# Numerical modelling of an unconsolidated aquifer, Birkelandsmoen, Sauda, Southwest Norway

DAVID SEGAR

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The aquifer formed by the fluvial deposit of the River Storelva at Sauda in Rogaland has been investigated by geophysical measurements, drilling, pumping and groundwater modelling techniques. This aquifer is being considered as a potential water supply source for Sauda municipality. The principal objectives of the study were i) to provide a more accurate assessment of the aquifer's capacity than that provided by previous studies, ii) to determine the effect of municipal abstraction on an abstraction borehole owned by a mineral water company and iii) to assess the use of artificial recharge to reduce any such effect.

The groundwater flow model MODFLOW and the particle-tracking model MODPATH were used to model the aquifer. This modelling indicated that the capacity of the aquifer is approximately 20 l/s. The modelling also indicated, however, that any significant municipal abstraction will alter the groundwater flow pattern in the aquifer and may lead to increased pumping costs for the mineral water company as a result of increased drawdowns in the aquifer. The modelling results also indicate that although artificial recharge may enable municipal abstraction to be increased without resulting in additional drawdown at the mineral water borehole, the integrity of the mineral water may be compromised.

*David Segar, Norges geologiske undersøkelse, Postboks 3006 Lade, 7002 Trondheim, Norway.*
*(Present address: 5 The Paddocks, Cockermouth, Cumbria, CA 13 0ZA, England)*

## Introduction

Due to the requirement for an alternative water source to the current surface water supply, the municipality of Sauda in the county of Rogaland asked the Geological Survey of Norway (NGU) to assess potential groundwater sources in the municipality. The capacity of the unconsolidated aquifer at Birkelandsmoen has been demonstrated in previous studies (Viak A/S 1991 and 1992). However, concerns over the possible effect of development of the aquifer on an existing abstraction borehole being operated by a mineral water company led to the request by Sauda municipality for an assessment of the effects of the construction of a new groundwater pumping station on the groundwater flow in the aquifer and, in particular, on the mineral water abstraction currently taking place.

Numerical groundwater modelling techniques were chosen to assess the potential effects of the construction of the pumping station as a method was required which could cope with the complexity involved in the assessment of the effects of abstraction from an anisotropic heterogeneous unconsolidated aquifer of limited lateral extent interacting with a river.

The initial field investigations consisted of a Georadar survey and a site visit. Data from previous field investigations on the aquifer were also used in the study. These data included investigation boreholes and test pumping results (Viak A/S 1991 and 1992) and a seismic survey (Geoteam A/S 1981). These data were then interpreted and entered into a three-dimensional mathematical groundwater flow model. Following calibration, the model was used to simulate the groundwater flow in the aquifer under various abstraction scenarios. The possibility of using artificial recharge was also assessed using the model. A particle-tracking model was used to determine groundwater flow paths and flow rates under these scenarios.

## Geology and hydrogeology

The aquifer studied lies in the area of Kleivflåta, Birkelandsmoen, next to the River Storelva in the municipality of Sauda, 80 km northeast of Stavanger (Fig. 1). This aquifer is a fluvio-glacial deposit and consists of interlayered gravels, sands and silts. There are no overlying low-permeability layers and the aquifer is consequently unconfined.

A bedrock shelf that extends from Herheim in the northwest to Særmyrhaugene in the southeast dominates the geometry of the aquifer. The location of this bedrock shelf is shown in Fig. 1. Borehole 9103 is located immediately adjacent to this shelf and shows 12-13 m of fine-grained material overlying the bedrock. The thickness of the aquifer increases rapidly downstream and by borehole 9102 the aquifer is approximately 20 m thick. The aquifer in the area of this borehole is much coarser grained and consists predominantly of sands and gravels. The aquifer shows a reduction in grain size again towards borehole 9104 which indicated unsorted medium- to fine-grained sands and gravels to a depth of at least 19 m. The Georadar profiles taken in the area support this interpretation.

