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Groundwater Recharge in Crystalline Bedrock

Processes, Estimation, and Modelling

BY

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Abstract

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Knowledge about the groundwater recharge is essential for the prediction of impacts of groundwater withdrawal and underground construction. Recharge in the bedrock is, however, difficult to estimate. The objectives of this thesis were to increase the understanding of groundwater recharge in crystalline bedrock, to investigate how the recharge could be estimated, and to develop new models to describe the recharge. The study was based on three approaches: groundwater dating using chlorofluorocarbons (CFCs), geohydraulic field measurements, and mathematical modelling.

Low concentrations of CFC-11 and CFC-113 were found in the bedrock groundwater, which in combination with low dissolved-oxygen levels indicated anaerobic degradation. The CFC-12 and tritium concentrations agreed fairly well, which means that apparent ages could be true ages. The results suggest that CFC dating may not be reliable at forested, humid sites covered by fine-grained soil.

A quick response in hydraulic head to precipitation was observed in the studied bedrock, despite the 10-m thick till cover. A substantial portion of observed head variations was found to be loading effects, involving no storage changes or water flow. The loading efficiency of the bedrock was estimated, from the air-pressure response, to be 0.95. The surface loading was calculated from measurements of air pressure, water in the soil, and snow. About 20% of the seasonal variation of the hydraulic head was estimated to be related to loading changes only. A simple conceptual model could be used to simulate the observed hydraulic heads. The loading effect had to be included to properly describe individual recharge events.

Numerical experiments were performed with a soil–bedrock profile. When the rock was modelled as a heterogeneous continuum, unsaturated zones developed at high hydraulic gradients. The phenomenon appeared in areas where low-conductive zones were located upstream of high-conductive zones, decreasing the effective hydraulic conductivity of the material.

Keywords: groundwater recharge, bedrock, crystalline rocks, tracers, CFC, surface loading, loading efficiency, barometric effect, heterogeneity, stochastic modelling

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*"Det bekymrar mig icke att veta,
hvarifrån grundvattnet kommer,
eller hvart det går: **här är det!**"*

Adolph Thiem (tysk 1800-talshydrolog)

List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals:

- I** Bockgård, N., Rodhe, A., Olsson, K.A., 2004. Accuracy of CFC groundwater dating in a crystalline bedrock aquifer: Data from a site in southern Sweden. *Hydrogeology Journal*, 12(2): 171–183. © Springer-Verlag 2004.
- II** Bockgård, N., Niemi, A., 2004. Role of rock heterogeneity on lateral diversion of water flow at the soil–rock interface. *Vadose Zone Journal*, 3(3): 786–795, VZJ Online, <http://vzj.scijournals.org/>. © Soil Science Society of America.
- III** Bockgård, N., 2004. Surface loading effects on groundwater pressure in a crystalline bedrock aquifer. Submitted to *Hydrogeology Journal* in June 2004.
- IV** Rodhe, A., Bockgård, N., 2004. Groundwater recharge in a hard rock aquifer: a conceptual model including surface-loading effects. Submitted to *Journal of Hydrology* in September 2004.

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In paper **I**, I participated in the sampling and made the data analysis, and I had the main responsibility for the writing. In paper **II**, I brought up the idea and made the simulations and analysis, and the authors shared the writing. In Paper **IV**, the first author made most writing, whereas I was responsible for the data processing and carried out the simulations and analysis.

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1 Introduction

1.1 Objectives and aims

Groundwater is one of the most important natural resources: It constitutes 98% of the liquid freshwater resources of the world (Shiklomanov, 1998), and groundwater is also the world's most extracted raw material (World Water Assessment Programme, 2003). With the increased demand for water, the importance and awareness of crystalline-bedrock aquifers has grown. The geohydrological conditions are also of great importance for underground construction in hard rocks, e.g., for tunnels and nuclear-waste repositories.

Fractured hard rocks occur over large areas in many regions of the world. A common geological setting in, for instance, the Scandinavian countries is crystalline bedrock covered by shallow till soil. Here the groundwater in the fractured crystalline bedrock is an important water resource. For example, the majority of the water supplies for individual or small groups of households in Sweden are bedrock wells, supplying altogether water to 8% of the Swedish population (SGU, 2003). In some areas, for example in coastal areas, the groundwater resources are too limited, resulting in water supply problems.

The groundwater recharge is a key variable for the assessment and management of groundwater resources (Scanlon and Cook, 2002). Quantification of the recharge is needed, for example, to estimate the sustainable yield of aquifers and to predict the impacts of underground construction, and most groundwater models are sensitive to the applied groundwater recharge (e.g., Sanford, 2002). The recharge to surficial soil aquifers can often be estimated by water budget methods (de Vries and Simmers, 2002), i.e., from observed precipitation and estimated evaporation, at least as a large-scale temporal mean value. In Swedish geological and climatological conditions, the specific runoff can be used as a measure of this mean recharge. The recharge to the bedrock groundwater from overlying soil aquifers is, however, generally much more difficult to estimate. These estimates may be uncertain, and the representation of the groundwater recharge in groundwater models may then be rough. Thus there is a need for better methods for estimation of groundwater recharge in the bedrock.

It should be pointed out that in this thesis, the term “groundwater recharge” is used in a wide meaning. Recharge is usually defined as the flow of water reaching the water table from the unsaturated zone (Freeze and

Cherry, 1979; de Vries and Simmers, 2002). However, in this thesis, by groundwater recharge in the bedrock is meant all water that enters the bedrock groundwater system, also including saturated flow from adjacent aquifers, sometimes called interaquifer recharge (Lerner et al., 1990; Alley et al., 2002).

The overall objectives of this thesis were to increase the understanding of groundwater recharge in crystalline bedrock, and more specifically, to investigate how the recharge could be estimated, as well as to develop new models to describe the recharge. Detailed aims were to:

- investigate the accuracy of the CFC groundwater dating method in fractured crystalline-bedrock environments (Paper I);
- investigate how the fracture-related heterogeneity influences recharge to the bedrock (Paper II);
- develop a methodology to isolate groundwater-pressure changes in the bedrock related to groundwater storage from those caused by surface-loading changes (Paper III);
- test the hypothesis that the recharge to a studied bedrock aquifer takes place by vertical flow from the overlying soil aquifer (Paper IV).

As seen above, this study is based on three main approaches: groundwater dating using chlorofluorocarbons (CFCs), geohydraulic field measurements, and mathematical modelling. Groundwater dating may be used to study the distribution of groundwater ages in the surficial bedrock, and the recharge flux may then be estimated from transport times and the flow porosity. This study includes an investigation of the CFC-dating method, conducted at Finnsjön in central Sweden, which is one of the first applications of the method in Sweden. Geohydraulic field measurements were performed at the Norunda site in central Sweden. The purpose of the geohydraulic measurements were to study the governing processes and the driving forces for the recharge to the bedrock groundwater, and to get data for input to, and validation of, the mathematical modelling. A simple one-dimensional vertical model, driven by the hydraulic-potential difference between soil and bedrock, was used to simulate the observed groundwater levels in a bedrock aquifer. A more complicated two-dimensional model accounting for the rock heterogeneity and unsaturated–saturated flow was also used.

1.2 Background

Groundwater recharge is an important factor in evaluating groundwater resources, but it is difficult to quantify. A general problem is the variability of the recharge in space and time. Estimation methods include direct measurements in the unsaturated zone, water-balance methods, Darcian approaches,

water-table fluctuation methods, tracer techniques, and numerical modelling. Recent reviews of groundwater recharge and recharge-estimation techniques are given by Alley et al. (2002) and de Vries and Simmers (2002), wherein most attention is given to recharge of unconfined (water table) aquifers.

The flux into semi-confined aquifers is governed by the hydraulic-potential gradient and the hydraulic conductivities, K , at the boundary. Hantush (1956) was the first to use Darcy's law to calculate the flow of water through confining beds into semi-confined aquifers, defining the leakage coefficient, or leakance, as the ratio of the vertical hydraulic conductivity and the thickness of the confining bed. The method requires measurements of the hydraulic head in the aquifer and above the confining bed. Since K is highly variable, the Darcian method is limited by the ability to determine a representative value of K (Healy and Cook, 2002).

Discharge from semi-confined aquifers may be described equivalently to leakage into aquifers, using a coefficient describing the resistance to drainage, or the inverse of the resistance, often called hydraulic conductance. If the drainage level outside the aquifer is constant, then the discharge is proportional to the hydraulic head or storage in the aquifer, that is, the aquifer shows linear reservoir (Zoch, 1934) behaviour. The hydraulic conductance is then a recession coefficient, which can be related to the response time, a characteristic time-scale of the reservoir.

Recharge rates may be estimated from groundwater ages determined by tracers. Tracer can be categorized into artificial tracers, which are applied by the investigator, and environmental tracers (Cook et al., 1996), which are found naturally or as a result of other human activities. Environmental tracers are advantageous over applied tracers in applications involving large areas, large water volumes, or long transport times. Examples of environmental tracers, suitable for young groundwaters (recharged within the past 50 years) are tritium, ^{36}Cl , and CFCs (Cook and Solomon, 1997). CFCs were proposed as a dating tool for groundwater in the mid-1970s (Thompson and Hayes, 1979). The CFCs used for dating purposes are CFC-11 (CFCl_3), CFC-12 (CF_2Cl_2), and CFC-113 ($\text{C}_2\text{F}_3\text{Cl}_3$). CFC dating became more widely used in groundwater after the development of the sample collection procedure by Busenberg and Plummer (1992), and is now used routinely in porous aquifers. The method has also been applied in fractured rock aquifers, but to a lesser extent (e.g., Busenberg and Plummer, 1992; Cook et al., 1996; Plummer et al., 2001, Shapiro, 2001, Rademacher et al., 2002). The interpretation of the of apparent groundwater ages was difficult in several studies due to , for example, complex spatial patterns of ages (Shapiro, 2001) and matrix diffusion (Cook et al., 1996).

