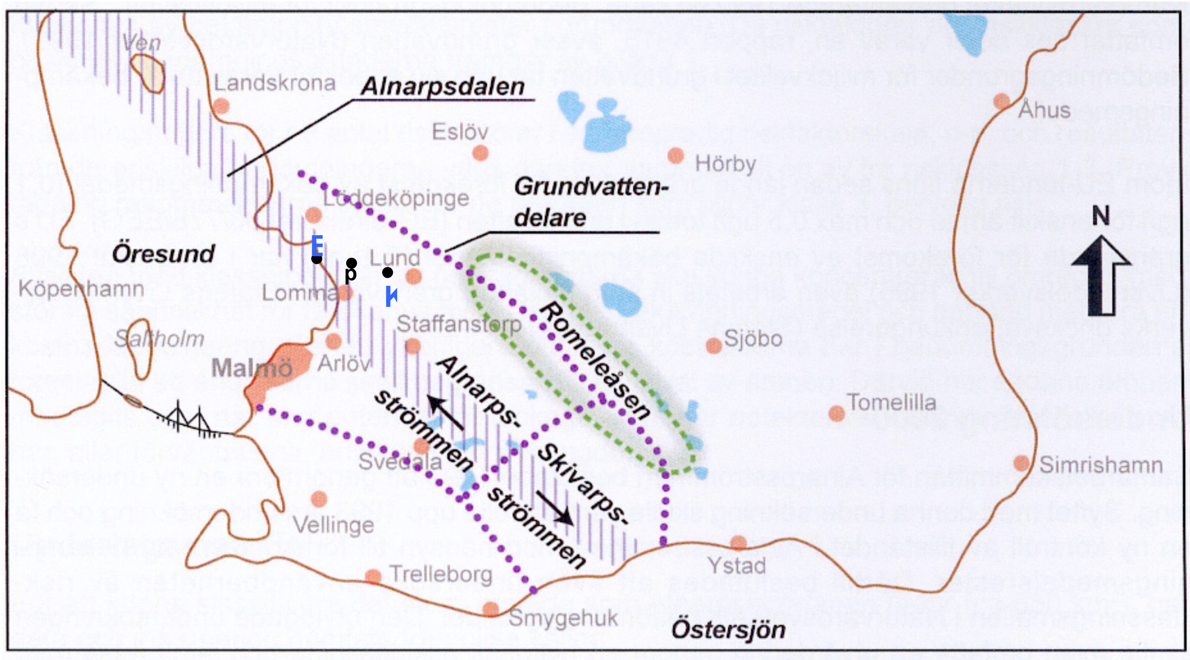

Figure 1 *The aquifer Alnarpsströmmen in south-western Scania, Sweden.*
The Alnarp Valley is striped and the groundwater divide is dotted.
The three wells discussed in the text, Bennikan, Prästberga, and Källby, are marked.

HYDROGEOLOGICAL BACKGROUND

For a century the aquifer Alnarpsströmmen has been of a great importance as a source of water for drinking, irrigation and small industries in the southwestern part of Scania, south Sweden. Alnarpsströmmen is one of the largest aquifers in Sweden and the potential extraction rate for the aquifer has been calculated to be 25 million m^3/yr, but the largest amount that has ever been extracted in a year was just over 18 million m^3. The water extraction during the 20th century is shown in figure 2. The two dips in the graph after 1950 and 1970 are due to surface water works being taken in use, decreasing the demand for groundwater. The extraction in 2001 was about 9,5 million m^3 and this is a reduction by nearly 50% compared to 1970, one of the top years. The extraction in 2001 is comparable to the one 60 years ago.

Geological signs show that south-western Scania has been under the influence of tectonic movement for hundreds of millions of years. A striking feature in the Scanian geology is the grabenlike depression, called the Alnarp Valley, which stretches parallel to the horst Romeleåsen in a north-western direction from the Östersjön south of Scania to the sound Öresund separating Sweden from Denmark. The valley is most likely to be a result of tectonic movement as faults and deep fractures limit it.

