Groundwater model, Mike She, of the salt water distribution in Alnarpsströmmen, southern Sweden

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Abstract-The most important groundwater supply for the city of Malmö, southern Sweden, is a well area called Grevie, situated in the confined aquifer of Alnarpsströmmen. The wells have been in operation for 106 years, producing approximately 200 l/s drinking water mainly for the city of Malmö. Groundwater levels, geology and groundwater chemistry have recently been investigated thoroughly, allowing the development of regional and local models in the software MIKE SHE.

The model consists of three different models built as finite difference, FD, models. Each model has a number of quadratic cells, with 3 different degrees of resolution: 1200m, 400m and 200m. Results from a coarse model grid can be extracted into boundary conditions for the subsequent finer models. The number of cells in each model are 4323, 15675 and 20601 respectively.

Besides the city of Malmö, there are a number of communities, industries and farmers that use the same groundwater resource. The aim has been to create a dynamic planning tool for all of these communities. Problems regarding salt water intrusion due to excessive groundwater discharge, water protection areas, groundwater recharge areas and salting or refreshing water flow transport have been illustrated and quantified. The work in producing this model also aims to develop useful tools for the adaptation of the proposed groundwater directive COM(2003)550 to Swedish rules.

At present the results are used for identifying a more correct influence area for the Grevie wells, and they will also be used for calculating the maximum allowed production volume in the area.

I. INTRODUCTION

As a result of the geological composition of the Alnarp valley, southern Sweden, Scandinavia, and the surrounding recharge area for Alnarpsströmmen, it has been very beneficial to extract water from the aquifer, figure 1. Until 1980, extensive pumping lowered the groundwater pressure below originally artesian levels. Thereafter, the extraction has been reduced and the groundwater levels and pressures have been restored. From 1965, the water quality and water pressures have been controlled by a regional co-operation "Samarbetskommittén för Alnarpsströmmen" or The Alnarp Aquifer Association (see a brief description in Leander and Persson, 1999). Saline groundwater has been found in various concentrations throughout south-western Scania (see Fransson et al, 2003).

A. Bedrock formation and characteristics

The majority of the bedrock in the south-western parts of Scania was formed during the Paleozoic era and consists of reef limestone, shale, alum shale, sandstone and conglomerate. Shale formed during the Silurian period is the most common rock found in this bedrock and was formed at great depths by a combination of erosion products and mountain-building activity (Fredén, 1994). The Romeleåsen horst is one of several crystalline horsts in Scania and lies just north-east along the Tornquist zone. The western fault and folding zone of the horst is the border of the aquifer.

The Alnarp depression was formed about 60 million years ago during the Tertiary period and stretches along the Tornquist zone from Landskrona to Ystad. It is a valley about 50 km long, 5 km wide and about 100 m deep. The exact cause of its formation remains unknown. However, it is speculated that the valley was formed by tectonic movement, since it forms a rather straight, narrow cut into the earth and is located on the Tornquist zone, which is an area known for repeated movement and faulting. The Alnarp valley has been filled and emptied by glaciers during the ice ages. The melt water from the glaciers distributed sand and gravel deposits along the valley and across the Scania region.

The sedimentary rocks formed during the Cenozoic era are considerably thin. They consist of Danian limestone, which forms the surface bedrock in south-western Scania. It is no more than 65 meters thick and is occasionally covered by younger sedimentary rocks (Fredén, 1994). Limestone is mostly made of calcite, but also contains strontium and magnesium at high levels.

B. Quaternary deposits

During the periods when the glaciers retreated from the Swedish landscape and the sea level was relatively low, erosion occurred and coarse materials, such as sand and gravel, were deposited. Many of these sediments then became

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covered by marine clays (Appelo, 1991). Therefore, the Quaternary deposits of south-western Scania are mostly made up by clayey till, but they also include small areas where glaciofluvial deposits, clay-silt and till are found. The map of Quaternary deposits shows that the region along the Alnarp depression is mostly covered by glaciofluvial sediments, also known as Alnarp sediments. They are usually situated directly on the bedrock surface. However, here and there till is found between the Alnarp sediments and the bedrock (Barmen, 1992). The local bedrock is often the main component of a glacial till Quaternary deposit, even if it does not fully determine the composition (Barmen, 1992).

Therefore, south-western Scania, with bedrock of limestone and shale that is easily eroded by glaciers to a very fine-grained product, has a soil cover predominantly consisting of clayey till and clay till with a high content of lime (Nilsson and Gustafsson, 1967). The sediments tend to become more fine-grained in the north-western direction of the Alnarp valley (Barmen, 1992). It has been assumed that these have been deposited by a large river that once flowed from the south-east into the Alnarp depression (Holst, 1911; Nilsson, 1959, 1973).

C. Implementation of conceptual geology on the groundwater model

The upper soil layers are expected to have a low permeability, figure 2. Through these layers a slow vertical groundwater transport is recharging the groundwater resource in Alnarpsströmmen. It is expected that some highly permeable areas, ”windows,” through which the water transport can be rapid from the ground surface down to the saturated groundwater body, will be found within the upper soil layers. It is also expected that the upper soil layers, Sediment 1, will be found generally over the entire model area.

The permeable sediments in the saturated zone, Grevie sand, are known to have the highest permeability some meters above the upper surface of the limestone bedrock. It is expected that, from there, a gradient with consecutively less permeable layers will be present. This package of sediment, called Sediment 2, is included in the model as present in the Alnarp Valley.