Processes that may alter the CFC concentrations in the groundwater are sorption, degradation, and mixing. Sorption is probably not important in crystalline-bedrock aquifers, at least not for CFC-11 and CFC-12 (Cook and Solomon, 1997). CFC-12 is chemically much more resistant to degradation

than CFC-113, which in turn is more resistant than CFC-11 (Khalil and Rasmussen, 1989; Plummer et al., 1998b). Degradation of CFC-11 and/or CFC-113 in anaerobic groundwater has been observed in several studies (e.g., Cook et al., 1995; Oster et al., 1996; Plummer et al., 1998a, 1998b; Goode et al., 1999; Katz et al., 2001; Rademacher et al., 2002). Degradation of CFC-12 has been observed or suspected under anaerobic conditions in a few studies in natural groundwater (Oster et al., 1996; Goode et al., 1999; Rowe et al., 1999; Happell et al., 2003) and in laboratory (Lovely and Woodward, 1992; Bauer and Yavitt, 1996; Oster et al., 1996).

A study of CFCs in glacial deposits and underlying crystalline bedrock at the Mirror Lake site, New Hampshire, USA, concerns conditions similar to Scandinavia, both climatologically and geologically (Goode et al., 1999). CFC-11 and CFC-113 were absent and the CFC-12 concentration was as low as one-third of modern concentrations just below the water table in anaerobic groundwater in the glacial drift. They concluded that degradation in shallow groundwater presumably may affect CFC dating at forested, humid sites underlain by glacial deposits. Rowe et al. (1999) suggested that, in general, CFC dating is not reliable in anaerobic groundwater systems. However, CFC-12 is usually supposed to be stable as long as the redox potential does not drop into methanogenic conditions.

Mixing is a general problem when estimating the age of a groundwater sample from tracer concentrations. If the input of the conservative tracer varies linearly over time, the age obtained, the “apparent age” represents the mean age of the sample. For non-linear inputs, such as those of the CFCs and tritium, a mixing model has to be assumed in order to estimate the age. Complete mixing (the exponential model) (Eriksson, 1958; Małozewski and Zuber, 1982), binary mixing, and piston flow are three common models (Katz et al., 2003).

Very large variations in groundwater levels may occur in response to recharge in unconfined crystalline-bedrock aquifers (e.g., Healy and Cook, 2002). Estimates of recharge from water-table fluctuations in fractured rocks may be highly uncertain. One problem is that often the permeability of the aquifer is low and the storativity of the aquifer is very low in relation to the storativity of the well, and water-level fluctuations in the well are then attenuated (Healy and Cook, 2002).

The quantification of interaquifer recharge is often based on measurement of groundwater levels (Healy and Cook, 2002), and observed changes in hydraulic head in an aquifer may simply be interpreted as changes in storage. However, hydraulic head variations are not always indications of storage, but may also be the effect of changes in the loading on the aquifer (e.g., Freeze and Cherry, 1979; van der Kamp and Gale, 1983). The cause may be air pressure variations or water-storage changes in overlying soils. Barometric effects are routinely considered in groundwater investigations (e.g., Rasmussen and Crawford, 1997; Healy and Cook, 2002; Spane, 2002), but

other loading effects are often ignored. On the other hand, the response to loading changes may provide information about the hydraulic and mechanic properties of the aquifer (e.g., Rojstaczer and Agnew, 1989). Observations of groundwater-pressure changes in a confined aquifer may also be used to estimate changes in the water storage in overlying materials (van der Kamp and Maathuis, 1991; Bardsley and Campbell, 1994; van der Kamp and Schmidt, 1997; Barr et al., 2000).

While a large number of studies have addressed numerical modelling of fractured media, e.g., in the research programmes related to nuclear-waste disposal, they have mostly focused on issues like parameter estimation and upscaling; see Niemi et al. (2000) for a recent review. Much fewer studies have addressed groundwater recharge and how it may be influenced by rock heterogeneity and the soil overburden. In principle, two different approaches to model flow in fractured media may be distinguished: discrete-fracture models and continuum models (e.g., Öhman and Niemi, 2003). For the continuum assumption to be valid, the rock has to be sufficiently densely fractured. Since the complexity of fractured rocks does not allow a complete deterministic description, stochastic models are often used in combination with, e.g., Monte Carlo simulation (Metropolis and Ulam, 1949), see Gómez-Hernández and Gorelick (1989).

The approaches for modelling flow and transport in saturated fractured media are relatively well established, whereas there is far less experience in modelling flow and transport in unsaturated fractured media. Consequently, because of the complexity of the problem and the difficulties in measuring the key variables, there are not even common accepted conceptual models of water flow in unsaturated fractured media (Wanfang et al., 1997; Pruess et al., 1999a; Berkowitz, 2002).

In relation to the objectives of this thesis, it can be stated that relatively few studies have directly addressed groundwater recharge in crystalline bedrock (see Bockgård, 2000). The knowledge about groundwater in bedrock emanates to a large extent from studies related to nuclear-waste disposal. This research has been focused on the deep bedrock. Recently, the interface between soil and bedrock, the hydrogeology of the surficial bedrock, and flow in unsaturated fractured rock have been recognized as some of the most important issues related to groundwater in hard rocks that need more research (KASAM, 2001).

2 Materials and methods

2.1 Study sites

2.1.1 The Finnsjön site

The Finnsjön site, the area of study in Paper I, is situated in central Sweden (60°21'N, 17°55'E, altitude 20–40 m above sea level), about 50 km north of Uppsala and 12 km from the Baltic Sea (Fig. 1). The mean air temperature is 5.5°C, the estimated mean annual precipitation is about 670 mm, and the mean annual evapotranspiration is about 430 mm (Ahlbom et al., 1992). The area is situated on the sub-Cambrian peneplain and is comparatively flat. The bedrock is composed of foliated granodiorite (Ahlbom and Smellie, 1991). Outcrops are common, and constitute about 15% of the area. The soils are dominated by till and peat deposits with a mean depth of about 2 m (Larsson and Jacobsson, 1982). The water table in the bedrock is typically less than 2 m below the ground surface in low-lying areas and 1–3 m below the ground surface in hillslopes and on the hills (Andersson et al., 1991), and the annual variation of the groundwater level is about 2 m. Depending on the local topography and the soil cover thickness, there may also be a separate water table in the soil.

The site was used from 1977 to 1992 by the Swedish Nuclear Fuel and Waste Management Company (SKB) for studies of groundwater flow in fractured rock (Ahlbom et al., 1992). The activities included, e.g., the drilling of a large number of boreholes of varying types and depths. Three 100-m-deep boreholes were selected for sampling of groundwater for an investigation of the CFC dating method (Paper I). The boreholes are situated along an 800-m transect, from a recharge area to a local discharge area (Fig. 1).

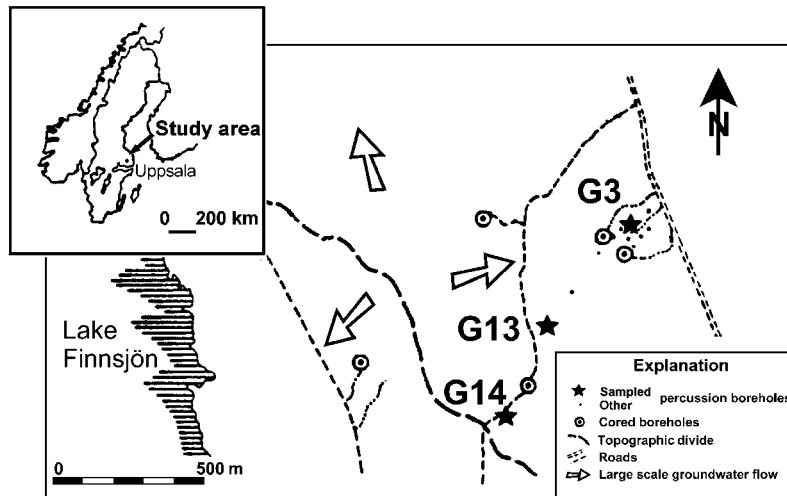


Figure 1. The Finnsjön study area and the location of the boreholes selected for groundwater sampling (modified from Paper I).

2.1.2 The Norunda site

The Norunda site, the area of study in Papers III and IV, is also situated on the sub-Cambrian peneplain in central Sweden ($60^{\circ}4'N$, $17^{\circ}28'E$, altitude 50 m above sea level), about 30 km north of Uppsala and about 50 km from the Baltic Sea (Fig. 2). The mean air temperature (for Uppsala 1961–1990) is $5.6^{\circ}C$, and the mean, uncorrected, annual precipitation is 544 mm (SMHI, 2004). The estimated corrected annual precipitation at the study site is about 700 mm (Seibert, 1994). The mean annual Penman open-water evaporation for Uppsala is 454 mm (Lundin et al., 1999). The topography is flat, with small-scale variation in altitude of up to 10 m. The bedrock of the area is composed of granite, gneiss, and leptite (Grånäs, 1990). The soil is an about 10-m-deep compact sandy till with a high content of blocks and stones. There are no outcrops of bedrock within a radius of approximately 1 km from the measurement site. The groundwater level in the soil typically varies between 0 m and 2 m below ground surface during the year. The site is forested, mainly with mature spruce and pine.

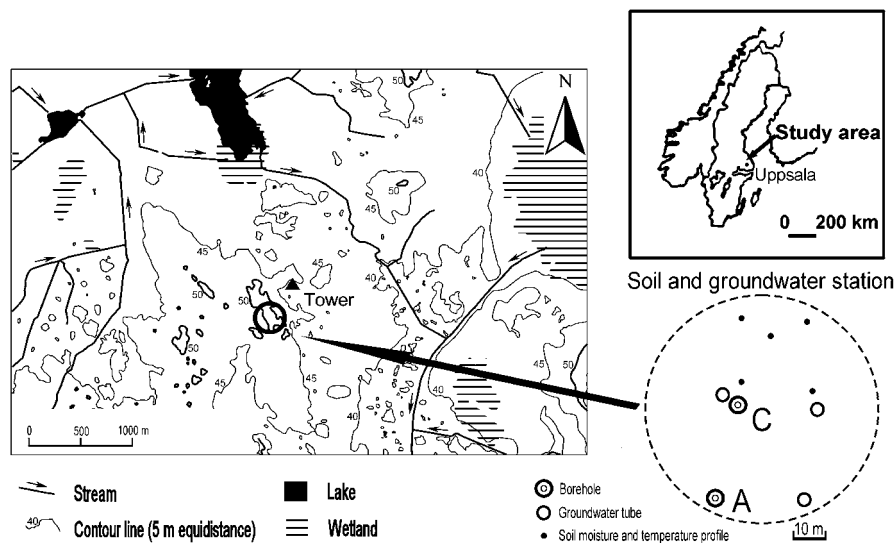


Figure 2. Topographical map of the Norunda study area (From the Topographical map © Lantmäteriverket Gävle 2004. Permission M2004/4046.) and a detail sketch of the soil and groundwater installations (modified from Paper III).