The upper part of the bedrock in south-western Scania consists mainly of limestone from the Danian epoch in the early stages of the Tertiary time period. The thickness of these sedimentary rocks is generally 60 m and below soft chalk from the Maestrichtian epoch can be found. On top of the bedrock lies Quartenary deposits and the deep sediments, mainly fine sand, within the Alnarp Valley are called the Alnarp sediments. These sediments are generally covered by clayey till, till clay and clay. This aquitard, covering the confined aquifer below, is 30-50 m thick (LEANDER & PERSSON, 1999, and BARMEN, 1992).

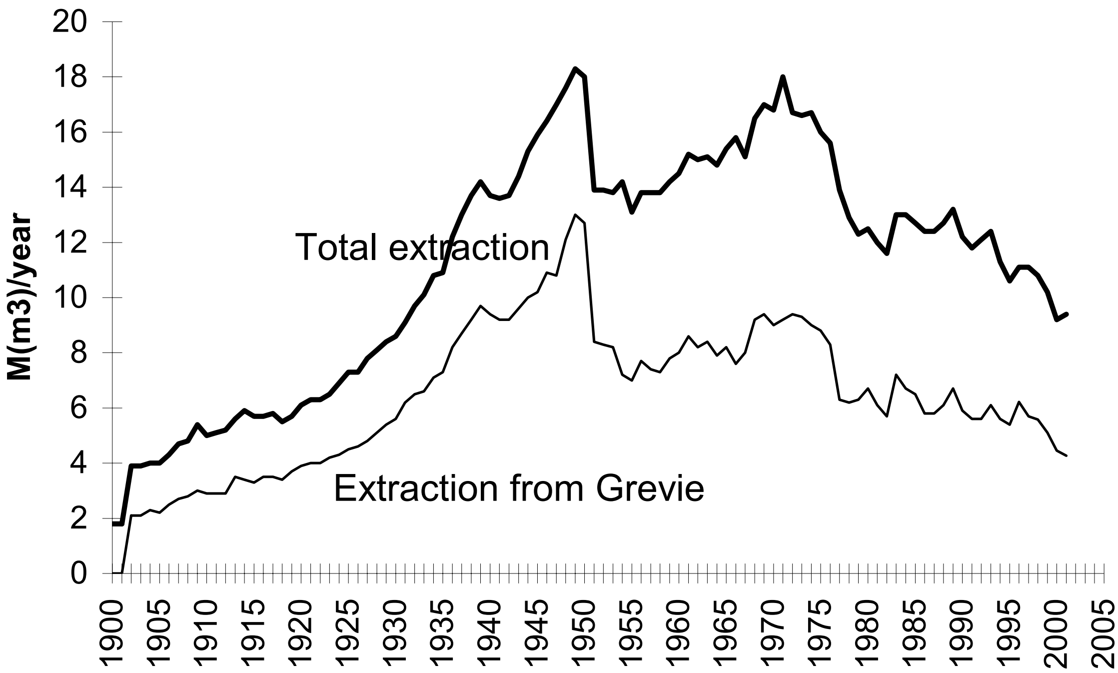

Figure 2 *Total water extraction from Alnarpsströmmen and the specific extraction from Grevie, supplying the Malmö-region with water.*

HISTORICAL EXTRACTION

As a result of the geological composition of the Alnarp Valley and the surrounding recharge area for Alnarpströmmen it has been very beneficial to extract water from the aquifer. Most of the water is taken from the Alnarp sediments closest to the limestone bedrock and these transport water very well. When no water was extracted, the groundwater pressure was so high that in several parts in the north-west area of Alnarpsströmmen, the conditions were artesian. Extensive pumping lowered the groundwater pressures below artesian levels. As a result of the decreased pumping from around 1980, the groundwater levels have more or less recovered and some areas have in the last two years gone artesian again. From 1965 the water quality has been controlled in a regional co-operation, named 'Samarbetskommittén för Alnarpsströmmen' ('The Alnarp aquifer association' in English), see LEANDER & PERSSON, 1999.