The model assumes that the first 5 meters on the bedrock around the Alnarp Valley have a higher amount of fissures and cracks, and therefore higher water permeability than the lower lying bedrock. It is not expected that such cracks will be found at the bottom of the Alnarp Valley. The model assumes that the limestone bedrock is present in the entire model area from Öresund to the Romeleåsen horst. At the horst, the limestone ends are replaced by solid rock, which is taken into account in the model, as having a totally different permeability.

The model consists of three sub-models, called the regional model, the semi-regional model and the local model. In the regional model, the south-western part of Scania is included. This step models the recharge of both the north-western and the south-eastern parts of the Alnarp valley aquifer. The north-western part is called Alnarpsströmmen, whereas the south-eastern part is called Skivarpsströmmen, figure 1. One of the goals behind this model has been to calculate the boundary conditions for the semi-regional and the local models.

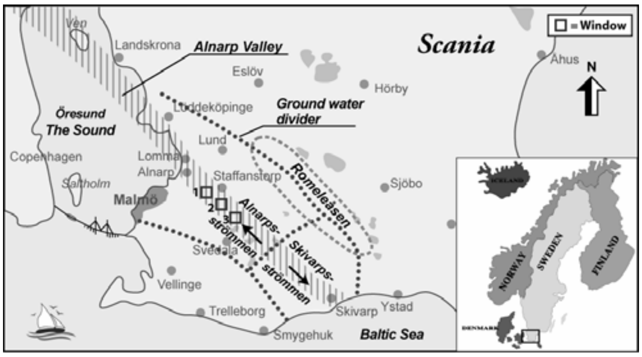

Figure 1 Plan view - the Alnarp valley with 3 possible windows

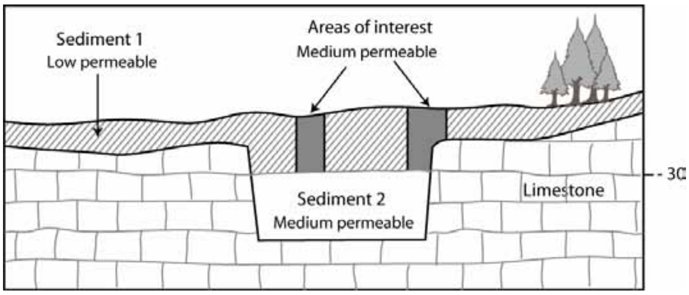

Figure 2 Assessment of the water permeability of the soil layers and the bedrock.

The model consists of three sub-models, called the regional model, the semi-regional model and the local model. In the regional model, the south-western part of Scania is included. This step models the recharge of both the north-western and the south-eastern parts of the Alnarp valley aquifer. The north-western part is called Alnarpsströmmen, whereas the south-eastern part is called Skivarpsströmmen, figure 1. One of the goals behind this model has been to calculate the boundary conditions for the semi-regional and the local models.

The semi-regional model describes the Alnarpsströmmen aquifer. It is mainly developed as a tool for modelling groundwater conditions and extraction possibilities in the area. The local model stretches over the groundwater well area of Grevie and is developed for the purpose of describing this part of Alnarpsströmmen in more detail. The boundary conditions for the local model are calculated over and against the semi-regional model.

After calibration of the three models, a comparison between the calculated and the measured conditions for the validation period (from year 1980 to 1995) was made in order to check the validity of the model. If the model is robust, the difference between the calculated and the measured values will be negligible.

D. Estimation of acceptable mean model error

An assessment of the acceptable differences between the simulated and the obeserved groundwater pressure levels in the aquifer was made as follows:

- Regional model: ± 3 m
- Semi-regional and local model: ± 2 m

The marginal of these errors can be compared with the absolute mean error (MAE), see also Sonnenborg (2001) and Refsgaard & Butts (2001).

1. Windows – vertical cross-cuts to the Grevie sand

A traditional section of the Alnarp valley and its geological layers is illustrated in figure 2. Actual conditions, illustrated e.g. through well drillings often show a more heterogenic picture, compared to what is suggested by figure 6. Local anomalies in the geological layers have been caused by glacial tectonics. These local variations may mean that impermeable till layers are not complete. There may be local, comparatively fast, vertical transport routes from the ground surface to the Grevie sand, so called windows. In this report, windows refer to areas where the vertical water transports occur faster than in their surroundings. The location of possible windows in the geological layers covering the Alnarp valley is of interest, partly in order to assess the vulnerability of a possible pollution of the groundwater in the Grevie sand, and partly to locate areas where refilling of the groundwater takes place.

The search for possible windows in the clayey till covering the Alnarp valley has mainly been conducted in accordance with the following list of procedures:

- Interpretation of the descriptions of geological layers from the wells in the archive of Swedish Geological Survey
- Calculation and interpolation of the proportion of coarse sediments above the -30 m level
- Interpolation of the upper surface of the sandy sediments located in the Alnarp valley and interpretation of the thickness of the impermeable layers overlaying the sandy sediments
- An evaluation of the reliability of the well protocols in the archive of Swedish Geological Survey
- The soil map

It is assumed that the -30 m level represents the approximate upper limitation of the Grevie sand under untouched conditions

In order to estimate the probability of the location of the possible windows, the soil map and the well protocols of the wells in the vicinity of the windows have been studied. The soil map provides further arguments for or against the existence of a window and acts as a complement to the well protocols, since some wells were drilled in old excavated wells and hence lack observations and soil samples close to the ground surface. The interpretation of the well protocols, together with the above mentioned analysed data, gave interesting results, though these results were sometimes difficult to interpret.

2. Window indication 1: Tottarp – West of Staffanstorp

Window indication 1 is located at Tottarp, between Staffanstorp and Åkarp. The window and its surroundings are illustrated in figure 3. The yellow dots mark the Swedish Geological Survey wells in the area.