The Norunda site was one of the central sites in the NOPEX project (Northern hemisphere climate-Processes land-surface EXperiment) (Halldin et al., 1999). A continuous climate-monitoring program has been running at the site, including measurements of, e.g., atmospheric fluxes and profiles, radiation, soil profiles of heat and water content, and precipitation. See Lundin et al. (1999) for a detailed description of the site and the NOPEX activities. This site was selected for geohydraulic measurements (Papers III and IV). The motivations for the selection of the area are that it was expected to be a recharge area for bedrock groundwater according to the topography; the existing installations and infrastructure; and the running continuous measurements at the site.

2.2 CFC dating

2.2.1 Sampling and chemical analyses

Groundwater sampling was done to a depth of 42 m in the three boreholes (Paper I). The water was sampled using a submersible pump; the majority of the samples were taken between double packers with 2-m spacing. Electrical conductivity and dissolved-oxygen concentration was measured on the pumped water. The water for CFC analysis was pumped to an apparatus for collecting and sealing water samples in glass ampoules, allowing sampling

without contamination from the atmosphere. Triplicates were collected for the CFC analysis. The equipment and procedure used to collect the CFC samples was similar to those described by Busenberg and Plummer (1992). Water was also stored for analysis of the tritium (^3H) content.

The CFC samples were analysed for CFC-11, CFC-12, and CFC-113. The analysis was done by using a purge-and-trap pre-treatment system coupled to gas-chromatographic separation and electron-capture detection. The tritium content was analysed with a low-level liquid scintillation counter.

2.2.2 Evaluation methodology

The basis for the CFC dating method is the assumptions that the CFC concentration in the recharging water in the unsaturated zone in soil or rock is in equilibrium with the present atmosphere, and that the CFCs are conserved in the groundwater (Busenberg and Plummer, 1992). The measured CFC concentration in the water is transformed to the corresponding atmospheric concentration, using the solubility relationships (see Warner and Weiss, 1985; Bu and Warner, 1995). An apparent time of recharge can then be determined by comparing the apparent atmospheric concentration with the time series of CFC in the atmosphere (see Walker et al., 2000; Walker et al., 2004). In addition to the CFCs, tritium was used as a tracer. Tritium input data were taken from the GNIP database (IAEA/WMO, 2004).

Mixing analysis was used to get indications of non-conservative behaviour of the tracers and to evaluate in which proportions water from different sources may have mixed. The analysis was based on mixing diagrams, i.e., a plot of the concentrations of two tracers in different samples against each other. If the tracers behave conservatively, all samples, both mixed and unmixed water, must fall within the envelope that is spanned by the “end-members”, in this case, the time series of the concentrations of the two tracers. In samples that fall outside the envelope, a non-conservative change must have taken place of at least one of the tracers, for instance by degradation or sorption. A binary mixing model was then used to evaluate which mixtures of two waters of different age that could explain the measured tracer concentrations.

2.3 Geohydraulic field study

2.3.1 Measurements

Measurements were made at the Norunda site from the beginning of 2002 to July 2004 (Papers III and IV). Data on air pressure, air temperature, summer-season precipitation, soil temperature, and soil-water content (measured using time-domain reflectometry, TDR) were received from the measure-

ment and data-collection system described in Lundin et al. (1999), and data were stored with a resolution of 10 or 30 minutes. Data on snow storage measured by a snow pillow were available for the winter 2002–2003. Winter precipitation data were taken from the weather station at the Earth Sciences Centre in Uppsala (Bergström, 2001).

The groundwater level in the soil was continuously monitored in two 3-m-deep groundwater tubes and in one 2.8-m-deep piezometer (Fig. 2), and 10-min averages were stored. The groundwater pressure in the bedrock was measured in two boreholes (Fig. 2). Borehole A (Bh A) was 49 m deep, and borehole C, (Bh C) was 40 m deep. The transmissivity of the boreholes was concentrated to one level in each borehole, above the base of the steel casing at 15 m depth in Bh A and at 32 m depth in Bh C. Bh A was left open, while, in September 2002, Bh C was divided into four sections (0–15 m, 16–30 m, 31–33 m, 33–40 m) using inflatable packers. Water levels were continuously monitored in standpipes connected to the borehole sections.

2.3.2 Evaluation of surface-loading effects

The response in the groundwater flow to laterally extensive and homogeneous changes in the surface loading is described by a version of the diffusion equation for transient groundwater flow that includes the change in the vertical stress σ_z . For a homogeneous and isotropic medium, the equation becomes (e.g., Neuzil, 2003):

$$\eta \left(\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} \right) = \frac{\partial h}{\partial t} - \gamma \frac{\partial \sigma_z}{\partial t}, \quad (1)$$

where h is the hydraulic head, η is the hydraulic diffusivity, and γ is the loading efficiency (van der Kamp and Gale, 1983). The loading efficiency is the proportion of a change in the vertical stress that is borne by a change in the groundwater pressure under undrained, or static-confined, conditions, i.e., when no water flow takes place (Rojstaczer and Agnew, 1989). The actual response to a surface-loading change is, according to Eq. (1), a combination of the instantaneous response to the loading change and the pressure change by diffusive pressure transport. The observed response is therefore dependent on the hydraulic diffusivity of the material, and is time-, or frequency-, dependent (Rojstaczer, 1988).

The loading efficiency of the bedrock at the Norunda site was estimated from the response to air-pressure variations (Paper III). The time dependency of the response was taken into account by applying a one-dimensional model of surface-loading-induced pressure changes in layered media, derived by Wang and Davis (1996). The model gives an analytical solution of the pressure change in Fourier space. A three-layer model was used to repre-

sent the site: unsaturated soil, saturated soil, and bedrock. The parameters of the model are the hydraulic diffusivity and the loading efficiency of each layer, and they were estimated by fitting the model to the empirical transfer functions between the spectra of observed air pressure and groundwater levels. This was done in the frequency range $0.1\text{--}1\text{ d}^{-1}$, where the air-pressure variation is the dominating component of the surface-loading variation.

The instantaneous component of observed groundwater-pressure changes may be determined if the surface-loading variation and the loading efficiency are known. The effect of the surface-loading variation on the groundwater pressure in the bedrock at the Norunda site was investigated in Paper III. The surface-loading variation at the site consists of the air-pressure variation, the variation in water storage in the soil (both in the unsaturated and the saturated zone), and the snow storage. The air pressure was measured at the site, the storage in the soil was calculated from the measured soil-water content and the groundwater level, and the snow storage was estimated by a degree-day model. The instantaneous pressure component was then estimated from the calculated surface-loading variation and the estimated loading efficiency. The diffusive pressure component, which is related to groundwater storage, was calculated by subtraction of the instantaneous component from the observed pressure.

2.3.3 Simulation of groundwater storage in the bedrock

A one-dimensional vertical flow model was used to simulate the groundwater storage in the bedrock aquifer in Paper IV. The water balance of a column of the semi-confined bedrock aquifer can be written:

$$Q_{in} + R = m \frac{dh'_b}{dt} + Q_{out} . \quad (2)$$

Here the flows and the storage change are expressed per unit horizontal area of the column ($\text{m}^3\text{ s}^{-1}\text{ m}^{-2}$), Q_{in} and Q_{out} are the bedrock groundwater flow into and out, respectively, from the column, R is recharge from the soil aquifer, m (–) is the storage coefficient of the bedrock aquifer, and dh'_b/dt is the change in hydraulic head in the aquifer due to the storage change.

By rearranging Eq. (2) and adding the instantaneous response to loading changes from Eq. (1), the total change in hydraulic head h becomes:

$$\frac{dh}{dt} = \frac{1}{m} (Q_{in} + R - Q_{out}) + \gamma \frac{d\sigma_z}{dt} . \quad (3)$$

Assuming vertical Darcian flow, the recharge can be described as:

$$R = K_v \frac{h_s - h_b}{h_s - h_1}, \quad (4)$$

where K_v is the mean vertical hydraulic conductivity between the groundwater table in the soil and the level h_1 in the bedrock at which the pressure is measured, and h_s and h_b are the hydraulic head in the soil (the groundwater level) and at level h_1 in the bedrock, respectively.

Two assumptions were made about the site under study: (1) $Q_{in} = 0$, that is, the site is on the groundwater divide, and (2) the bedrock behaves as a linear reservoir, i.e., the outflow is proportional to the hydraulic head in the bedrock aquifer according to:

$$Q_{out} = am(h - h_0). \quad (5)$$

Here a (s^{-1}) is a recession coefficient and h_0 is the drainage level, i.e., the groundwater level in the bedrock at which the flow ceases (\geq sea level).

A successful simulation of the hydraulic head in the bedrock aquifer using this model (Eq. 3 with Eqs. 4 and 5), after tuning the three parameters a , $b = K_v/m$, and h_0 , would support the hypotheses upon which the model is based, i.e., that the bedrock aquifer is recharged by Darcian flow from the overlying soil aquifer, and that it can be regarded as a linear reservoir without lateral inflow. If the model has been supported, the relative variation over time of the recharge to the bedrock aquifer may be estimated using Eq. (4). Since only the quotient $b = K_v/m$ can be determined by calibration to groundwater levels, it is not possible to calculate the absolute value of the recharge, unless K_v or m has been obtained by some other method.

The differential equation (3) was solved numerically, using the groundwater level in the soil and instantaneous pressure change estimated in Paper **III** as driving variables. The model was calibrated using soil and bedrock groundwater data from April 2002 to December 2003. The calibration was performed by a Monte Carlo technique: Possible ranges of each parameter value were defined based on their physical interpretations, and parameter sets were then generated using random numbers from a uniform distribution within the range given for each parameter. The Nash and Sutcliffe (1970) model efficiency R_{eff} was used as the measure of goodness-of-fit.