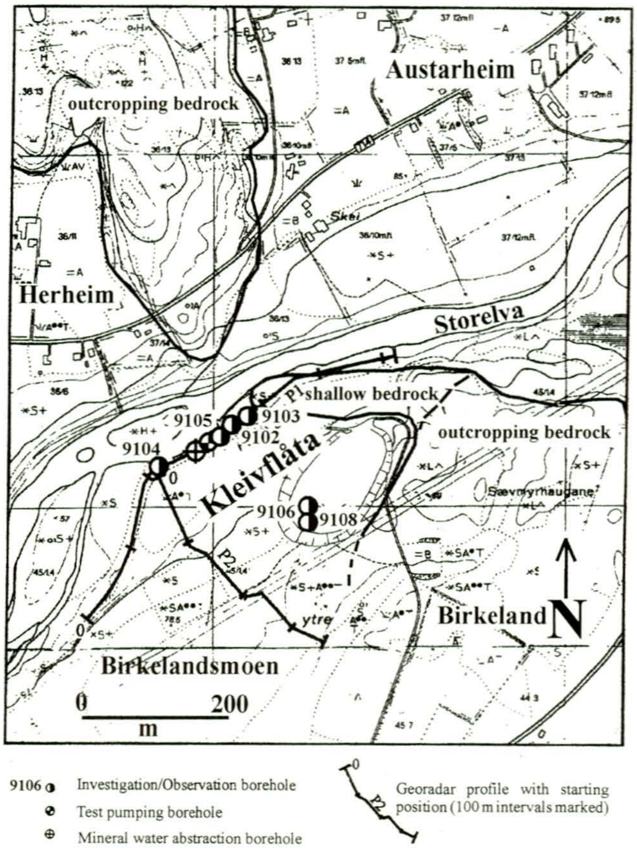

Fig. 1. Map of the Kleivflåta and Birkelandsmoen study area showing the investigation boreholes and Georadar profiles.

No clear vertical division of the aquifer can be established on the basis of geological logs from boreholes or the Georadar profiles taken in the area. Crude field measurements of permeability taken by Viak A/S (1991) suggest, however, that the geological profile can be divided into four layers. The hydraulic properties of these layers vary considerably laterally, however, and in areas such as the bedrock shelf, no geological differentiation of the vertical profile is possible. A summary of the generalised characteristics of these layers is given in Table 1.

The aquifer's lateral extent and thickness were assessed on the basis of topography, a seismic investigation carried out by Geoteam A/S (1981), a Georadar survey and field mapping undertaken by NGU in 1996 and an interpretation of a pumping test on a borehole adjacent to borehole 9105 by Viak A/S (1992). Areas with exposed bedrock were mapped in the field. These areas were considered to represent the physical limit of the aquifer.

| Layer | Geological description | Approximate thickness (m) |
|---|---|---|
| 1 | Predominantly highly permeable sandy gravels. | 11 |
| 2 | Permeable to highly permeable coarse sands and gravels. | 3-6 |
| 3 | Permeable gravels and sands. Highly permeable near borehole 9105. | 3-6 |
| 4 | Bedrock | - |

Table 1. Simplified characteristics of the geological profile in the Kleivflåta area.

Data on the aquifer's permeability, porosity and specific yield were obtained from grain-size distributions using the Bayer method (Langguth & Voigt 1980). Estimates of the aquifer's transmissivity and specific yield were also obtained from the test pumping results from Viak A/S (1992) using the Neuman (1975) and Cooper & Jacob (1946) methods.

Interpretation of drawdown data from borehole 9108 during the test pumping by Viak A/S (1992) using Stallman's method (Kruseman & de Ridder 1992) indicates that low-permeability material exists approximately 32 m from this borehole (the method gives no indication of direction). A site visit revealed that bedrock was exposed in an area southeast of borehole 9108 that was consequently interpreted as an aquifer boundary. Interpretation of drawdown data from borehole 9104 using Stallman's method also indicated that there is low-permeability material approximately 93 m from this borehole. The site visit showed that there are springs in this area.

Layers 1, 2 and 3 are assumed to extend over the entire area but borehole logs, grain-size distributions and Georadar profiles from the area indicate that these layers vary considerably in composition both vertically and horizontally.

The aquifer is recharged by precipitation and infiltration from the River Storelva, which is regulated. Groundwater levels in the area along the River Storelva are controlled by the water level in the river (Viak A/S 1991). Viak A/S (1991) also state that this infiltration is reversed during periods of low flow in the river. The flow in the river is usually low and flows between 0.7 and 1.7 m3/s are most common (NVE 1996) but it can increase to between 2-85 m3/s for short periods. Recharge from precipitation was estimated as a percentage of total precipitation. A preliminary value of 770 mm/yr (35% of the total precipitation) was used.

Abstraction from the aquifer at the mineral water borehole (see Fig. 1) currently takes place at an average rate of approximately 1.7 l/s.

## Simulation of groundwater flow in the aquifer

The United States Geological Survey (USGS) three-dimensional groundwater flow model MODFLOW (McDonald & Harbaugh 1988) was selected to simulate the groundwater flow in the aquifer. The USGS particle tracking code MODPATH (Pollock 1989) was used to calculate groundwater flow lines and residence times. By calculating groundwater residence times in the aquifer under different abstraction scenarios, MODPATH can be used to investigate the effect of exploitation of the aquifer from a new groundwater pumping station at Kleivflåta.

The data files which MODFLOW and MODPATH require were constructed using Visual MODFLOW (Waterloo Hydrogeologic Inc.) which was also used to present the output results graphically.