Well 842 was drilled 1989 with cable tool drilling, which normally render a comparatively good soil testing possible. Still, the description of the soil layers is brief: 0-2 m clay; 2-82 m sand. This brief description of the soil layers in combination with a lack of soil samples decrease the reliability. This does not mean that the description is false, since soil layers consisting of fine sand, medium sand, course silt and thin lenses of clay could be summarized as sand (compare with well 114, window indication 2).

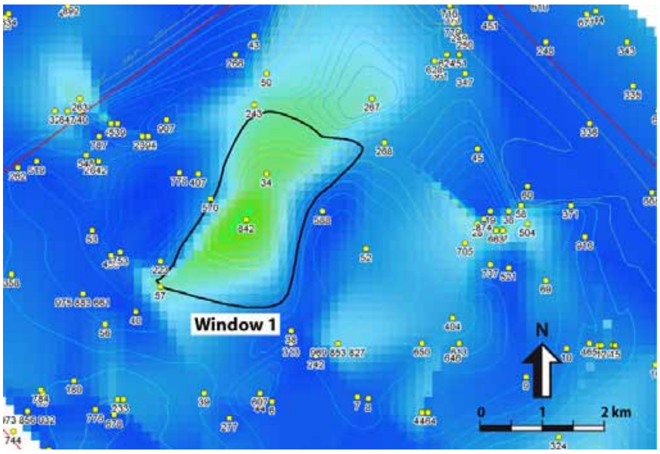

Figure 3 Window 1 and the Swedish Geological Survey wells in the area.

Samples from well 34 and 57 are stored in archive, and the interpretation of the soil layers have been conducted by the Swedish Geological Survey. Samples were collected through the method of sludge sampling. The wells 243 and 267 are more reliable, since they also indicate an increased proportion of coarse sediments in the vicinity of the window.

In conclusion, there are indications of a window, but a verification of the existence of this window is not possible, since the reliability of the drillings have been judged as comparatively low.

3. Window indication 2: Hälledal – between Bara and Klågerup

Window indication 2 is located between Bara and Klågerup. The window and its surroundings are illustrated in figure 4. The yellow dots mark the Swedish Geological Survey wells in the area.

Interpolation of the upper surface of the Alnarp sediments and the proportion of coarse sediments above the -30 m level indicate that window indication 2 might be a local elevation of the upper surface of the fine sand sediments, and an increased proportion of coarse sediments. These conditions imply that this area probably constitutes a window.

Well 114, situated at Hälledal, was drilled in 1963 and the stratigraphy is estimated as credible, despite the fact that almost only sand and gravel have been found (gravel, fine gravel, course silt, medium sand, loamy fine sand, sand). Samplings have been taken at approx 30 different levels along the drilling. Near this bore, some dug sections also exist. These are shown in the description of the soil map Malmö SO (Ringberg, 1980, p.76).

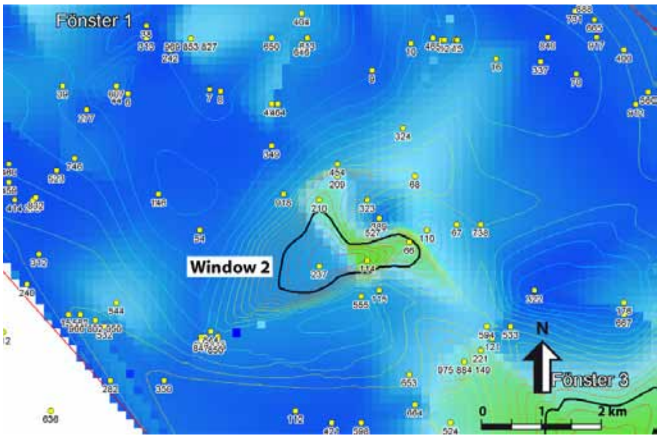

Figure 4 Window 2 and the Swedish Geological Survey wells in the area.

Well 237 was drilled in 1970 with cable tool technique and the stratigraphy is considered to be credible. Samplings have been taken at 7 different levels. The well is rather shallow (27 m) since the drilling not could be finished. The drilling water drained away, which suggests permeable conditions. According to the well archive, this well is located at a height with a ground surface of approximately +50 m. Based on the drilling record, the level of the upper surface of the coarse sediment has been interpreted to be approximately +40m, while the ground water pressure ought to lie below +20m. In 1970, the observation well at Vinninge, situated about 2 km from well 237, had an observed ground water level at approximately +10 m. Accordingly, the level of the observation well at Hyby, about 3 km eastwards, was approximately +25 m. Bearing in mind the expected transport of subsoil water in the coarse sediments within the Alnarp valley, it is reasonable that the ground water pressure at Hälledal should have been, between +10 m and +25 m in 1970, which supports the theory put forward above.

The calculation of the proportion of coarse sediments for well 237 is probably misleading. Only data from the top soil profile, which measures not quite 30 m, have been used in the calculation, which has resulted in a relatively low proportion of coarse sediments. Since the well only reaches down to the level of approximately +20 m, there is another, approximately 50 m deep deposit of unknown sediments, which not has been taken into account in this calculation.

Well 66 was drilled in 1940 and the stratigraphy is considered doubtful. The stratigraphy includes ”16.4 m – 86 m medium sand and coarse silt” plus ”86 m-96.4 m coarse silt and sand”. The thick layers of sandy sediments decreases the trustworthiness, even if the drilling records display similarities with well 114, situated approximately 800 m westwards. The samplings have been taken at 7 different levels.

Wells 209 and 210, situated in the vicinity of window 2, also suggest an upper surface of the coarse sediments situated fairly near the surface and these can be accepted as trustworthy.