Data from the period December 2003 to July 2004 were then used for validation of the model. Since data on soil water and snow storage were not processed for this period, the instantaneous response to surface-loading changes could not be calculated. The flow model was therefore run without accounting for the effect of surface loading.

2.4 Numerical experiments

2.4.1 Conceptual model

Numerical experiments were performed with a model of a hypothetical soil–bedrock profile with the aim to study flow diversion at the soil–rock interface (Paper II). The model represented a two-dimensional profile of a soil layer on top of the fractured bedrock. The model domain was assumed to be situated at the topographic water divide at the very upper part of a ridge (Fig. 3).

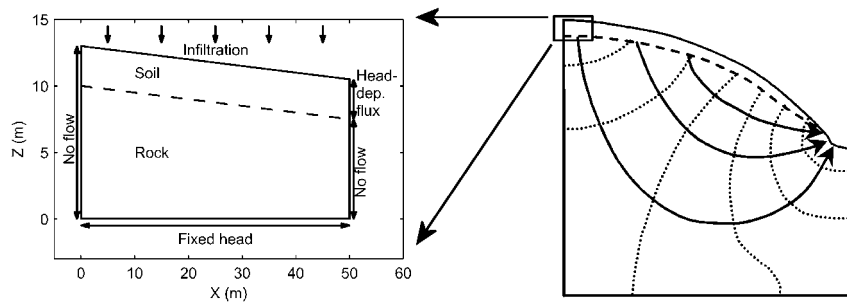


Figure 3. The model domain and types of boundary conditions used in the numerical experiments (left). The domain was thought to be a part of a large-scale flow system (right) (from Paper II).

A no-flow boundary condition was used at the left boundary of the model domain, formed by the water divide (Fig. 3). Near the water divide, the groundwater in the bedrock was assumed to flow almost vertical, recharging the large-scale flow system. A no-flow boundary was therefore used also at the right boundary of the bedrock zone. The hydraulic head at the lower boundary of the model was varied to study the effect of different hydraulic gradients in the bedrock. The water in the soil was allowed to discharge from the model also laterally, to simulate, e.g., local discharge to a stream, using a head-dependent flux boundary condition (Cauchy or mixed condition) (e.g., Bear, 1972; Sanford, 2002). The upper boundary condition was given as a spatially uniform and steady net flux through the ground surface. Rates of 150 and 200 mm yr⁻¹, typical for Swedish conditions, were used.

2.4.2 Parameterization and simulations

The hydraulic properties of the modelled soil and bedrock were selected to represent those of a medium-textured soil and typical fractured crystalline bedrock, as encountered in Sweden. The properties of the soil material resembled those of the sandy-loamy till at the Norunda site (Lindahl, 1996). For the rock material, the values of the hydraulic properties were based on

data from various sources. The model of the rock was built on the so-called fracture-continuum approach (Birkholzer et al., 1999; Finsterle, 2000), meaning that flow in fractures was assumed to dominate the flow, and that the rock was assumed to behave as a continuum at the support scale. For a discussion concerning the validity of stochastic-continuum models, see Neuman (1987). The second assumption was justified, since the very uppermost part (10 m) of the bedrock was considered. The fact that the flow is dominated by the fractures, allowing the matrix contribution to be neglected, is also relatively well established for this type of crystalline rock under saturated conditions (e.g., Niemi et al, 2000; Öhman and Niemi, 2003).

Two different methods to simulate the hydraulic behaviour of the heterogeneous fractured rock were compared: The rock was first described as a homogeneous equivalent continuum and then as a heterogeneous stochastic continuum and modelled by means of Monte Carlo simulation. The first method should reproduce the “average” behaviour of the rock, provided that the right effective, or average, properties are used in the model. The second method also gives the mean behaviour, but shows the variability in the outcome as well, i.e., the uncertainty in the prediction that comes from the uncertainty in the model parameters. The soil was modelled as a homogeneous continuum in all cases. In the heterogeneous simulations, the saturated hydraulic conductivity K_s was assumed to be lognormally distributed and spatially correlated, using a 0.5-m support scale. The values of the hydraulic properties were chosen on the basis of data from other fractured rock sites (see Paper II).

There were no data available on unsaturated hydraulic properties from Scandinavian crystalline rocks; a model and parameter values (Birkholzer et al., 1999) developed for the fractured rock at Yucca Mountain (Bodvarsson et al., 1999) were therefore applied. The expressions by van Genuchten (1980) were used, both for the soil and the rock, to describe the relations between capillary pressure P_c , unsaturated hydraulic conductivity K , and effective liquid saturation S_e :

$$P_c = -1/\alpha \left(S_e^{-1/\lambda} - 1 \right)^{1-\lambda} \quad (6)$$

$$K = K_s S_e^{1/2} \left[1 - \left(1 - S_e^{1/\lambda} \right)^\lambda \right]^2, \quad (7)$$

where α and λ are empirical parameters. In the heterogeneous simulations, the value of α , which describes the “capillary strength”, was scaled by the saturated hydraulic conductivity according to Leverett’s (1941) rule:

$$\frac{\alpha_{ref}}{\alpha} = \sqrt{\frac{K_{ref}}{K_s}}, \quad (8)$$

where α_{ref} is the value of α at K_{ref} , the reference value of the saturated hydraulic conductivity, and K_s is the actual saturated hydraulic conductivity. The parameter λ in Eqs. (6) and (7) was assumed to be constant, which means that the spatial distribution of fracture apertures was assumed to be statistically homogeneous (Birkholzer et al., 1999).

The numerical simulation code TOUGH2 (Transport Of Unsaturated Groundwater and Heat, Pruess et al., 1999b) was used to solve the steady-state unsaturated-saturated flow. For each case, 100 stochastic realizations of the saturated-hydraulic-conductivity field in the bedrock were generated for the Monte Carlo simulation. Statistical convergence of the output statistics was normally reached after about 50 simulations.

3 Results and discussion

3.1 Accuracy of CFC dating in crystalline bedrock

The observed CFC concentrations in the groundwater in the bedrock at the Finnsjön site were generally low (Paper I). The exception was a sample taken just below the water table, which according to the assumptions that underpin the CFC method should have modern CFC concentrations. There was almost no CFC-113 in the samples. The observed CFC-113 content and the CFC-12 dating agreed in the respect that CFC-113 was absent in water with CFC-12 recharge date before 1965. The CFC-113 concentration was very low also in samples with younger CFC-12 age. Therefore CFC-113 was not further analysed in study. The apparent recharge date evaluated from CFC-11 was around 1950 for most samples (Fig. 4). The CFC-12 concentrations was higher, and the range of recharge dates was from pre-CFC age to 1975 (Figs. 4 and 5). The CFC-11 recharge date was earlier than the CFC-12 date for all samples, and the difference was up to 15–20 years for several samples (Fig. 4). The variation between individual samples from the same sampled borehole section was small, less than 2 years. The estimated uncertainty in the apparent recharge dates, based on measurement uncertainties and the uncertainties in the recharge temperature and the atmospheric-concentration curves, was less than 3 years.

All samples fell outside the mixing area for CFC-11 and CFC-12, the shaded area in Fig. 4. This shows that CFC-11 have been removed in relation to CFC-12. A low dissolved-oxygen content (generally below 1 mg l^{-1}) and the presence of hydrogen sulphide (H_2S) in most samples show that the sampled groundwater was sulphate-reducing. These facts, and the absence of CFC-113, indicate degradation of CFC-11 and CFC-113 at the site. This result supports the findings by Rademacher et al. (2002) that CFC-11 may be significantly affected by degradation in sulphate-reducing fractured-rock environments and by Goode et al. (1999) that CFC-11 and CFC-113 may become almost completely degraded at humid, forested sites.

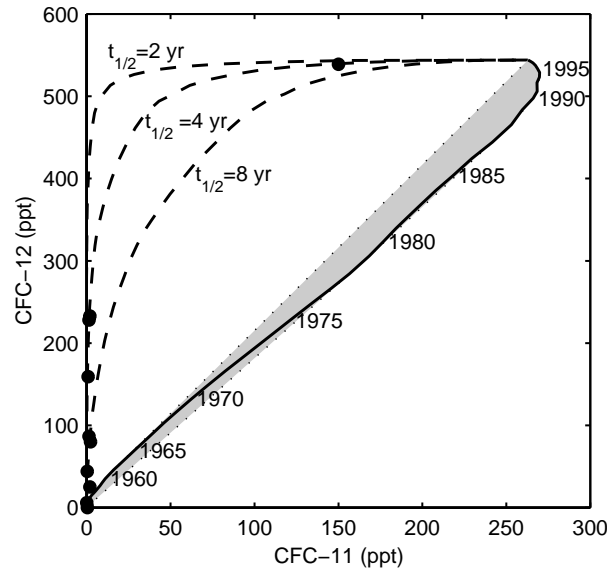


Figure 4. Apparent atmospheric CFC-11 and CFC-12 concentrations in groundwater at Finnsjön, Sweden, (large dots) and the atmospheric-concentration curve from Walker et al. (2004) (full line) with corresponding recharge dates indicated. Curves showing first-order degradation of CFC-11 with $t_{1/2} = 2, 4$, and 8 years are also shown (broken lines). The shaded area encloses all possible combinations by mixing (from Paper I).

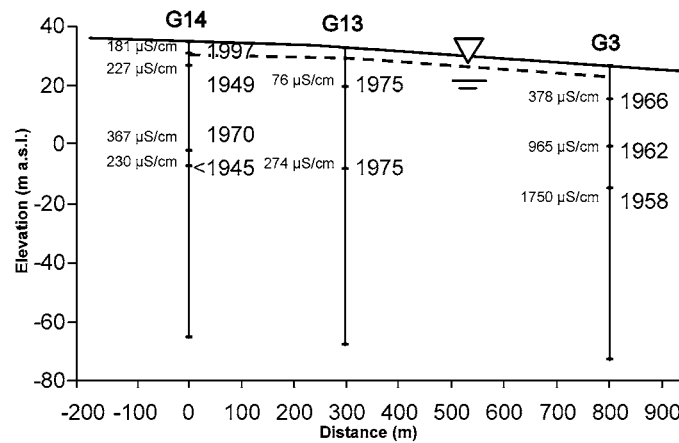


Figure 5. Schematic profile of CFC-12 recharge date and electrical conductivity in groundwater sampled in three boreholes at Finnsjön, Sweden (from Paper I).