## The mathematical model

The finite-difference grid and the hydraulic boundaries used to simulate the aquifer are shown in Fig. 2. The grid consists of four layers, which represents layers 1-4 shown in Table 1. The outer edge of the grid represents a no flow boundary with the river acting in such a way as to direct the regional groundwater flow in a southwesterly direction. The cells representing the aquifer occupy the valley trending northeast-southwest across the grid. Outside of the aquifer the grid is formed of cells representing low-permeability bedrock. In areas where bedrock is considered to crop out, all layers were assigned the hydraulic properties of the bedrock. In order to check the validity of the grid boundaries, the model was tested with alternative boundary conditions. As no discernible effect could be seen on the groundwater flow in the vicinity of the aquifer it was considered that the boundaries were satisfactory.

The grid consists of smaller blocks in the vicinity of the pumping boreholes in order to increase the model's accuracy in this area. Each block in each layer is assigned a preliminary value for aquifer thickness, permeability, recharge rate (from precipitation) and a starting groundwater head value. The preliminary values for aquifer thickness, permeability and recharge rate were adjusted during model calibration.

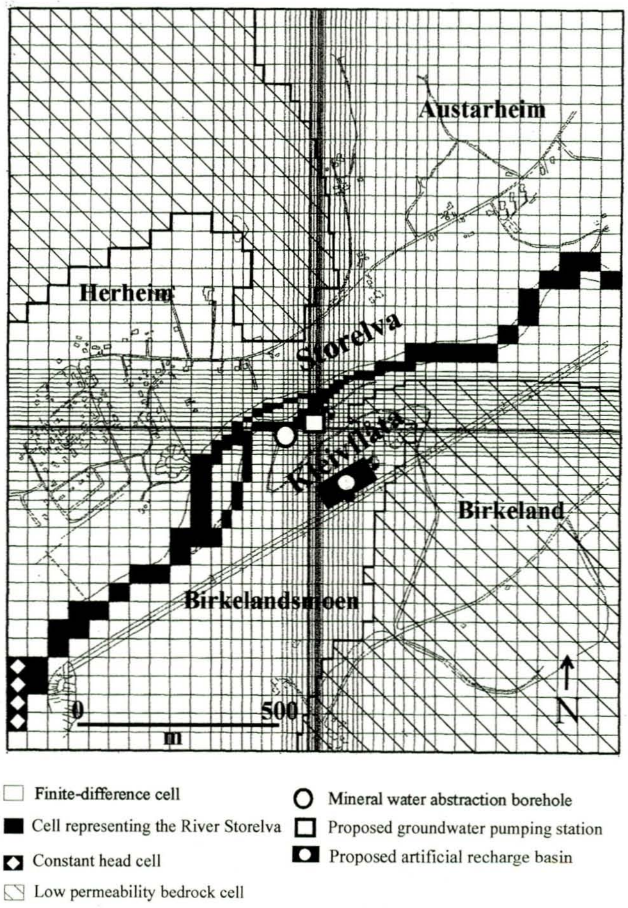

Fig. 2. The MODFLOW finite-difference grid used to simulate the aquifer at Birkelandsmoen (grid numbers shown in metres).

A topographic map at a scale of 1:5 ,000 of the area was digitised using SURFER (Golden Software Inc.) and the resulting data file was imported into Visual MODFLOW. A digitised map of physical features in the area (roads, rivers, buildings, etc.) was also constructed using CorelDraw and imported into Visual MODFLOW.

The River Storelva was simulated using the river package in the MODFLOW model. Water levels in the river were taken from level data measured by Sauda municipality during the pumping test carried out by Viak A/S in 1992. The flow in the river at the time these measurements were taken was approximately 0.7-1.5 m3/s (NVE 1996). The transient model took into account observed changes in the river water level during the pumping test simulated. River leakage factors were adjusted during the model calibration process.

## Calibration of the MODFLOW model

A steady state version of the MODFLOW model was calibrated by simulating the observed groundwater levels prior to the test pumping undertaken by Viak A/S (1992). The estimated recharge rate was fixed during the calibration procedure and the estimated hydraulic parameters adjusted until the simulated groundwater levels were sufficiently close to the observed levels (based on a minimising of the root mean square of the errors in observed versus simulated groundwater head). Adjustments were only made to parameters for which imprecise estimates were available or where data were lacking.

A time-variant version of the model was calibrated by simulating the groundwater levels during the test pumping by Viak A/S (1992). The steady state version of the model was used as a starting point for this process. The estimated hydraulic parameters from the steady state version of the MODFLOW model were further adjusted until the model successfully simulated the groundwater levels during the first 14 days of the pumping test. Following a successful simulation of these data, the model was then run again as a steady state model in order to check whether the adjustments that had been made had altered the steady state version of the model. This process was repeated until the model could simulate both the steady state groundwater levels before the test pumping and time-variant drawdown during the test. Assessment of the success of the model calibration process was undertaken by a visual inspection of a comparative plot of simulated and observed groundwater heads. The pumping test was carried out during a period of negligible recharge from precipitation and the errors involved in the time-variant calibration are consequently expected to be comparatively small.