MATERIALS AND METHODS

PHREEQC2.0

The modelling section of the study was carried out using the computer program PHREEQC version 2, a geochemical model developed by USGS. PHREEQC2.0 can handle batch-reaction and one-dimensional (1-D) transport calculations involving both reversible reactions, such as ion-exchange equilibria, and irreversible, such as kinetically controlled reactions. The basis for the model is ion-associated and equilibrium calculations are used when interacting aqueous solutions with e.g. minerals, solid solutions, gases and ion exchangers. The computer program can also handle inverse modelling where sets of mineral and gas mole transfers that account for differences in composition between waters, different in time and/or distance, are found.

For speciation and batch-reaction calculations, the Newton-Raphson method is used to iteratively find the solution to non-linear mole-balance and mass-action equations defining the ion-association model. For the 1-D transport modelling, an explicit finite difference algorithm is included to solve the calculations for advective and dispersive transport. The chemical equilibration for each cell is solved using the same procedure as for batch-reaction calculations. In case kinetic reactions are modelled with the transport, a fifth order Runge-Kutta method is used on the ordinary differential equations of the kinetic reactions.

The input file in PHREEQC2.0 consists of different keyword data blocks and the input is completely free format, based on chemical symbolism. For each data block certain identifiers may be specified. The order of the keywords in the input file is irrelevant, with the exception of END. The databases connected to PHREEQC2.0 are extensive to make it possible to apply the reaction-, transport-, and inverse-modelling tools to almost any chemical reaction that is known to affect the water quality. For more detailed information see PARKHURST & APPELO, 1999.

PHREEQC2.0 was chosen as the modelling tool for this study as the model is easy to handle, well defined and has had many previous users.

TRANSPORT

For this study, the main keyword data block used when modelling in PHREEQC2.0, is TRANSPORT. This keyword makes it possible to look at the advection, dispersion, diffusion, and chemical reactions that take place as water moves through a 1-D column. The column is divided into separate cells, number chosen by the user, and for each cell the solution and reactant compositions and occurring reactions can be defined. When running a TRANSPORT-command the solution in one cell in the column is shifted to the cell next to it and the empty cell is filled with a user-defined solution. The cells have the same pore volume but the user defines the lengths of them. The modeller also decides the time it takes for one volume to shift to the next cell and so; the velocity of the water in each cell is determined by dividing the length of the cell by the time step. After each advective shift and dispersion step, kinetic reactions and equilibria are calculated. To use the TRANSPORT-keyword, most information must be input by other keywords, such as the defining of solutions by the SOLUTION-data block or the exchange assemblage by using EXCHANGE.

MODELLING PARAMETERS

The scheme of the modelling in this study is shown in figure 3. To model the rinse out of Chloride-ions in the well of Bennikan, water from the well Prästberga, further inland, has been used as the solution forcing the Bennikan water downwards in the column. Prästberga, in its turn, has been modelled with water coming from Källby. This approach was also chosen trying to simultaneously take the horizontal and vertical movement of the groundwater in Alnarpsströmmen into account.

The initial solution in the cells was defined from water analysis and experience from nearby areas. All cells were set to be in equilibrium with Calcite because of the characteristics of the sediments in Alnarpsströmmen. The amount of the ion exchanger was chosen to 60 mmoles and put in equilibrium with the system. The solution entering the column of Prästberga has been defined as water from the well Källby and the values are taken from actual water analysis. When modelling for Bennikan, a water from the simulation from Prästberga was chosen. The water comes from the depth of 13 m and from the shift in which the concentration of Cl has been reduced with approximately 50% compared to the start concentration.

For the identifiers in the TRANSPORT keyword data block the following was chosen:

The simulation was run over a time period of 100 years. The water was shifted from the top of the column and down. The boundary conditions were set to flux conditions. The dispersivity was set to 0.001 m. The diffusion coefficient was chosen to have the default value of $0.9*10^{-9}$ m^2/s. The number and lengths of the cells were determined after an overview of the geology around the two wells. To account for the permeability of the different geological layers in Alnarpsströmmen, the cells were given certain lengths that divided by the time step would give an appropriate velocity. Preliminary results from modelling with low permeabilities show that the results regarding the final chloride concentrations do not differ much from the ones when permeabilities are kept higher. The number of shifts and cells were kept constant so that every cell got washed through at least one time by the now, by diffusion and dispersion, altered solution that entered the column.