To sum up, several indications suggests the presence of a window, and it is very probably that a window exists in this area.

4. Window indication 3

Window indication 3 is located near Holmeja, north of Lake Fjällfotasjön and north-east of Lake Yddingen. The window and its surroundings are illustrated in figure 5. The yellow dots mark the Swedish Geological Survey wells in the area.

The number of Swedish Geological Survey wells in this area is low and the distances between them are large. Interpolations of the upper surface of the Alnarp sediments and the proportion of coarse sediments above the -30 m level, show major influence from well 574. The existence and the distribution of the area of Window 3 is uncertain. A number of arguments for and against the location of this window follow below. A feasible conclusion is that there is a potential window near Holmeja, but the exact location is uncertain.

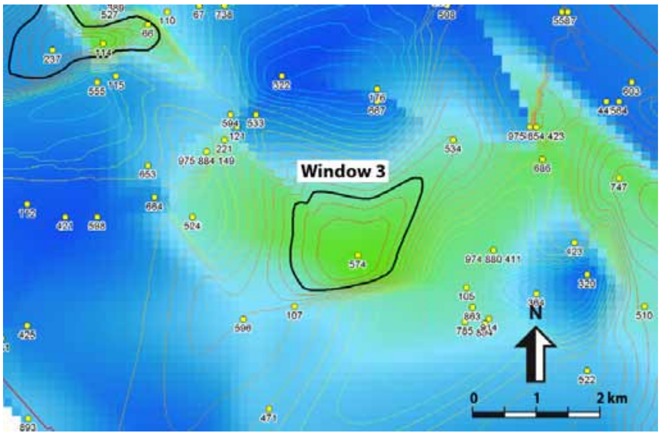

Figure 5 Window 3 and the Swedish Geological Survey wells in the area

Well 574 was drilled in 1961 with cable tool technique, which normally provides opportunities for taking proportionately good samplings. The description of the stratigraphy is however brief: 0-0.5 m soil; 0.5-9 m; clay and gravel; 9-124 m sand; 124-132 m limestone and flint. This short description of the stratigraphy, along with the lack of samplings gives a low degree of credibility. The first two layers in the stratigraphy for well 574, consisting of soil, clay and gravel respectively, might in principle be anything. The third layer, 9-124 m sand, is also doubtful but is not necessarily wrong. The same discussion as that referring to well 66 (window 2) and 842 (window 1) above may be applied here. The stratigraphy for well 574 can also be compared to that of well 114 (window 2).

Three credible descriptions of stratigraphy support the plausibility of a window in the area. These bores indicate a large proportion of coarse sediments in the stratigraphy.

The wells 534 and 686 were drilled by cable tool technique in 1980 and 1990 respectively. The samplings are considered credible and have been taken at levels 15m and 5m respectively. It was discussed whether well 686 at Assartorp, would also be a separate window, but since that well was artesian, it was assumed this is not a window. According to an oral tradition, there is also a well near well 686 which is said to have a very high proportion of sand. Data from well 534 have been used in order to evaluate the upper surface (+25m) of the coarse sediments, situated comparatively near the surface.

Well 107 was drilled in 1954. The drilling technique is not known from the well protocol. Samplings have been taken at 27 levels. Data from well 107 have been used in order to evaluate a relatively superficially situated upper surface (+15 m) of the coarse sediments.

On the hydro-geological map from 1977 (Trelleborg NO/Malmö SO), a west-easterly profile by Holmeja, just south of window 3, is illustrated. The illustration of the soil layers of the profile shows a part which consists of a comparatively thin till layer at the surface and then sandy sediments down to the bedrock. Of the above mentioned wells, only wells 107 and 574 existed when the map was produced, (figure 5-6).

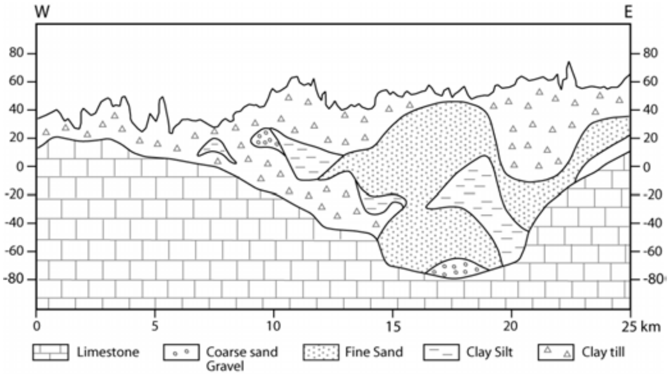

Figure 6 Simplified description of the soil layers from the Alnarp Valley, after section B-B’, Hydrogeological map Trelleborg NO/Malmö SO (Swedish Geological Survey, 1977). Holmeja is located at approximately the 15 km mark. Eksholm is located approximately at 18 km.

The description appended to the hydrogeological map (Gustafsson, 1978) mentions that fluvial-glacial-deposits exist at Eksholm, Råbergsslätt and Assartorp. These are located approximately 1-2 km east of window 3 (figure 5-6). The fluvial-glacial-deposits at Eksholm may be in contact with coarse sediments, and it is not unlikely that this is also the case at several locations in this area.

As a conclusion, there are indications of a window, but the existence of a window cannot be verified, since the reliability of the centrally located drilling hole has been judged as comparatively low.

5. Summary: Windows

To sum up there are indications of different reliability of the existence of windows in these three areas. Window 2 is considered to be the most trustworthy, while window 3 and especially window 1 are less reliable. The existence of the windows has not been verified.