## Simulation of flow in the aquifer during different abstraction scenarios

Following calibration, MODFLOW was used to simulate the groundwater flow in the aquifer using different abstraction scenarios. The particle-tracking model MODPATH was then run using the data output from MODFLOW. The use of MODFLOW and MODPATH together produced data on the groundwater flow directions, flow rates, residence times and groundwater head values under a number of abstraction scenarios. In order to investigate the hydraulic conditions existing in the aquifer and the likely conditions given further exploitation, the models were run using five abstraction scenarios:

1. *Current conditions* with pumping from the mineral water abstraction borehole.

2. *Assessment of the capacity of the proposed groundwater pumping station at Kleivflåta.* This scenario assumes pumping from both the mineral water borehole and the proposed groundwater pumping station. MODFLOW was run a number times with increasing abstraction rates from the pumping station until changes in groundwater flows and drawdowns reached an unacceptable level with respect to the mineral water abstraction borehole.

3. *The effect of construction of a groundwater pumping station.* The MODFLOW and MODFLOW models were used to assess the changes in groundwater flow directions, residence times, etc. which would occur following the construction of a groundwater pumping station at Kleivflåta.

4. *The effect of a reduced abstraction from the proposed groundwater pumping station.* In this scenario it is assumed that abstraction from elsewhere in the aquifer (at a distance where no effect on the Kleivflåta area will occur) results in a reduced abstraction requirement from Kleivflåta.

5. *The effect of artificial recharge.* This scenario assesses the use of artificial recharge to increase the aquifer's capacity and reduce the drawdown at the mineral water abstraction borehole.

## The simulation scenarios

### Current conditions

A map of the groundwater table elevation immediately prior to the test pumping by Viak A/S (1992) is shown in Fig. 3. This map shows that the regional groundwater flow in the aquifer is towards the southwest and that the River Storelva controls the elevation of the water table. The River Storelva recharges the aquifer in the area immediately upstream of the boreholes at Kleivflåta but the groundwater discharges into the river downstream of this area.

Figure 3 shows flow lines for groundwater traced from the mineral water abstraction borehole back to its recharge area. This figure shows that groundwater abstracted at this borehole is derived predominantly from the aquifer northeast of the borehole. The figure also shows that some of the mineral water abstracted is recharged upstream of the bedrock shelf.

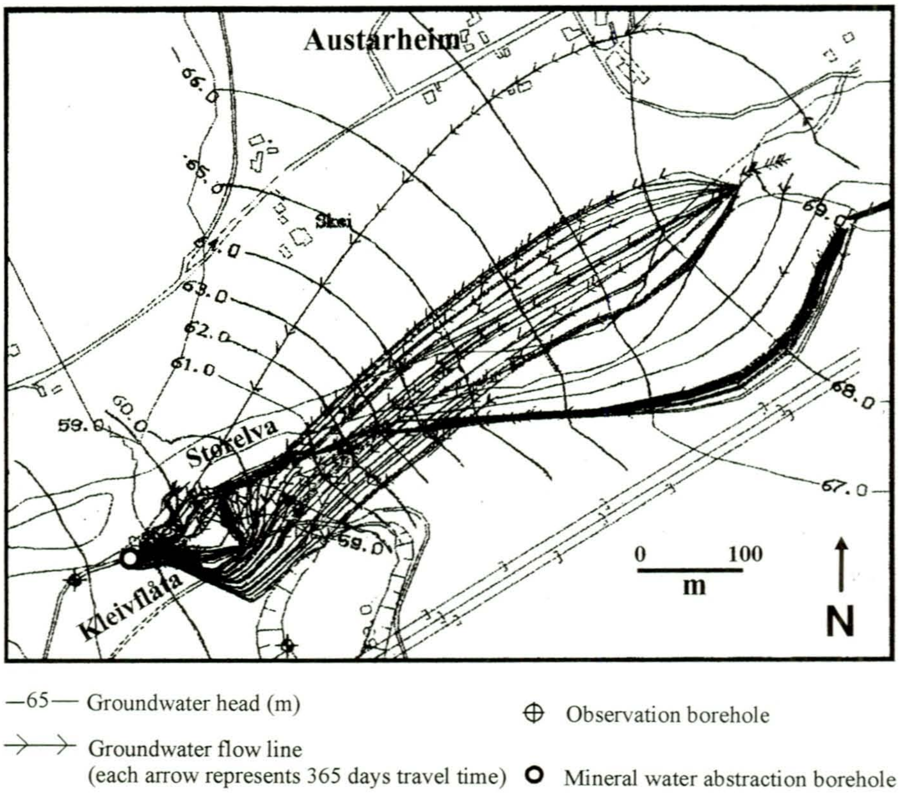

Fig. 3. Simulated groundwater flow pattern occurring during pumping from the mineral water abstraction borehole (1.7 l/s). Grid numbers show scale in metres.