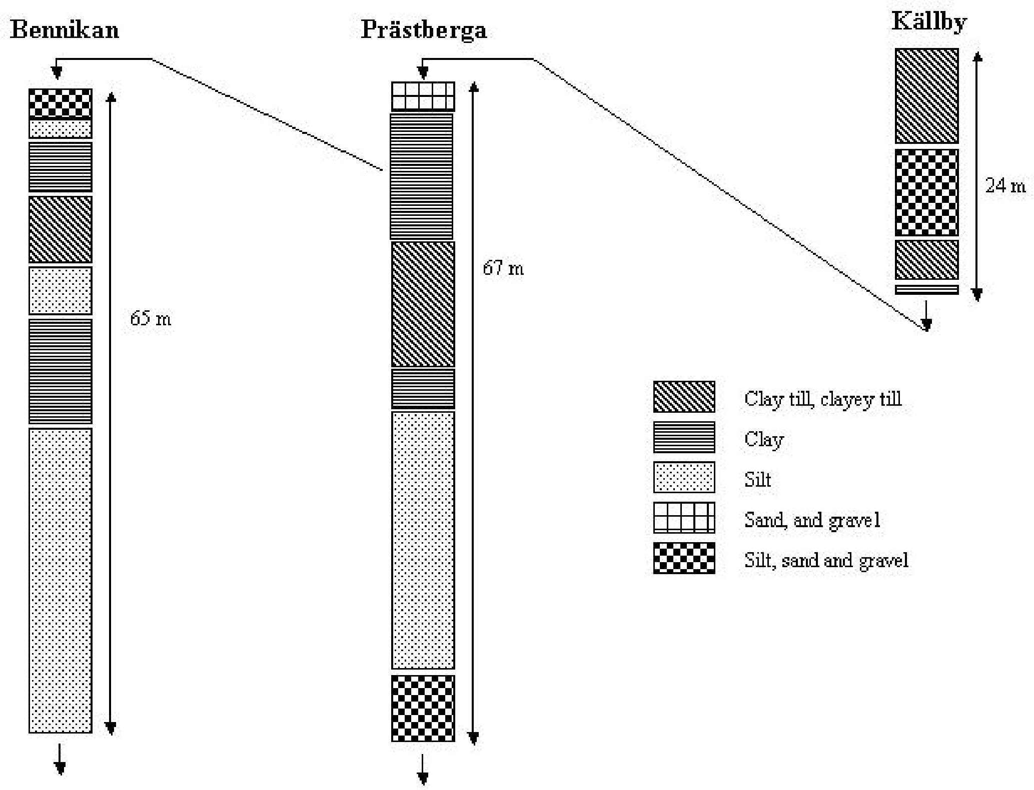

Figure 3 *Scheme of the modelling carried out with PHREEQC2.0*

RESULTS

Observed chloride concentrations and water pressures

More or less frequently, water samples have been taken from the wells of Bennikan, Prästberga and Källby from the mid-30's on. The samples have been analysed and recorded. In Bennikan, the water level has been measured just as long.

Bennikan

Figure 4 show the concentration of chloride in Bennikan as well as the groundwater levels from the late 1930's. Apart from 6 measurements between 1971 and 1992, the chloride concentration has been more or less constant at 210-220 mg/L. The extremely low value of 24 mg/L, in 1986, cannot be explained satisfactory as anything else but a measurement or transfer mistake when recording the result. The last 4 years the value has been 220 mg/L.

The measurements of the water pressure show three different trends. The first one, between late 1930's and mid-1960's, show the water level fluctuating between one meter above sea level and one meter below. The second trend shows a drastic drop of water pressure of almost four meters, in a time period of five years. In the 1990's the trend is a recovery of the water pressure as it has risen with 2 meters. The levels nowadays are at the same level, or higher, as they were in the late 1930's.