Drillings 842, 66 and 574 have a large effect on these analyses, but since the reliability of the drillings are questionable, the existence of the windows is also questionable. The fact that the drillings that have a major effect on the analyses are of questionable reliability is troublesome. Still, even if there are no entire reports of proper tests of a particular drilling hole, the drilling results cannot be disregarded. After all, it is areas with similar layer sequences and fast vertical transport routes that are of interest for the purpose of protecting the groundwater.

II. REGIONAL AND SEMI-REGIONAL MODELS

A. A conceptual geological model

The conceptual geological model is based on the geological description presented above.

The groundwater model is principally based on a stratigraphy that consists of three layers:

Soil layer above the sandy Alnarp sediments
Grevie sand and sandy Alnarp sediments
Bedrock

B. Groundwater recharge

Large groundwater outtakes have been made from the Grevie source of supply in the aquifer of Alnarpsströmmen for more than 100 years. Groundwater is taken from the so called Grevie sand, i.e. from drilled wells. As a result, large depressions of the pressure levels of the groundwater have occurred. Early on, groundwater recharge was expected through infiltration in elevated areas around Svedala and on the hillsides of the Romeleåsen horst. When the pressure level depressions developed, additional leakage was generated from the upper soil layers down to the Grevie sand. Outflow areas can transform into inflow areas in cases where groundwater leakage to the soil layers ceases.

A leakage has been created from the upper soil layers to the Grevie sand. The amount of leakage is dependent on the local hydrogeological conditions. In cases where the upper soil layers covering the Grevie sand is comparatively impermeable, the soil does not release any water to the Grevie sand. Hence, the effects on the groundwater in the soil layers are minor.

Leakages from soil layers to the Grevie sand may occur as long as there is water in the soil layers. A large leakage between groundwater aquifers does not necessarily bring severe consequences. As long as a recharge of the upper aquifer takes place simultaneously with the leakage, a groundwater surface is maintained in the soil layers.

C. Hydrological boundaries

The hydrological boundaries of the regional model consist of the sound between Sweden and Denmark (Öresund) in the west, the Baltic Sea in the south and the Romeleåsen horst in the north-east. The Romeleåsen horst is considered a water divider, while Öresund and the Baltic Sea are considered constant heads.

D. Background material

The characteristics of the model are based on studies of maps and literature and on the analyses described in section 1. No complementary field studies have been conducted.

E. Hydraulic characteristics

The bedrock aquifers of the area covered by the model has been divided into 9 categories according to their characteristics. The groundwater map of the Swedish Geological Survey has been used for the classification. The description of the categories, according to the map, is presented in table 1 below (Gustafsson, 1999). The categorical areas are presented as lenses in the groundwater model. The characteristics of one of these lenses (aquifer in fractured and porous bedrock) has been used as an initial characteristic of geological layer 3 (bedrock), table 2. For each categorical area, hydraulic characteristics, such as hydraulic conductivity, effective porosity and specific storage, have been assigned to the model.

TABLE 1 THE HYDRAULIC CHARACTERISTICS OF THE BEDROCK, ACCORDING TO THE GROUNDWATER MAP OF SCANIA

Description	Exploitation potential	Median capacity (m^3/d)
Aquifers in fractured and porous bedrock	Extraordinarily good	>1500
Aquifers in fractured and porous bedrock	Excellent	500-1500
Aquifers in fractured and porous bedrock	Very good	150-500
Aquifers in fractured and porous bedrock	Good	50-150
Aquifers in fractured and porous bedrock	Fairly good	15-50
Aquifers in fractured bedrock	Very good	150-500
Aquifers in fractured bedrock	Good	50-150
Aquifers in fractured bedrock	Fairly good	15-50
Small ground water resources	Poor	<15

To assign values of hydraulic conductivity, the values of the outtake capacity from the groundwater map have been utilised. Random samples have been conducted, based on available pumping tests previously conducted. Also, in the calibration process, some corrections have been made in order to reach the final values of hydraulic conductivity assigned to each categorical area.

F. A conceptual numerical groundwater model

The conceptual numerical model contains all the limitations and uncertainties associated with the conceptual geological model. Additionally, there are the differences between conceptual geological and conceptual numerical models.

The hydraulic calculation model is designed as a system of right angle cubes (cells). The cells in the regional model have a surface of 1,200 m x 1,200 m, i.e. 1.44 km^2, while the cells in the semi-regional model have a surface of 400 m x 400 m, i.e. 0.16 km^2

In the model, the cells form a system of rows, columns and layers. The regional model has a total surface of 2,075 km^2, or a total of 1441 cells/calculation layers, while the semi-regional model has a total surface of 836 km^2, or a total of 5225 cells/calculation layers.

G. Assigning boundary conditions

In the regional model, the boundary condition 'constant head' has been used for the outer cells in the Baltic Sea and Öresund. In calculation layer 1 'Soil layer/Sediment 1' the boundary condition 'constant head' has been used for cells located in the ocean. For the calculation cells by the north-eastern limits of the model, along the Romeleåsen horst, the boundary condition 'impermeable border' has been used for all the calculation layers.

Precipitation is included in the groundwater model. In the upper calculation layer, drainage was included, meaning that when the groundwater level is approaching the ground surface, the groundwater is drained as shallow runoff.

The drainage in the model is located 2 m below the ground surface. This is motivated by the fact that the most shallow soil layers tend to have a higher permeability. The time constant for the drainage was assigned a value of 1x10^{-7} s-^{1}.