### Assessment of the capacity of the proposed groundwater pumping station

In order to assess the capacity of the proposed groundwater pumping station at Kleivflåta, MODFLOW was run a number of times with a constant abstraction of 1.7 l/s from the mineral water abstraction borehole but with an increasing abstraction rate from the proposed groundwater pumping station. The pumping station's capacity was considered to be the maximum abstraction that does not result in an unacceptable drawdown at the mineral water abstraction borehole.

A graph of abstraction from the pumping station against steady state drawdown at the mineral water borehole is shown in Fig. 4a. The corresponding groundwater levels assuming that the groundwater level with no abstraction from either the pumping station or the mineral water borehole lies at 3.44 m below ground level (b.g.l.). This level represents the level which existed prior to the pumping test carried out by Viak A/S (1992); the results are shown in Fig. 4b. There are no concrete criteria that can be used to determine what drawdown would be unacceptable at the mineral water borehole and this complicates the determination of a new pumping station's capacity. A maximum drawdown of 1.5 m was selected based on the groundwater levels and assumed filter level at the mineral water borehole and the likely errors involved in the modelling process. Using this maximum drawdown, a capacity of approximately 20 l/s is obtained for the proposed pumping station.

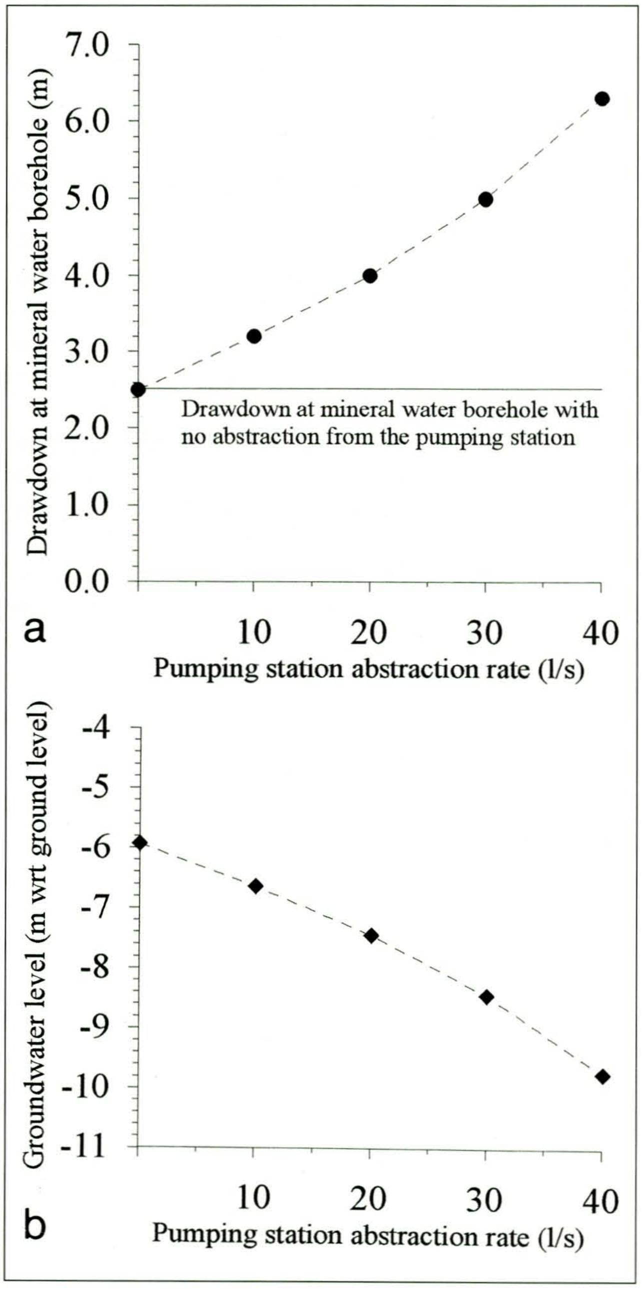

Fig. 4. (a) Simulated relationship between pumping station abstraction rate and drawdown at the mineral water abstraction borehole. No artificial recharge. (b) Simulated relationship between the pumping station abstraction rate and the groundwater level at the mineral water abstraction borehole. Groundwater level without abstraction from the pumping station or mineral water borehole is assumed to be 3.44 m below ground level. No artificial recharge.