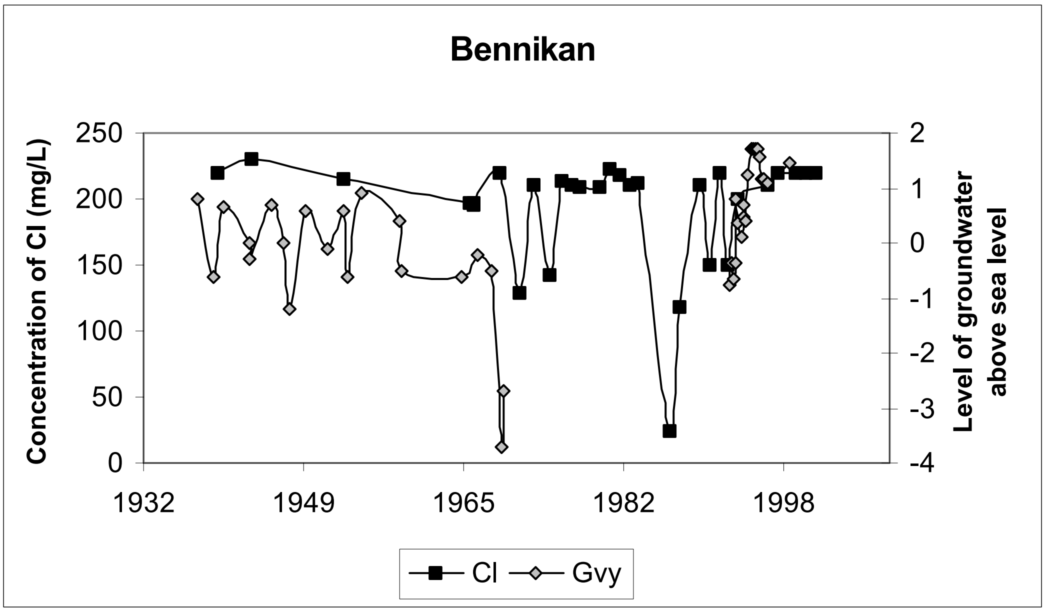

Figure 4 *The chloride concentration and groundwater level in the well Bennikan.*

Prästberga

The chloride concentrations in Prästberga can be seen in figure 5 where they are showed with the concentrations from Bennikan and Källby. In Prästberga the water analysis from late 1930's up to today show an almost constant trend of 160 mg/L. An exception to this is the high value of 210 mg/L in 1995. An interesting point is that the pumping station in Prästberga was being repaired around this time and not in full use.

In the early 1990's the water pressure recovered strikingly by rising five meters, placing the water level above sea level. The end of the 1990's seemed to lower it a little bit but the level is still above sea level.