H. Assigning hydraulic characteristics

The geological soil map of the area consists of 75 different classes (soil types, outcroppings of bedrock etc.). The soil layers of the model have been divided into five classes, based on the soil map. These areas have been modified into lenses in a layer when translated to the groundwater model. Another modification has been made since the shapes in the soil map are natural, while the cells of the groundwater model are square shaped.

The modified soil map class 3 comprises, among others things, sandy till. An estimate of the hydraulic conductivity of this soil type, k value, is in the interval of 1 x 10^{-6} - 1 x 10^{-8} m/s (Knutsson & Morfeldt, 1973). More recent research has shown that microstructure and particle orientation have a large impact for the k value, and also that the difference is substantial between horizontal and vertical k value. A summary of Swedish and Nordic tills, mainly coarse-grained, from depths greater than 40 cm gives a mean value of 3 x 10-6 m/s (Knutsson & Morfeldt, 1993; Lind, 1990).

In Sweden, a common value of (Kh/Kv)0.5 is approximately 5 (Landberg, 1982). Hence, in soil layers containing fine materials, the vertical k value has been assigned as approximately 20 times less permeable than the horizontal, table 2.

TABLE 2 HYDRAULIC CHARACTERISTICS IN THE LAYERS OF THE GROUNDWATER MODEL

Layer	**Description**	**Hydraulic conductivity K_h (m/s)**	**Hydraulic conductivity $K_{,v}$ (m/s)**	**Effective porosity (%)**	**Specific storage (1/m)**
1	Sediment 1	1×10^{-8}	5×10^{-10}	2	1×10^{-5}
2	Sediment 2	1×10^{-6}	5×10^{-8}	5	1×10^{-5}
3	Bedrock*	8×10^{-6}	8×10^{-7}	2	1×10^{-5}

* Corresponds to aquifer in fractured and porous bedrock with excellent exploitation potential, see table 1

In the process of assigning horizontal k value to the categorical areas in table 2, values from experience (Knutsson & Morfeldt, 1973, 1993), as well as Hazen's formula, have been used. Modifications have been made in order to improve the calibration. The final values are presented in table 2.

I. *Assigning effective precipitation*

The precipitation in the south-western part of Scania varies between the coastal areas and the elevated areas. The effective precipitation (precipitation minus evaporation) is also dependent on the proportion of precipitation lost through evapotranspiration. The evapotranspiration is estimated as 400 mm/year. The mean annual precipitation varies between approximately 600-700 mm/year. Hence, the effective precipitation is estimated as approximately 200-300 mm/year. This corresponds to a total runoff of approximately 6 l/s, km^2.

J. *Groundwater outtakes*

Available information about municipal and industrial water outtakes from Alnarpsströmmen has been utilised. Information regarding private water outtakes, e.g. for irrigation, was not available.

III. CALIBRATION AND VALIDATION

A. *Calibration and validation data*

Calibration was conducted for the period from 1st of March 1965 to 1st of March 1980. The results for each 28th day have been saved, and compared to observed values from the observation wells, figure 7-9. In the same manner, validation was conducted for the period from 1st of March 1980 to 1st of March 1995, figure 10.The observation wells used are part of the control programme for Alnarpsströmmen. In the regional model, 34 observation wells were used, in the semi-regional model, 32 wells and in the local model, 14 wells.

B. *Results*

Calibration has been conducted for the extracted amounts of groundwater and also for the measured groundwater level variations. The values used derive from the groundwater control programme for Alnarpsströmmen.

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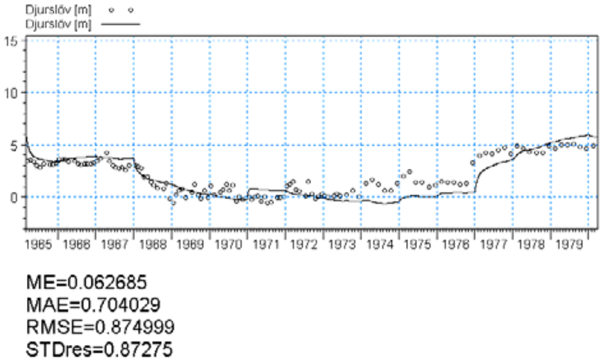

Figure 7 Calibration results from the observation well at Djurslöv from the regional model. Circles correspond to observed values, and the line corresponds to simulated values.

When evaluating the calibration, it can be concluded that the differences between the simulated and the actual pressure heads exist when comparing individual wells. This is due to the fact that the model is unable to reproduce the conditions of Alnarpsströmmen exactly.

As an attempt to quantify the differences, the differences between the measured and the simulated values were calculated

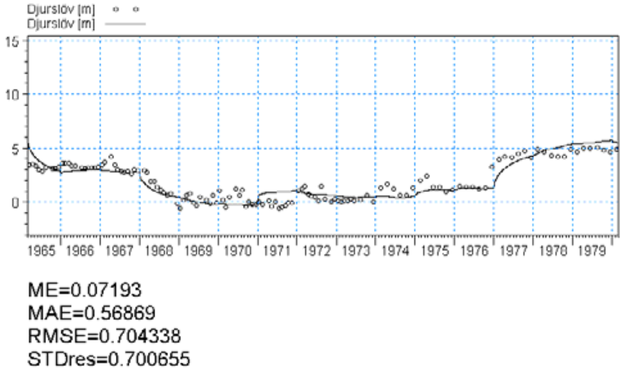

Figure 8 Calibration results from the observation well at Djurslöv from the semi-regional model. Circles correspond to observed values, and the line corresponds to simulated values.

C. *Summary of the regional and semi-regional models*

The regional and semi-regional models have been calibrated and validated for a large area. The average model errors are in the same order of magnitude as expected for large scale groundwater models. The regional model has a mean MAE of 2.3 m (calibration) and 2.8 m (validation), while the semi-regional model has a mean MAE of 2.0 m (calibration) and 2.2 m (validation).