There were not enough data to evaluate degradation models. However, a first-order degradation model with half-life $t_{1/2} \leq 4$ years for CFC-11 and

stable CFC-12 is consistent with observed concentrations (Fig. 4). This is within the range of the half-life for CFC-11 in anaerobic groundwater reported in the literature, which is from 3 years to less than 1 year (Cook et al., 1995; Oster et al., 1996). Because CFC-12 is much more resistant than CFC-11, CFC-12 was assumed to be stable in the mixing analysis, using the combination of CFC-12 and tritium.

The tritium content in the groundwater samples was between 9 and 19 tritium units (TU). In one of the boreholes (borehole G3, see Figs. 1 and 5), there was a significant decreasing trend in tritium content with depth, from 16 TU at 10 m depth to 9 TU at 40 m depth. All observed tritium concentrations were in the range of the concentration in present precipitation.

Most samples agreed fairly well to the CFC-12 to tritium curve (Fig. 6), meaning that the apparent CFC-12 recharge date may be equal to the true recharge date. By taking the measurement uncertainties into account, the analysis showed that one sample (recharge date 1949 in Fig. 6) deviated significantly from the curve, and the apparent CFC-12 date was probably not the true recharge date for this sample. Since all samples fell into the mixing area for CFC-12 and tritium, all samples could also be mixtures of waters with different ages. For binary mixtures of water from after 1960, the difference is small between the true mean age and the apparent CFC-12 age.

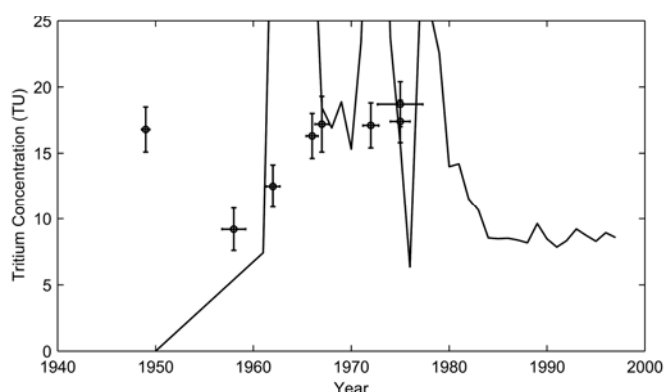


Figure 6. Tritium concentration in groundwater at Finnsjön, Sweden, as a function of apparent CFC-12 recharge date. The error bars show the estimated analytical uncertainty. The solid curve shows the tritium content in precipitation, corrected for decay to 2001 (IAEA/WMO, 2004) (from Paper I).

Since there was no clear spatial pattern in CFC-12 ages (Fig. 5), quantitative conclusions could not be drawn about flow paths and groundwater recharge. The presence of CFCs and tritium in all samples showed that they contained a fraction of water recharged after 1940, at least 5–10% (Paper I). The evidences of degradation of CFC-11 and CFC-113 make also the CFC-12 dating at the site questionable. The relatively high sulphate content in the

groundwater in the area indicates in general sulphate-reducing conditions, although measurements show values of the redox potential above as well as below the limit to methanogenic conditions (Ahlbom et al., 1992). Some degradation of CFC-12 could thus not be excluded. Degradation is actually suspected in two of the samples. The sample with the oldest CFC-12 age (Fig. 6) was taken from shallow depth (borehole G14 in Fig. 5) and was supposed to be younger, and it also showed a large deviation from the atmospheric CFC-12–tritium curve (Fig. 6). Also, a sample with anomalously low electrical conductivity and humic colour (borehole G13 in Fig. 5) contained water that probably was supplied from an adjacent mire, where methanogenic conditions are likely.

The experience from other applications of the CFC method in central Sweden, related to this thesis, shows that the interpretation of CFC data is complicated, and that there is often a systematic divergence in the dating by the different CFCs, presumably caused by degradation. Hjerne (2003) found indications of degradation of CFC-11 in a number of confined aquifers, and that water tapped from production wells was contaminated by CFCs, possibly from the urban environment or the machinery in the wells. However, there was a good agreement between the three CFCs in samples from two natural springs in a coarse-material esker system.

At the Norunda site, the difference between CFC-11, which gave the oldest ages, and CFC-113, which gave youngest ages, was about 10–15 years (unpublished data). CFC-113 thus appears to be the most stable CFC at this site. The CFC-113 recharge date of the water in the bedrock wells was from 1967 to 1977. The CFC-113 date of water in a 3-m-deep piezometer in the till (one of the groundwater tubes in Fig. 2) was 1973–1981. More modern water, and particularly a larger difference in age to the groundwater in the bedrock, may have been expected. The findings were similar for dating of shallow groundwater in forested till hillslopes at a nearby site (unpublished data) and by Hjerne (2003). The CFC dating showed about 20-year-old groundwater, when modern water was expected. These findings support the suggestion by Goode et al. (1999), that CFC dating may not be reliable at forested, humid sites with fine-grained soil.

3.2 Surface-loading effects on groundwater pressure

The seasonal groundwater-level fluctuation in the soil at the Norunda site was about 1.5 m during the observed period (Paper III). The water table almost reached the ground surface at the snowmelt in spring 2002 and after a heavy rainstorm in late July 2002. The groundwater level showed a recession from April to October and then a fast recovery during the remainder of the year.

The hydraulic head in the boreholes was about 2 m (Bh A) and 3 m (Bh C) below the groundwater level in the soil (Paper III). The seasonal water-level fluctuation in the two boreholes was about 1 m (Fig. 7). The levels were highest after the snowmelt in April and lowest in late October. Diurnal and semi-diurnal fluctuations in water levels, with amplitude of about 5 mm, due to Earth tides were observed. A very quick response in water levels in the wells in the bedrock was observed at precipitation events, even though the bedrock is covered by thick till (Fig. 8).

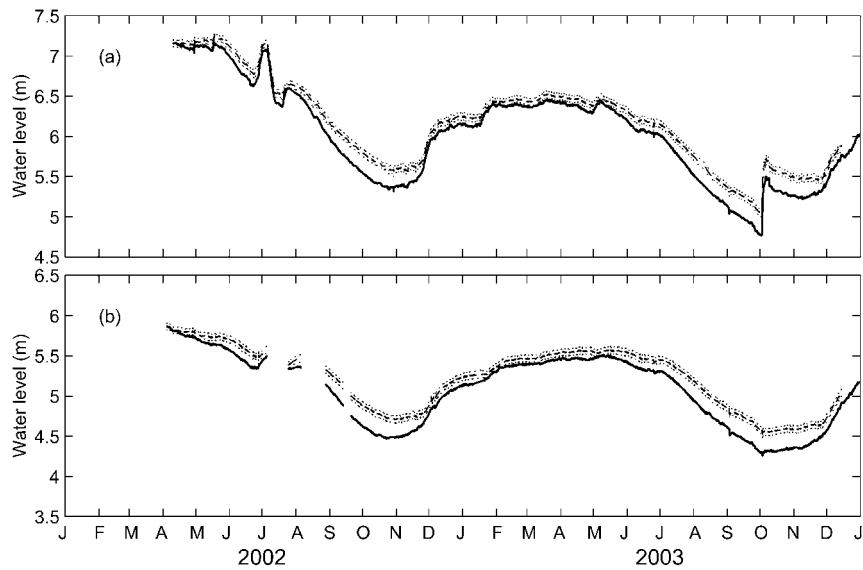


Figure 7. Observed hydraulic head (full line) and calculated diffusive pressure component (broken line) in (a) borehole A and (b) borehole C at the Norunda site. The dotted lines indicate estimated uncertainty. The sudden rise in water level in Bh A in October 2003 was related to neither precipitation nor the groundwater level in the soil, but occurred immediately after pumping for water sampling in the borehole (from Paper III).

By calibration of the analytical model to the observed groundwater-pressure response to air-pressure changes, the loading efficiency of the bedrock was estimated to 0.95 (Paper III), which is equal to an undrained barometric efficiency of 0.05. The hydraulic diffusivity was roughly estimated, also from the response to air-pressure changes, to $2 \cdot 10^{-3} \text{ m}^2 \text{ s}^{-1}$, which was equal to the estimated hydraulic diffusivity of the till.

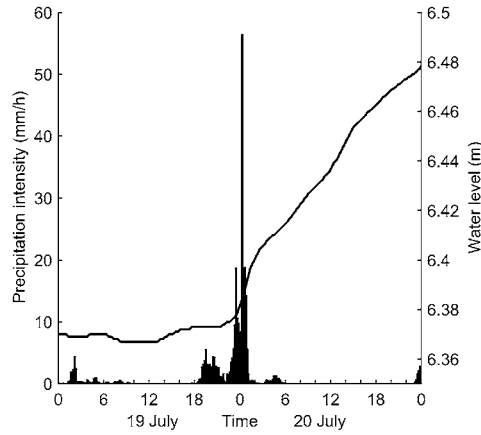


Figure 8. Precipitation intensity in 10-min intervals (bars, left axis) and water level in borehole C (line, right axis) at Norunda, Sweden, during a rainstorm in July 2002. The total precipitation during the two days was 47.9 mm, of which 42.5 mm fell in the night of 19–20 July. The water table in the soil rose about 0.5 m during the period shown. Ground surface is at 10 m in the local datum (from Paper III).

The terms of the surface loading was estimated from the measured air pressure, the measured soil-water content by TDR, groundwater levels, and the simulated snow storage. The range of the total water storage in the soil, including both the unsaturated zone and the groundwater zone, was about 325 mm (Fig. 9). The maximum simulated snow storage, assumed to include both the snow pack on the ground and intercepted snow, was about 60 mm (Fig. 9). This was 20–30% of the seasonal variation in water storage. The contribution from the air-pressure variation to the total surface-loading variation was a small noisy component with amplitude of about 5 mm water equivalent, or about 2% of the total seasonal loading variation.