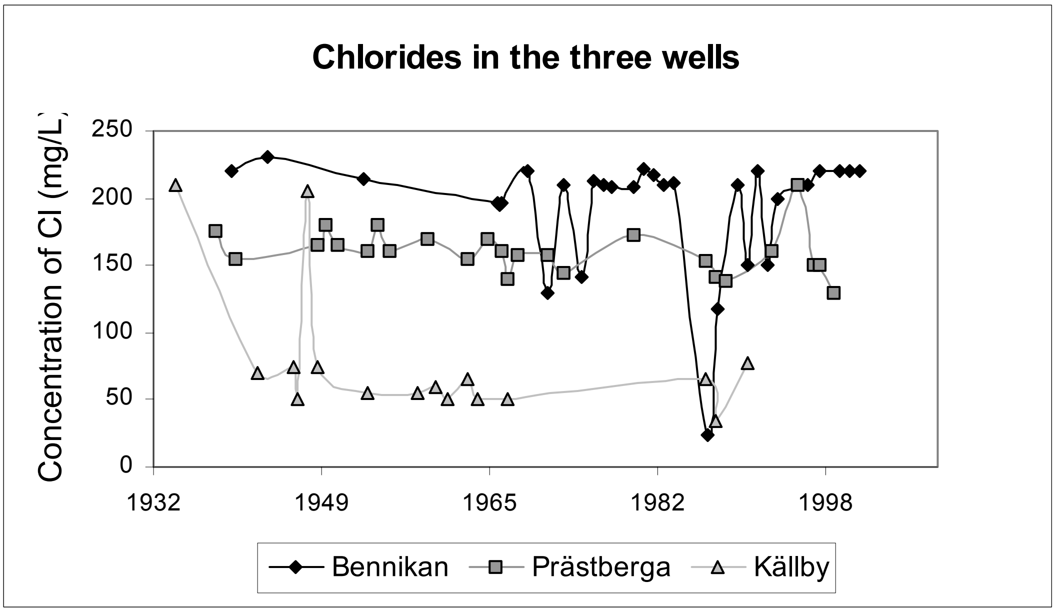

Figure 5 *Chloride concentrations in the wells Bennikan, Prästberga and Källby.*

Källby

Figure 5 shows, with the exception of two measurements since mid-1930, that the chloride concentration in Källby has been almost constant around 60 mg/L, 100 mg/L less than the water in Prästberga and 160 mg/L lower than Bennikan. The two values higher than 200 mg/L are most likely a measurement mistake.

During the 1990's, the water pressure has seemed to be stabilising around 9 meters above sea level. Källby is topographically higher located than the other two wells so it is not surprising that the level is higher here.

Modelling simulations in PHREEQC2.0

Figure 6a and 6b show the modelled Cl-fronts through Prästberga and Bennikan. The Cl-front can be seen at different time steps. The slope of the front changes as the front goes through the profiles. The highest concentration of Cl in Prästberga, occurring before the simulation starts, is 160 mg/L and when the simulation is over the washed out value, achieved between the depths of 0 and 31 metres, is 80 mg/L. After 100 years of shifting water through the column, the front has not yet passed the depth of 67 m, and the concentration here is 110 mg/L. For Bennikan, the initial Cl-concentration is 200 mg/L and the value in the upper part of the profile after outwash is 140 mg/L. As in Prästberga, the front has not yet passed the bottom of the well after 100 years of shifting water. The concentration at 65 m and after 100 years is 170 mg/L.

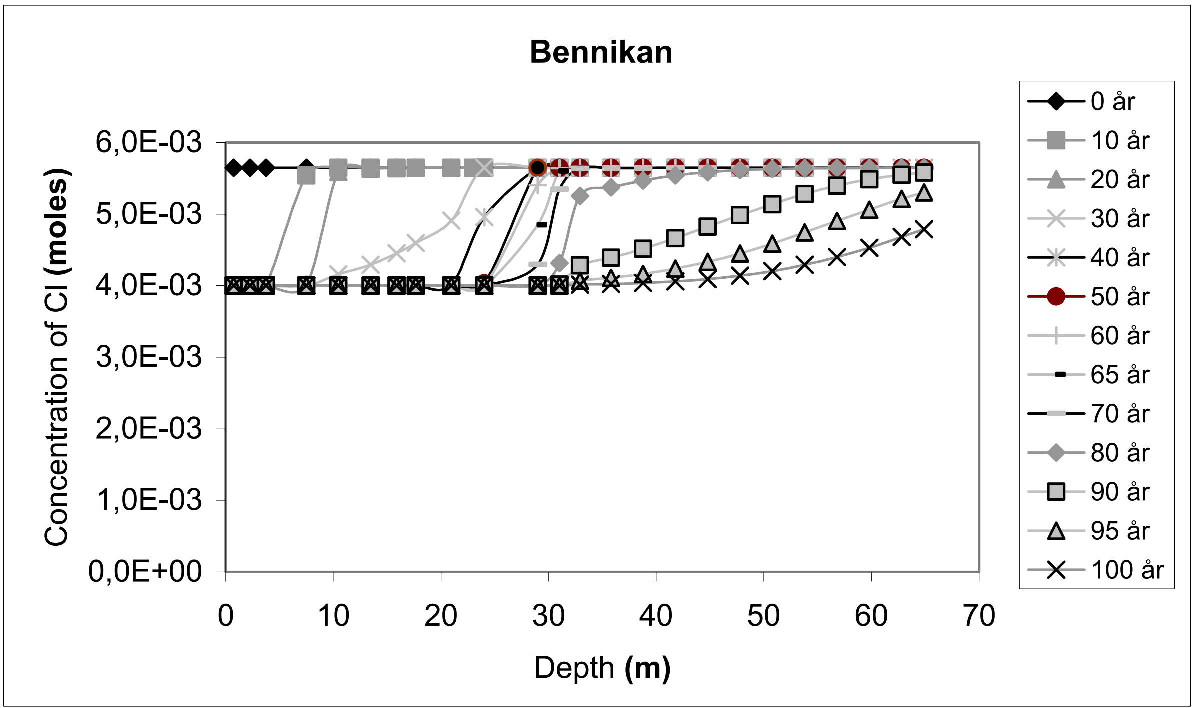

***Figure 6a** The chloride front in Bennikan after modelling a 100-year-outwash with PHREEQC2.0. The front is shown after certain time lengths according to the legend.*