The results from the individual observation wells differ, but the majority of the deviations are less than ±3 m for the regional model. The calibration goal is achieved for 72% and the validation goal is achieved for 75%. The higher goal of the semi-regional model ±2 m is achieved in 63% and 47% of the observation wells, respectively.

The calculations show varying results. Even if the absolute water level is wrong in many wells, which to a large extent is caused by the large cells, the dynamics of the simulated time series indicate that the model is able to describe the effects of the large groundwater outtakes conducted during 1965-1995. Also, the average STDres values are moderate, again indicating that the dynamics of the model are well described.

D. A local model – A conceptual numerical groundwater model

The hydraulic calculation model is designed as a system of right angle cubes (cells). The cells in the local model have a surface of 200 m x 200 m, i.e. 0.04 km2. The local model has a total surface of 275 km^2, or a total of 6867 cells/calculation layers.

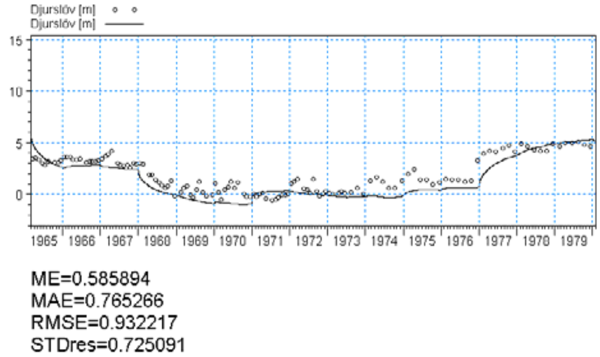

Figure 9 Calibration results from the observation well at Djurslöv from the local model. Circles correspond to observed values, and the line corresponds to simulated values

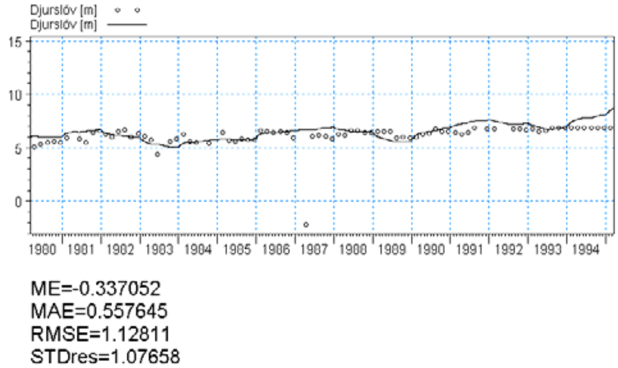

Figure 10 Validation results from the observation well at Djurslöv from the local model. Circles correspond to observed values, and the line corresponds to simulated values

IV. SCENARIO SIMULATIONS

A. Scenario 1 and 2 - ground water recharge

In scenario 1 and 2, the groundwater outtakes at Grevie have been assigned for the period 1994-2002. The outtakes were assigned to 200 l/s and 270 l/s, respectively. The outtakes were divided between the existing groundwater wells and 11 new wells.

B. Results from scenario simulations 1 and 2

The results from scenario 2 are presented in figure 11. In the figure, the vertical groundwater transport through calculation layer 1, or sediment 1, is presented. Four different colours illustrate calculated groundwater transport upwards or downwards, exceeding or falling below 25 mm/year. Downward transport represents recharge of groundwater to the Grevie sand, while upward transport represents a groundwater flow from the Grevie sand to an outflow area. Based on the precipitation data, the year 1994 has been chosen for presentation. This year correspond to a wet year.

Figure 11 shows large areas with a downward vertical groundwater transport between 0 and 25 mm/year. At the three windows, a downward transport exceeding 25 mm/year is illustrated. An interesting area can be seen at Sturup airport, where both the Torreberga stream and river Höje å have their sources. The ground surface here is comparatively elevated and the soil map indicates sandy till, and, at Sturup, filling on sandy till.

The calculated outflow areas are shown, e.g. at Lake Yddingen, and parts of river Sege å and the Torreberga stream.

The maps for the scenarios and for different years look very similar. Only small differences can be detected between them. If the maps from a wet year, 1994, and a dry year, 1997, are compared, a difference in downward vertical groundwater transport exceeding 25 mm/year can be detected at Sturup. If the maps for scenario 1 and 2 are compared, it can be concluded that the vertical transport at the Torreberga stream, by the Torreberga outtake wells, has changed from being directed upwards for a groundwater outtake of 200 l/s to being directed downwards for an outtake of 270 l/s.

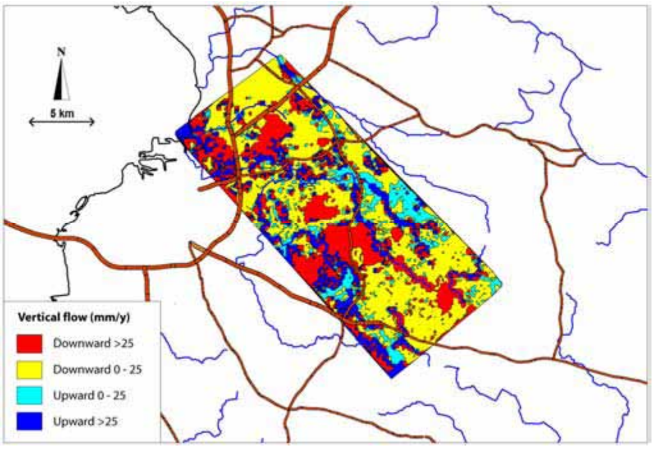

Figure 11 Vertical groundwater transport through the upper soil layers, (calculation layer 1)

There have also been some calculations of particle tracking at the Grevie wells. These calculations show that only some of the recharge areas shown in figure 11 are important for the Grevie wells, and these have now been assigned as water protection areas.