### The effect of the construction of a pumping station at Kleivflåta

The flow lines for groundwater abstracted at the mineral water borehole and the proposed pumping station (with an abstraction of 20 l/s) are shown in Fig. 5. This figure shows that, even with an abstraction of 20 l/s from the pumping station, most of the water abstracted from the mineral water borehole is now derived from the River Storelva. The groundwater pumping station has taken over the catchment area of the mineral water borehole. The residence time of the groundwater abstracted at the mineral water borehole is therefore considerably shortened and this may have some effect on the chemistry of the abstracted water, possibly resulting in a softening of the water. The disturbance of the groundwater flow in the aquifer may also have unfavourable consequences with regard to marketing of the abstracted water as 'natural mineral water'. The increased drawdown at the mineral water borehole will also result in increase pumping costs for the company responsible for the abstraction.

### The effect of a reduced abstraction rate from the groundwater pumping station

With abstraction from another part of the aquifer the abstraction required from the proposed groundwater pumping station at Kleivflåta can be reduced. A scenario with a reduced abstraction rate of 10 l/s was therefore considered using the MODFLOW and MODPATH models.

Figures 4a and 4b show that a reduced abstraction from the pumping station gives a much reduced drawdown at the mineral water borehole. The groundwater flow pattern simulated by MODPATH is, however, very similar to that shown in Fig. 5. The results of this scenario therefore indicate that even with this lower abstraction rate the groundwater flow patterns in the vicinity of the mineral water boreholes are significantly altered. This is due to the fact that even an

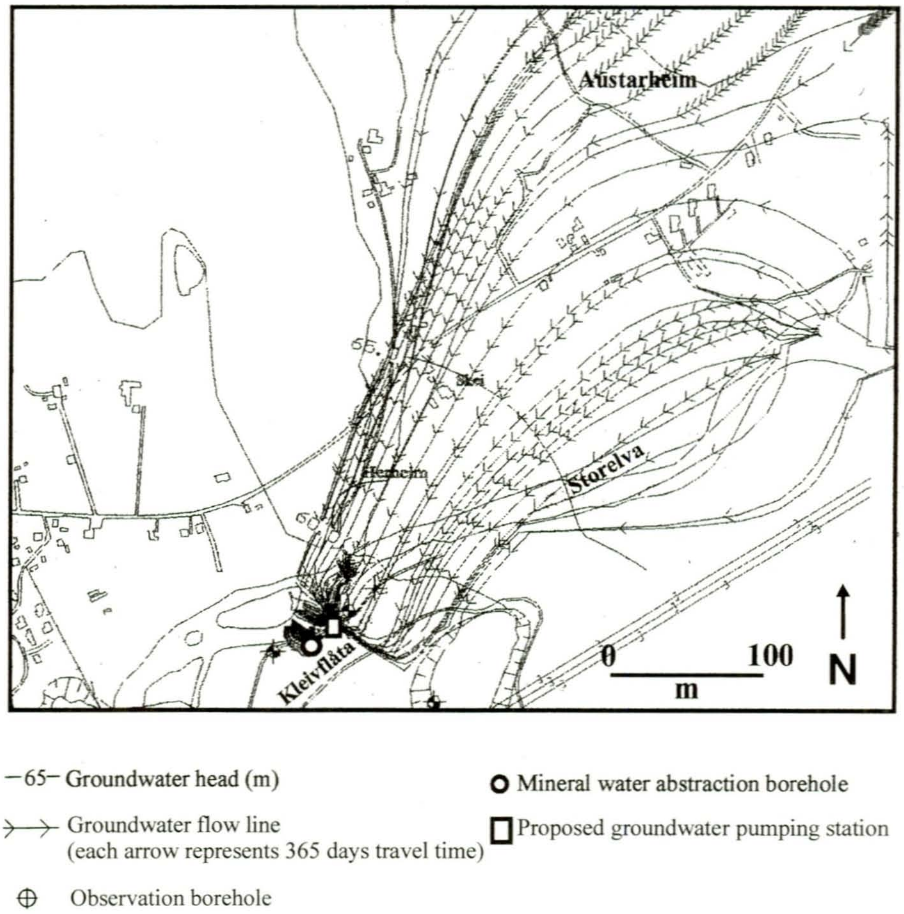

Fig. 5. Simulated groundwater flow pattern occurring during pumping from the proposed groundwater pumping station (abstraction rate 20 l/s) and the mineral water abstraction borehole (1.7 l/s).