The model has not yet been calibrated sufficiently and therefore the results should be seen as preliminary. However, the model is found to be reliable and stable enough to show the accurate movements of water and is therefore included in this study.

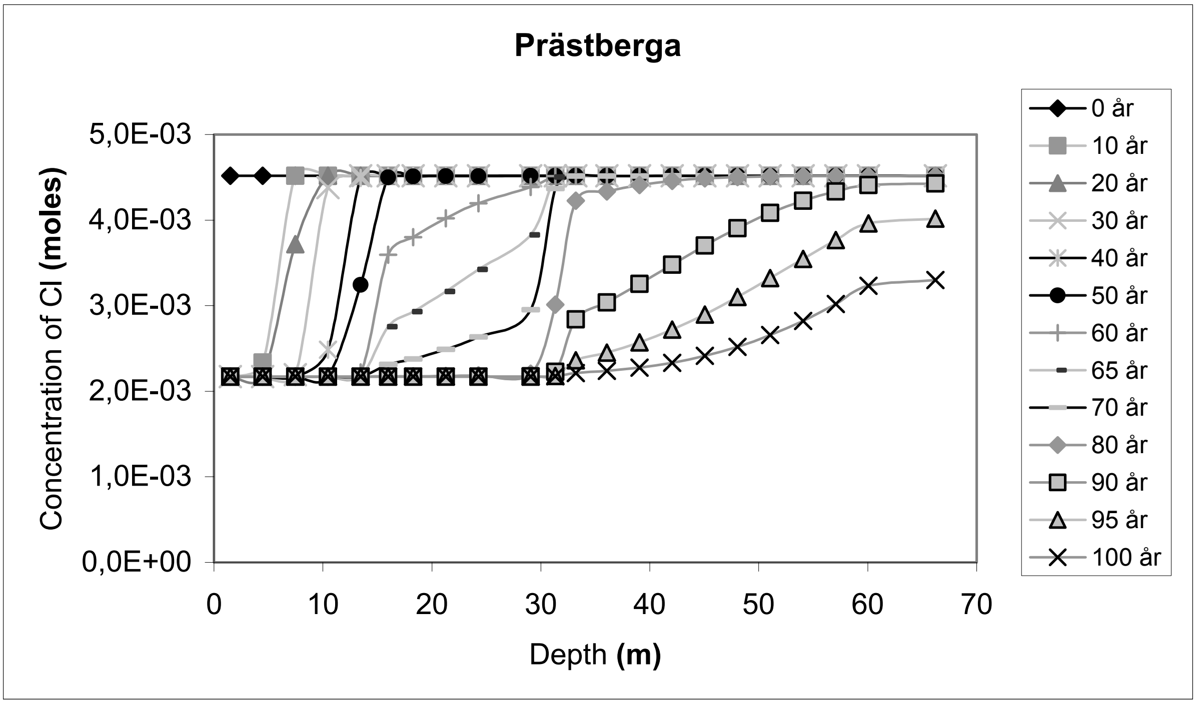

Figure 6b *The chloride front in Prästberga after modelling a 100-year-outwash with PHREEQC2.0. The front is shown after certain time lengths according to the legend.*

DISCUSSION

Observed chloride concentrations and water pressures

The water pressure has both dropped and recovered in some of the wells in Alnarpsströmmen in the last 60 years. Bennikan is one of them. The drastic drop of the water level in the end of the 1960's is the result of a combination of extensive pumping from Alnarpsströmmen at that time and the fact that some of the years were very dry. And accordingly, the recovering of the water pressure in both Bennikan and Prästberga during the 1990's is a reaction to the decreased pumping during this time. Bennikan is one of the wells that used to be artesian, lost that capacity, and now in the last few years has regained it.