The diffusive pressure component was then calculated by subtraction of the instantaneous surface-loading-related component from the observed groundwater levels (Fig. 7). The instantaneous pressure component due to loading change was estimated to be about 20% of the annual groundwater-pressure variation, with an estimated uncertainty of about 50 mm. A closer look at some individual recharge events during recession periods, the events in July 2002 and around 1 May 2003 (visible in Fig. 7), shows that the diffusive pressure component was delayed about 12 and 24 hours in Bh A and C, respectively, in relation to the observed water-level response, and that the instantaneous component was from about 15% to over 60% of the total response; see further discussion below in section 3.3.

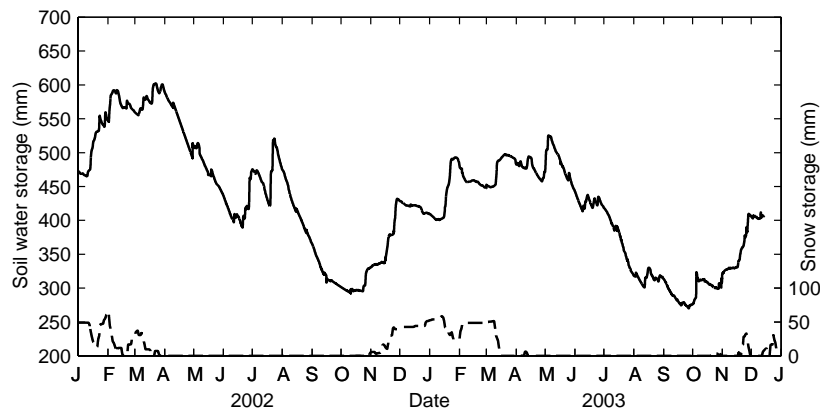


Figure 9. Estimated water storage in the soil down to 1.7 m depth (full line, left axis) and simulated snow storage (broken line, right axis) at the Norunda site (from Paper III).

The presented approach to separate the groundwater-pressure changes caused by storage changes from those related to surface-loading changes only was successful. The loading efficiency of the bedrock could be estimated, recognizing the non-confined response to air-pressure changes, and the detailed measurements of the water content in the soil allowed a good estimation of the dominating surface-loading component. Misleading conclusions may easily be drawn when interpreting groundwater-pressure changes, if the effects of surface-loading changes are overlooked. In this case, the seasonal storage change would be overestimated by about 25% if it was estimated from the seasonal pressure variation without the compensation for the change in the surface loading.

The estimation of the loading efficiency from the response to the air-pressure variation was done under the assumption that the air pressure was the only significant source of pressure variations in the frequency range $0.1-1 \text{ d}^{-1}$. In reality, water-table fluctuations probably influenced the groundwater pressure in the bedrock at the lower end of this frequency interval, and Earth tides clearly influenced near the frequency 1 d^{-1} (Paper III). The loading efficiency determined by this method was consistent with values determined directly from some individual air-pressure episodes. The estimated value of the loading efficiency of the bedrock can be compared to some theoretical results. The low porosity of crystalline rocks causes a high loading efficiency (Rojstaczer and Agnew, 1989); a typical range may be 0.9–1. Rojstaczer and Agnew (1989) reported a loading efficiency of 0.9 for a fractured granodiorite aquifer. Due to the relatively high hydraulic diffusivity of the bedrock, diffusive pressure changes dominated, and the groundwater-pressure measurements in the bedrock could therefore not be used to estimate the changes in water storage in the overlying soil.

3.3 Conceptual model of recharge to the bedrock aquifer

In Paper IV it is shown that it is possible to find parameter sets for which the observed hydraulic head in the boreholes at the Norunda site can be simulated reasonably well by the model (Eqs. 3–5) of groundwater storage in the bedrock ($R_{eff} = 0.76$ for Bh A; $R_{eff} = 0.95$ for BhC). Recharge events were simulated fairly well, but recession periods were simulated less successfully (Fig. 10). For Bh A, there were considerable deviation during the early fall 2003, but the model recovered after the sudden rise in the borehole water level in October 2003.

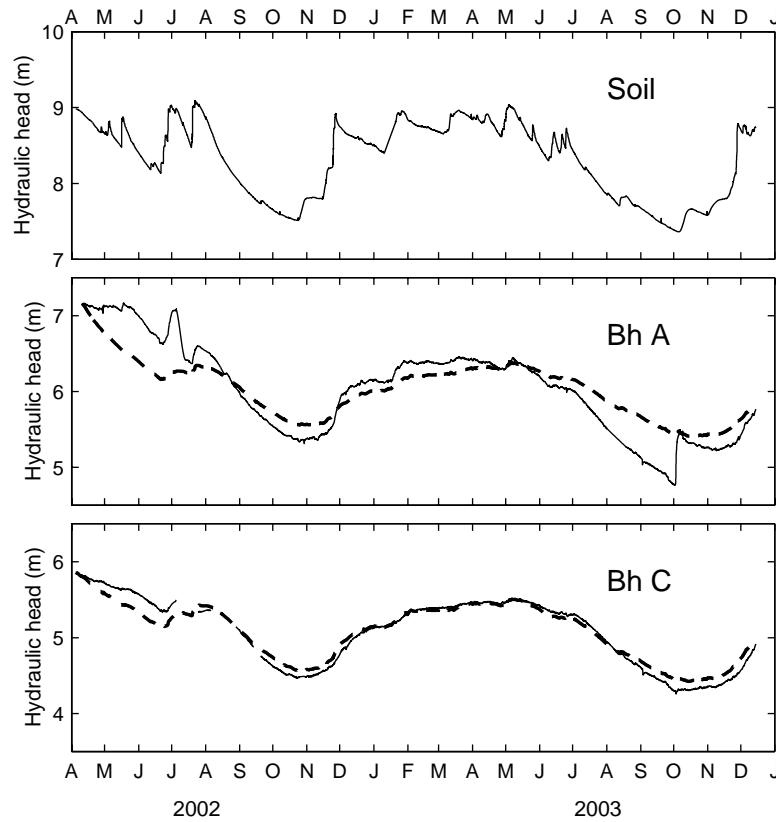


Figure 10. Observed groundwater level in the soil (top), simulated hydraulic head (broken lines) in the bedrock using a model with variable surface loading, and observed hydraulic head (full lines) in the boreholes at the Norunda site from the calibration period.

When the model was calibrated without taking surface loading into account, i.e., neglecting the last term in Eq. (3), the overall fit was similar as for the

simulations with variable surface loading, and R_{eff} was the same. Recharge events, however, could not be equally well simulated when surface loading was disregarded, as exemplified by the event in early May 2003 shown in enlarged scale in Fig. 11; note the Earth-tide fluctuations in the observed hydraulic head. The response in hydraulic head for the model without the variable surface loading was delayed compared to the observations and the simulations with surface loading; in the example the delay was about five days.

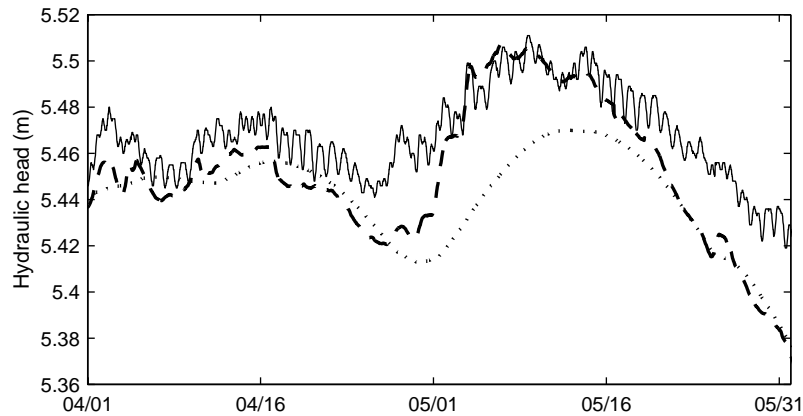


Figure 11. Observed hydraulic head (full lines) in borehole C at the Norunda site and simulated hydraulic head using models with and without variable surface loading (broken and dotted line, respectively). Detail from April–May 2003 in the calibration period.

As pointed out by Barr et al. (2000), the effect of water-table fluctuations in an open aquifer on the storage in an underlying semi-confined aquifer is the result of two processes that partly counteracts each other: A rise of the water table tends to force the downward flow into the aquifer, whereas the increased load of the water in the open aquifer tends to force the flow out from the semi-confined aquifer. This was studied here by calibrating the model with the loading term included in the model, and then running the model with the same parameter values but without the loading term. The results were very similar when looking at larger time-scales, meaning that, by this model, the two effects almost cancel each other out.

The optimum values of the parameters a and b were quite well determined by the calibration (see Paper IV). The optimum value of h_0 , on the other hand, was less distinct. There was, however, a clear increase in R_{eff} as h_0 was decreased down to about -40 m (corresponding to sea level).

The model without surface loading was validated using the parameter set obtained from the calibration. The fit for the validation period was quite

good for Bh C ($R_{eff} = 0.84$), whereas the fit for Bh A was bad ($R_{eff} = -0.45$) due to a sudden jump in water level triggered by pumping of a small volume of water in the borehole in June 2004.

The finding that the hydraulic head in the bedrock could be rather well simulated by the model supports the underlying assumptions. It was therefore considered justified to calculate the recharge to the bedrock by Eq. (4) and to estimate the discharge from the aquifer by Eq. (5). As commented above, only the relative temporal variation in the fluxes could be calculated, as long only the ratio K_v/m is known and not K_v and m separately. The simulated fluxes, calculated for Bh C, are shown in Fig. 12 as the fraction of the mean influx over the period shown, which includes both the calibration period and the validation period. The relative recharge resembled the groundwater level in the soil (Fig. 10). It varied from about 0.9 to 1.25 during the period. The relative temporal variation was thus moderate, being from -10% to $+25\%$. The relative discharge varied from 0.99 to 1.02, giving a much smaller relative temporal variation, about $\pm 1\%$.