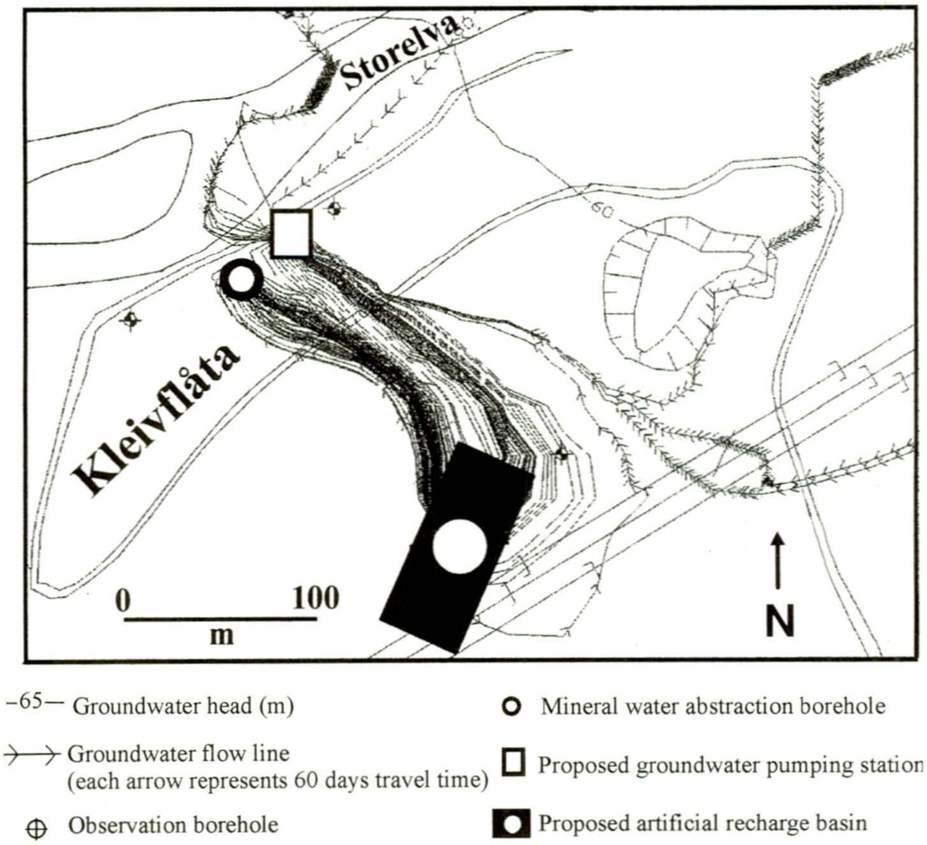

Fig. 7. Simulated groundwater flow pattern occurring during pumping from the proposed groundwater pumping station (abstraction rate 40 l/s) and the mineral water abstraction borehole (1.7 l/s) together with artificial recharge at 40 l/s.

abstraction rate of 10 l/s is still nearly six times that of the mineral water borehole and the pumping station borehole will therefore still take over the catchment area of the mineral water borehole. In this case the mineral borehole is again forced to take more water from the River Storelva.

A reduced abstraction rate from the proposed groundwater pumping station will therefore still have a significant effect on the groundwater flow patterns in the vicinity of the mineral water borehole.