C. Ongoing calculations

Groundwater extraction at Grevie has increased during some periods and decreased during other periods over the last

100 years. There are intentions to use the ground water models for calculating the maximum production volume. This is interesting, since there have been some discussions of increasing the ground water extraction in order to provide an extra fresh water supply for other Swedish, or maybe even Danish, communities. Another area of interest is the potential ground water transport from the limestone to the production wells, up coning, and also salt water intrusion in the coastal areas.

Up coning was expected in the early 1950s and early 1970s, when there was a great ground water discharge from Alnarpsströmmen. Important questions regarding the amount of water which can be produced, and where to put the production wells in order to avoid salt water transport, have to be examined.

Calculations on pollution transport have also been made near the possible water protection area. Examples of calculations are fictive highway accidents, figure 12, old land fills and closed petrol stations

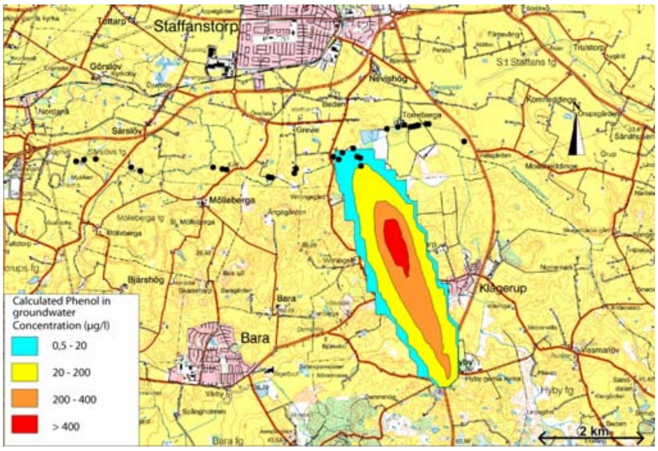

Figure 12 Calculation on pollution transport - fictive highway accident – 30 years transportation

V. DISCUSSION

The groundwater model of Alnarpsströmmen is a summary of several parts of information and data, some of them more than 100 years old. All these parts, as well as the model itself, are associated with some uncertainties and errors. Even if the uncertainty of each part of the input data were known, the overall uncertainty of the model result would still be impossible to calculate, since the groundwater model is non-linear.

In the documentation of the model, the uncertainties in a groundwater model are summarized. All these limitations are probably present in the groundwater model of Alnarpsströmmen. One example is the difference between simulated and observed groundwater pressure levels in the observation wells. The results vary and for some check-points, the model and the observed value coincide, whereas at other check-points, they differ considerably.

The validity of the model and the calculated results of specific scenarios are partly dependent on these uncertainties. It is however necessary to evaluate the importance of the uncertainty as a function of the overall goal of the model. Without knowing what that final goal is, any limitation of the model has no physical meaning and causes no problem either. Our effort has been to model the recharge and discharge areas of the aquifer, especially those related to the Grevie well area and to calculate the variation in the groundwater pressure of the aquifer.

The regional and semi-regional models indicate that both the static values and dynamics of pressure levels can be modelled accurately within the large geographical area covered by the model. The total errors according to the validation process are the same as in the calibration process and of the same size as one expects for groundwater models stretching over such a large area. The errors originate mainly from the fact that the observation wells are not always centred in the middle of the FD-cell. Even so, the accuracies of the regional and semi-regional models are sufficient for providing border conditions for the local model.

The requirements of the local model are set higher, since the model aims to calculate the groundwater pressure sufficiently accurately for any scenario at any given point of the area covered by the model. The calibration and validation processes show that the local model can be used for representing the dynamics and the pressure levels in the well area (Grevie) and in the areas north of Grevie (Djurslöv, Uppåkra, Åkarp), but that the areas to the south of Grevie (Hyby, Vinninge) cannot be modelled with the same precision.

South of Grevie, the geology is very complex due to glacial tectonic movements. Given the limited number of observation points of the soil and bedrock in this part of Alnarpsströmmen, it is probably not possible to describe this complex geology correctly. The geological and hydrogeological properties of this area are probably not accurately modelled.

The conclusion is still that the local model can be used to describe the groundwater dynamics at the Grevie well area. The local model can be used to predict different operational conditions in the well area. The calibration and validation processes have been performed on extracted conditions applicable between 1965 and 1995, a time span during which both very high and more modest extractions were conducted. Since the model has represented the reality during this entire period, it gives a robust and reliable impression and should be capable of calculating the effects of different water extraction situations on recharge, discharge and groundwater pressures even for the future.

From a water protection point of view, the model needs to predict recharge and discharge areas. It should identify any potential threat for the Grevie water well area. The question is how well the location of the so called windows have been identified.

Three possible windows have been introduced into the models. One is situated west of Staffanstorp, one in the present water protection area between Bara and Klågerup, and one at Holmeja. These windows are the result of the efforts that have been put into interpreting the present data from the well archive and from soil maps of the region. Our conclusion is that the local groundwater model is sufficient for describing the different recharge and discharge areas, but that the exact position of the possible windows is uncertain. According to the different scenarios, it is still obvious that short-cuts allowing water to infiltrate rapidly through these windows down to the groundwater will affect the water quality negatively. The location of the windows should be identified and sufficient actions taken to protect them against damaging water infiltration.

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