With the recovery of water pressures, a decrease in chloride concentrations can be expected if the chlorides appear because of saltwater intrusion from the sound Öresund. Neither Bennikan nor Prästberga show any signs of increasing or decreasing concentrations of chloride, taking the last 60 years into account. This indicates either that the chlorides do not come from the seawater in the sound but from somewhere else, or that the processes of saltwater intrusion, in regards of chloride concentrations, are so slow that the reactions to the pressure changes can't be seen yet. One possible reason for the slow processes is the fact that Alnarpsströmmen is a confined aquifer.

The flow regime in the aquifer is directed towards the Sound/the Sea. Deposits, maybe of fluvial or alluvia origin, has covered the area and made a "check-valve" like porosity. Hence, flow may pass from the aquifer out into the sea, whereas flow from the sea into the aquifer is hindered. Thus, the net flow of chlorides from the sound into Alnarpsströmmen is more or less limited to the diffusion.

If the chlorides come from somewhere else but the sound, one theory is that they are the result of a very slow outwash of relic water. This would have been captured in the sediments when the area was below the sea level or under the influence of ice, which depressed the land several 100 metres. In favour of this theory is the fact that the chloride concentrations in Bennikan, Prästberga, and Källby are somewhat constant in the last 65 years and the same goes for the difference between them. The process of relic water outwash is very slow and 65 years would be too short of a time span to see any changes.

Modelling simulations in PHREEQC2.0

The changes of the slope are a result of the way the TRANSPORT-keyword data block is set up. As every cell is connected to a specific geological material and its permeability, the front will move downward trough the column with different velocities. This result in steeper slopes in the layers with lower permeability, such as the layers consisting of sand and gravel, and flatter slopes in layers with a high permeability, i.e. the clay layers. Comparing the modelled front and its slopes with the found geological layers, it can be seen that this is the case. To get a more precise picture of the front's movement through the profiles, the differences in permeability between the layers have to be adjusted for more accurately. A higher accuracy leads to slower simulations because of more iteration. In this study it was not found justified to increase the accuracy, as the general picture was considered to be enough for the purpose.
The results from the modelling show the slow vertical movements of water in Alnarpsströmmen, as not even 100 years is enough to shift the chloride front all the way through the profiles. In Prästberga the concentrations at the bottom has to be lowered with an additional 30 mg/L to have the same value throughout the profile. The same difference, 30 mg/L, goes for Bennikan. This can be achieved by modelling for a longer time period or by deciding on a larger amount of shifts than cells.

FINAL REMARKS

The unique situation we have in Alnarpsströmmen, a large aquifer with recovering water pressures due to less pumping, enables us to see how slow or fast the changes in chemical composition of the water is. The evaluation of the water samples and the groundwater pressures show that the processes are very slow. Even when the water levels have recovered noticeably the chloride concentration has not showed the same development. When modelling with PHREEQC2.0, the trend of slow processes and changes is also observed.
To determine if the chloride ions originate from relic water or from the sound, it is important to determine the age of the water. Knowing this would add to the understanding of the aquifer.

Future studies on Alnarpsströmmen might include modelling in a 3-D hydrogeological model in trying to understand how the processes in the aquifer work.

ACKNOWLEDGEMENTS

We are grateful to The Alnarp aquifer association for providing us with aquifer data and financially supporting our participation at SWIM17. We are also grateful for the help and ideas that Rasmus Jakobsen, Technical University of Denmark, has provided us with for the modelling section of this study.

REFERENCES

BARMEN, G. (1992) On the combination of isotope hydrogeology with regional flow and transport modelling, Diss. Lund University, Dept of Engineering Geology.

LEANDER, B. & PERSSON, K.M. (1999) Salt-Water Intrusion in the Limestone Bedrock of South-Western Scania. In: W. de Breuck and L. Walschot (Ed.) Proceedings of 15th Salt-Water Intrusion Meeting, Ghent, Belgium, p.178-184.

PACKHURST, D. & APPELO, C.A.J. (1999) Geochemistry, groundwater and pollution, AA Balkema, Rotterdam, The Netherlands.