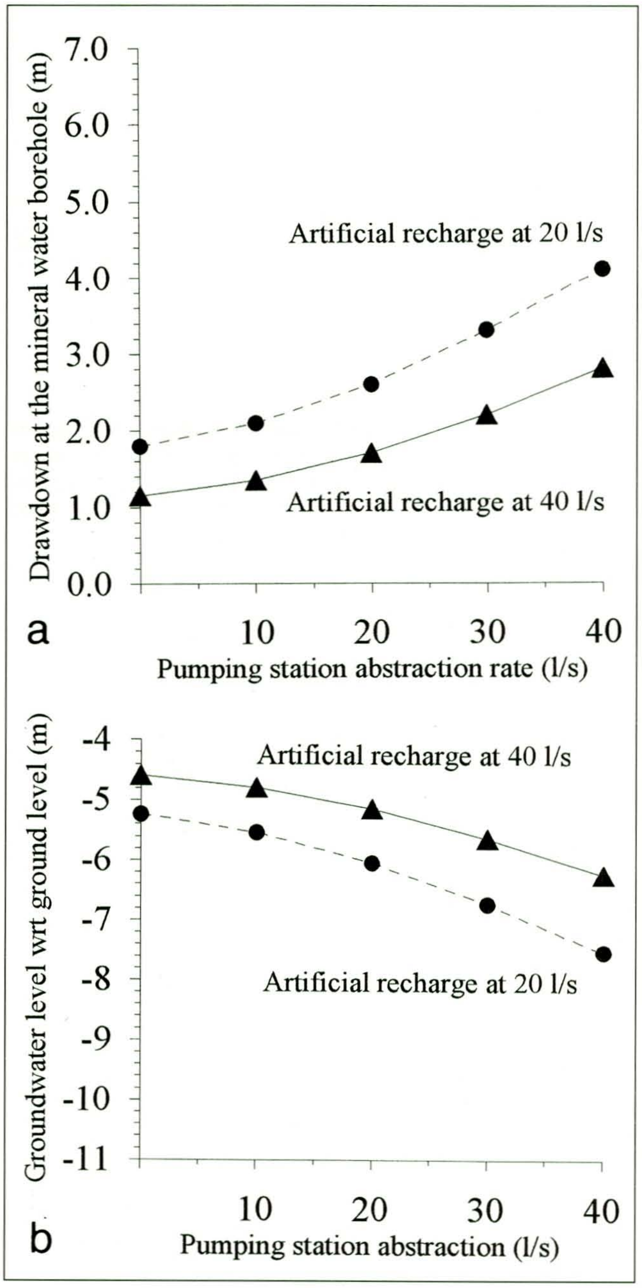

Fig. 6. (a) Simulated relationship between abstraction from the proposed pumping station and the drawdown at the mineral water abstraction borehole. Artificial recharge. (b) Simulated relationship between the abstraction rate from the proposed pumping station and the groundwater level at the mineral water abstraction borehole. Groundwater level with no abstraction is assumed to be 3.44 m below ground level. Artificial recharge.

## Artificial recharge at Kleivflåta

Artificial recharge represents a potential solution to the problem at Kleivflåta. The use of artificial recharge would enable the aquifer's capacity to be increased at the same time as reducing the drawdown at the mineral water borehole. In order to simulate artificial recharge, the MODFLOW model was run with artificial recharge rates of 20 and 40 l/s from a simulated recharge basin in the area southwest of the gravel quarry at Kleivflåta (see Fig. 2). This area was selected as there is a thick unsaturated zone there which will increase the groundwater residence times and enable better cleansing of the water before reaching the saturated zone.

Figures 6a and 6b show the simulated drawdowns and corresponding groundwater levels that will occur with abstraction from the groundwater pumping station and artificial recharge rates of 20 and 40 l/s near the gravel quarry. These figures show that the drawdown in the vicinity of the mineral water borehole is greatly reduced. The use of artificial recharge therefore increases the capacity of the aquifer to approximately 40 l/s without resulting in greater drawdowns.

Figure 7 shows the groundwater flow pattern in the vicinity of the boreholes with an artificial recharge rate of 40 l/s. This figure shows that the mineral water borehole and the groundwater pumping station now draw most of their water from the recharge basin. The groundwater residence times from the basin to the pumping station are less than 20 days and up to 80-100 days to the mineral water borehole. This will result in greater cleansing of the water abstracted from this borehole but may have unfavourable consequences in terms of the marketing of this water as 'natural mineral water'.

With a lower artificial recharge rate the pumping station and the mineral water borehole will draw more water from the River Storelva. This will reduce the effect of the artificial recharge on the mineral water borehole but will also reduce any positive effects in terms of reduced drawdown in the aquifer.

The use of the MODFLOW and MODPATH models therefore indicates that artificial recharge represents a possible solution to the lack of aquifer capacity at Kleivflåta. The model also indicates that the use of this method may have unfavourable consequences for the mineral water company in terms of altering the natural groundwater flow patterns in the aquifer.

## Conclusions

Groundwater modelling techniques combined with detailed field investigations were successfully used to assess the aquifer capacity and the effect of the construction of a new groundwater pumping station in the vicinity of a mineral water abstraction borehole at Kleivflåta in Sauda municipality.

The model results indicated that under current conditions the mineral water abstraction borehole draws most of its water from the River Storelva to the north of the borehole and the aquifer immediately northeast of the borehole. Groundwater residence times are short, being in the order of 30-60 days.

With pumping from both the mineral water borehole and a new groundwater pumping station the groundwater flow patterns in the aquifer are altered significantly. The pumping station borehole will take over the catchment area of the mineral water borehole forcing the latter to draw more water from the River Storelva nearer the borehole. Groundwater residence times are shortened, possibly resulting in small chemical changes in groundwater chemistry. These hydraulic and chemical changes will occur if the abstraction from the pumping station is larger than that of the mineral water borehole.

The model results also indicate that 20 l/s represents the aquifer capacity given the need to avoid excessive drawdowns at the mineral water borehole. Any additional drawdown at this borehole will, however, inevitably result in increased pumping costs for the mineral water company.

The model results have shown that artificial recharge of water from the River Storelva or other source should not have any negative effect on groundwater quantity at the mineral water borehole. Some changes in groundwater chemistry may occur, however, although these changes should not be in any way negative in terms of the water quality. Inevitable changes in groundwater flow patterns within the aquifer occurring as a result of artificial recharge may, however, have negative consequences in terms of the marketing of the water as 'natural mineral water'.

The use of numerical groundwater modelling techniques to study the hydrogeology in the Kleivflåta area has enabled the prediction of hydraulic and, to a certain extent, chemical conditions in the aquifer under a number of possible aquifer development scenarios for the development. In particular, the model results have shown that, although there should be no hydrogeological or technical limitations preventing the exploitation of the aquifer, consideration must be given to the effects of this exploitation on the pumping costs of the mineral water company. The ability of the company to continue to market the water as natural mineral water must also be assessed.

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