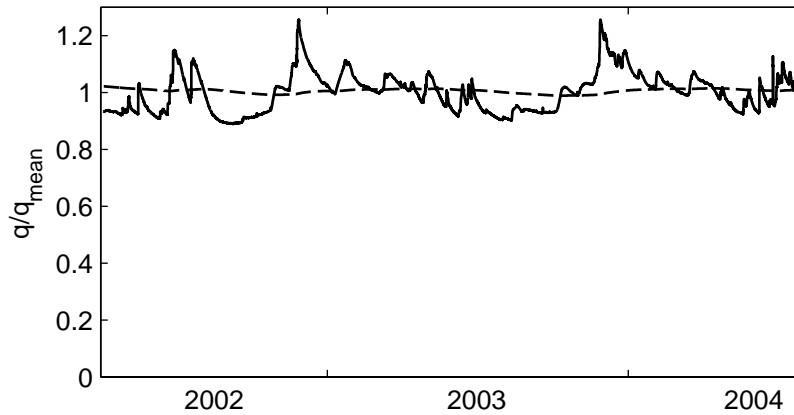


Figure 12. Simulated inflow (full line) and outflow (broken line) from the bedrock reservoir (using a model without variable surface loading). The flow is normalized by the mean inflow.

The absolute values of the fluxes may be estimated if K_v or m can be determined. The storativity S of the bedrock penetrated by the boreholes has been roughly estimated to $5 \cdot 10^{-4}$ from a short-term pump test (unpublished data). The assumption that S could represent m , the storage coefficient of the model, gave $K_v = 7 \cdot 10^{-9} \text{ m s}^{-1}$ from the calibrated ratio K_v/m for the model without variable surface loading. The resulting simulated mean recharge over the 28-month period in Fig. 12 was about 20 mm yr^{-1} , which is considered to be a reasonable magnitude. The corresponding vertical particle velocity in the bedrock is 20 m yr^{-1} , assuming one-dimensional vertical flow and a

flow porosity of 0.001. This should be compared to the transport time of 25–35 years through the soil, as inferred from CFC-113.

A comparable conceptual model was used by Bergström and Sandberg (1983) to simulate groundwater levels in a number of geologically different aquifers, among others a semi-confined aquifer. The soil profile was represented by a runoff model based on a series of linear reservoirs. When the groundwater-pressure variations in the aquifer were interpreted, the surface-loading effects were overlooked. The aquifer was confined by a clay layer but open at the circumferential boundary. The model was calibrated to observed water levels, and the changes in water levels were interpreted as storage changes. There was a significant difference in the amplitude of the water-level variations at the centre of the aquifer and at the boundary that was thought to be related to differences in storativity in the aquifer. In reality, the diffusive pressure changes induced from the boundary were probably strongly damped in the central aquifer. The observed water-level variations in the middle of the aquifer were thus probably to a large degree caused by seasonal storage changes in the overlying clay, not representing storage changes in the aquifer.

3.4 Heterogeneity and flow diversion at the soil–rock interface

The influence of the fracture-related heterogeneity on recharge to bedrock was investigated with numerical experiments in Paper II. The results from the simulations with the stochastic heterogeneous model, using Monte Carlo simulations, were compared to the results from the homogeneous model, using the geometric mean of the hydraulic conductivity probability distribution as an effective hydraulic conductivity. A number of cases were simulated, where the hydraulic head at the lower boundary of the model was varied to represent situations with different hydraulic gradient in the bedrock. Figure 13 visualises the result of one simulation with a relatively large flux into the rock.

There was a considerable variability in the results among different realizations. The proportion of the applied water that flowed into bedrock varied from about 50% to 100% (Fig. 14); the latter number means that there was no lateral outflow in the soil. The mean flux into the rock increased with increasing hydraulic gradient in the rock (i.e., decreasing hydraulic head at the lower boundary). The increase was more pronounced for the homogeneous model than for the heterogeneous model. The mean flux with the heterogeneous model was therefore smaller than with the homogeneous model at high hydraulic gradients. A difference between the homogeneous and the heterogeneous model is also seen in the simulated elevation of the water

table (Fig. 15). With the homogeneous model, the water table was lowered by an increased hydraulic gradient in the bedrock, whereas the mean water table elevation of the heterogeneous model was almost independent of the imposed hydraulic gradient.

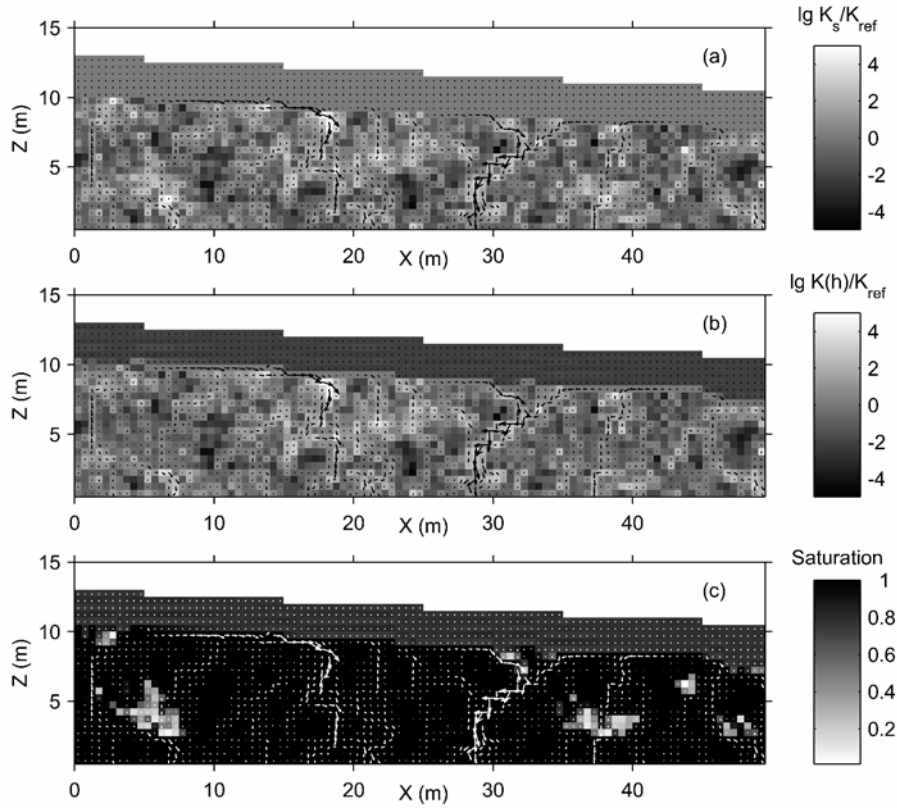


Figure 13. The result of the simulation of one realization of the stochastic model showing (a) the saturated hydraulic conductivity field, (b) the resulting unsaturated hydraulic conductivity field, and (c) the water saturation. The hydraulic conductivity of the soil was $1 \cdot 10^{-6} \text{ m s}^{-1}$, and the geometric mean hydraulic conductivity of the rock K_{ref} was $1 \cdot 10^{-8} \text{ m s}^{-1}$ (modified from Paper II).

The difference between the mean behaviour of the heterogeneous model and the homogeneous model is probably related to the development of local unsaturated zones within the rock, below the water table, with the heterogeneous model. This phenomenon did not occur with the homogeneous model, where the entire rock domain below the water table remained saturated. The unsaturated zones appeared at locations with large hydraulic-conductivity contrasts where low-conductive zones overlie high-conductive zones (i.e., intact rock overlying heavily fractured rock), and this effect increased with an increased vertical hydraulic gradient. An analogous result that shows

variable saturation in a network of fractures with different apertures is the numerical simulations by Kwicklis and Healy (1993). In their work, large fractures connected to the inflow boundary and draining to the outflow boundary through small fractures became saturated, whereas large fractures connected to the inflow boundary through small fractures became unsaturated, because the small fractures could not supply water at rates sufficiently high to maintain them saturated.

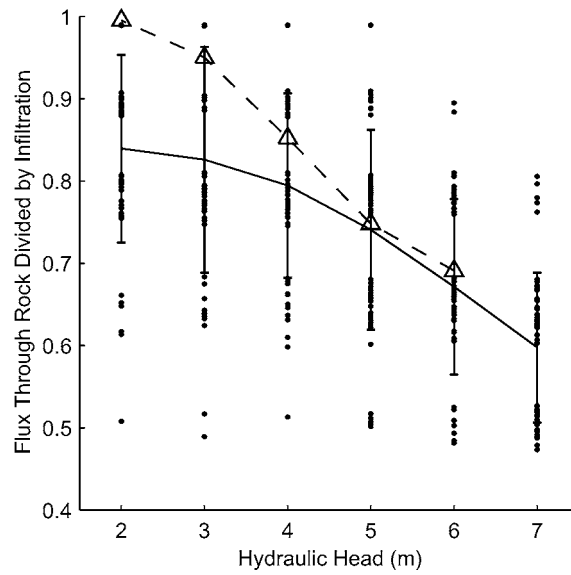


Figure 14. The flux through the bedrock domain as a function of specified head at the lower boundary of the model. The dots indicate individual realizations and the solid line shows the arithmetic mean of the realizations. The error bars indicate the standard deviation. The dashed line shows the results from the homogeneous simulations (from Paper II).

When unsaturated zones appear, the effective hydraulic conductivity will be smaller than if the material is saturated. The geometric mean of the local unsaturated conductivities was thus evaluated as an estimate of the total effective hydraulic conductivity of the total bedrock domain for each realization. The estimated effective hydraulic conductivities showed a dependency on the hydraulic gradient, coupled to the increase of unsaturated zones with increasing hydraulic gradient. The correlation between the estimated effective hydraulic conductivity and the resulting flux for individual realizations was rather weak, indicating that other factors than the mean unsaturated hydraulic conductivity influenced the flux. The geometric configuration of the observed high-conductive pathways may also be important.

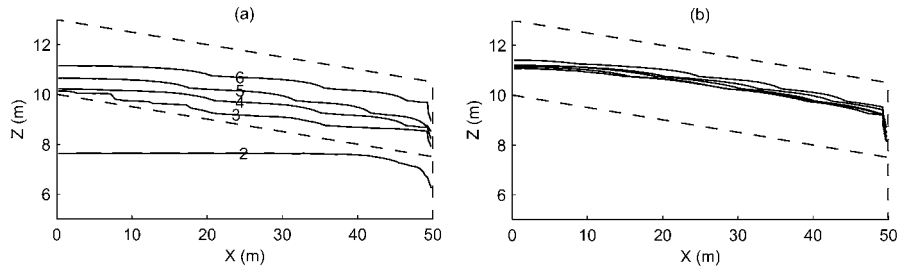


Figure 15. The position of the water table based on (a) the homogeneous simulations and (b) the mean of the heterogeneous simulations. Lines 2–6 correspond to various specified values for hydraulic head at the lower boundary (units in meters). The upper boundary of the model and the soil–rock interface are indicated with broken lines. The net infiltration was 200 mm yr^{-1} and the hydraulic conductivities of the soil and the bedrock were $1 \cdot 10^{-6}$ and $1 \cdot 10^{-8} \text{ m s}^{-1}$, respectively (from Paper II).

The presented study is an estimate of how rock heterogeneity may influence the flow diversion at a soil–rock interface. Future studies should consider other boundary conditions and the effects of the degree of heterogeneity. Furthermore, three-dimensionality and transient effects should be taken into account. Finally, field measurements are needed to further investigate the occurrence of local unsaturated zones in heterogeneous rock under large hydraulic gradients.

4 Conclusions

An improved understanding of a number of issues related to recharge in crystalline-bedrock aquifers has been achieved with this thesis. The results concerning the applicability of the CFC dating method and the interpretation of groundwater-level measurements in crystalline bedrock are of methodological interest, while the surface-loading effects, as well as the modelling results regarding strong heterogeneity, have implications on groundwater modelling.

The main conclusions were:

- CFC dating may not be reliable at forested, humid sites with fine-grained soil, where rapid degradation of at least CFC-11 is likely (Paper I).
- A substantial portion of observed groundwater-level changes in crystalline bedrock may be instantaneous loading effects, involving no storage changes or water flow. This explains observed quick responses to precipitation in groundwater pressure in bedrock at considerable depths (Paper III).
- The hydraulic head in the studied bedrock aquifer could be simulated using a simple conceptual model describing vertical recharge from the overlying soil aquifer. The effect of the variable surface loading had to be included to properly describe individual recharge events (Paper IV).
- The results indicate that local unsaturated zones may develop in strongly heterogeneous rock at high hydraulic gradients, decreasing the effective hydraulic conductivity of the material. Thus when modelling flow in fractured rock, it is especially important to account for heterogeneity effects when hydraulic gradients are large (Paper II).

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6 Summary in Swedish

Grundvattenbildning i kristallin berggrund. Processer, uppskattning och modellering

Grundvatten är en av våra viktigaste naturresurser och är världens mest utvunna råmaterial. Det utgör 98 % av det ofrusna sötvattnet på jorden. I och med det allt större nyttjandetrycket på vattenresurserna har betydelsen av, och medvetenheten om, grundvattnet i den kristallina berggrunden ökat.

Sprickig kristallin berggrund förekommer över stora områden i många delar av världen. I Skandinavien är kristallint urberg med ett tunt moräntäcke en vanligt förekommande geologisk miljö, och i sådana områden är grundvattnet i berggrunden en viktig vattenresurs. I Sverige försörjer bergborrade brunnar ett mycket stort antal enskilda eller små grupper av hushåll med vatten. I vissa områden, särskilt i skärgårdarna, är grundvattentillgångarna otillräckliga, vilket leder till vattenförsörjningsproblem.

Grundvattenbildningen är en nyckelfaktor att ta hänsyn till vid förvaltningen av grundvattenresurserna, och uppskattning av grundvattenbildningens storlek krävs till exempel för att man ska kunna bedöma det hållbara uttaget från akviferer eller förutsäga påverkan av byggnation under grundvattenytan. Grundvattenbildningen i ytliga jordakviferer kan ofta uppskattas med vattenbalansmetoder, åtminstone som ett långtidsmedelvärde. Vattenflödet från jordtäcket ner i berggrunden är däremot i allmänhet mycket svårare att uppskatta. Denna avhandling behandlar detta flöde, grundvattenbildningen i berggrunden.

Det övergripande syftet med avhandlingen var att öka förståelsen av grundvattenbildningen i kristallin berggrund, och mer specifikt, att undersöka hur grundvattenbildningen ska uppskattas samt att utveckla nya modeller för att beskriva grundvattenbildningen. Detaljerade mål var:

- att studera användbarheten av grundvattendatering med freoner (CFC) i sprickigt kristallint berg
- att få ökad förståelse hur vattenflödet vid gränsytan mellan jordtäcket och berggrunden påverkas av heterogeniteten i det sprickiga berget
- att utveckla en metod för att särskilja de förändringar i grundvattnets tryck som är relaterade till magasinförändringar från dem som endast beror på förändrad ytbelastning

- att pröva hypotesen att grundvattenbildningen i en studerad bergakvifer sker genom vertikalt flöde från det ovanliggande jordtäcket

Studien baseras huvudsakligen på tre angreppssätt: grundvattendatering med CFC, geohydrauliska observationer och matematisk modellering. Om grundvattnets åldersfördelning i den ytliga berggrunden kunde bestämmas vore det möjligt att uppskatta grundvattenbildningen. Denna studie är en av de första tillämpningarna av CFC-metoden i Sverige. Syftet med de geohydrauliska mätningarna var att studera processerna och drivkrafterna för grundvattenbildningen i berggrunden, samt att få data till den matematiska modelleringen. En enkel endimensionell modell, driven av skillnaden i hydraulisk potential mellan jord och berg, användes för att simulera de observerade grundvattnivåerna i en bergakvifer.

Analys av CFC-11, CFC-12 och CFC-1113 samt tritium gjordes på grundvatten från tre bergborrhål i norra Uppland. De mycket låga halterna av CFC-11 och CFC-113 i kombination med låg syrgashalt och förekomsten av svavelväte i grundvattnet tyder på att det hade skett anaerob nedbrytning av dessa två CFC. Det är känt att CFC-12 är mycket mer motståndskraftig mot nedbrytning än CFC-11, och CFC-12 antogs därför vara stabil. Eftersom det inte fanns något klart rumsligt mönster i CFC-dateringen kunde inga kvantitativa slutsatser dras vad gäller flödesvägar eller grundvattenbildning. Koncentrationerna av CFC-12 överensstämde ganska väl med de uppmätta tritiumkoncentrationerna i de flesta proverna, vilket betyder att den skenbara åldern kan vara den verkliga åldern. Analysen visar också att proverna skulle kunna vara binära blandningar, alltså blandningar av två olika vatten med skilda åldrar.

Den geohydrauliska fältstudien utfördes vid NOPEX-projektets fältstation i Norunda häradsallmänning, Uppland. Området är flackt och utgörs av kristallin berggrund överlagrad av ca 10 m kompakt morän. Grundvattnivåer mättes i moränen och i två borrhål i berget. Dessutom observerades klimatologiska variabler och markvattenhalten i ett antal profiler.

Vid nederbörd observerades ett mycket snabbt svar i berggrundvattnets tryck trots det mäktiga jordtäcket. Variationer i grundvattentrycket kan bero på dels magasinförändringar (en diffusiv tryckförändring), dels förändringar av endast belastningen på berggrunden (en momentan tryckförändring). Dessa belastningsförändringar kan orsakas av t.ex. lufttrycksvariationer och varierande mängd vatten i den ovanliggande marken. Hur stor del av en förändring av ytbelastningen som motsvaras av ett förändrat grundvattentryck under odränerade förhållanden, beskrivs av belastningseffektiviteten. Utifrån gensvaret på lufttrycksvariationer uppskattades belastningseffektiviteten till 0,95 i den aktuella bergakviferen. Den totala ytbelastningens variation beräknades utifrån data på lufttryck, markvattenhalt och uppskattat snömagasin. Den diffusiva tryckkomponenten kunde sedan beräknas genom att subtrahera de momentana tryckförändringarna från det observerade grundvatten-

trycket. Den momentana tryckförändringarna uppskattades att stå för omkring 20 % av berggrundvattentryckets årtidsvariation.

En endimensionell vertikal modell användes för att simulera grundvattennivån i bergborrhålen i Norunda. Jordtäckets och berggrunden beskrevs som två reservoarer förbundna med varandra, där berggrundvattenbildningen antogs vara direkt proportionell mot skillnaden i hydraulisk potential mellan jord- och bergreservoarerna. Utflödet från bergreservoaren antogs vara proportionellt mot den hydrauliska potentialen i reservoaren. Dessutom infördes en term för att beskriva den momentana effekten av ytbelastningsförändringar. Modellen kunde kalibreras och valideras mot de observerade berggrundvattennivåerna i det ena borrhålet med tämligen god överensstämmelse, vilket stödjer de underliggande antagandena för modellen. I det andra borrhålet förekom flera oförklarade språng i grundvattennivån, vilka inte kan simuleras med denna modell.

Numeriska experiment gjordes med en modell av en hypotetisk sluttning för att simulera vattenströmningen vid gränsytan mellan jord och berg. Modellen utgjordes av en tvådimensionell profil med ett jordtäck ovanpå sprickigt berg. En konstant infiltration påfördes vid modellens markyta, och den resulterande stationära strömningen studerades. Bergmaterialet modellerades som ett sprickkontinuum. Två olika metoder för att representera det heterogena berget jämfördes: Berget beskrevs först som ett homogent ekvivalent kontinuum och sedan som ett heterogent stokastiskt kontinuum med hjälp av Monte Carlo-simulering. Den första metoden ska återge ”medelströmningen” förutsatt att rätt medelegenskaper används i modellen. Den andra metoden visar också medeluppförandet, men ger även lösningens statistiska egenskaper. För att lösa strömningsproblemet numeriskt användes simuleringskoden TOUGH2.

Det resulterande medelflödet över gränsytan mellan jord och berg var mindre i den heterogena modellen än i den homogena modellen vid stora hydrauliska gradienter. Skillnaden beror troligen på att det bildades lokala omättade zoner i berget, under grundvattenytan, i den heterogena modellen, vilket inte skedde i den homogena modellen. Detta fenomen uppträdde i vissa områden med stora kontraster i hydraulisk konduktivitet, där en zon med liten hydraulisk konduktivitet låg uppströms en zon med hög hydraulisk konduktivitet, och effekten ökade med ökad hydraulisk gradient. Detta ledde till att materialet fick en lägre effektiv hydraulisk konduktivitet än om materialet var mättat.

Denna avhandling har givit en ökad förståelse av flera problem som är relaterade till grundvattenbildningen i den kristallina berggrunden. Resultaten rörande användbarheten av CFC-datering och tolkningen av grundvattennivåmätningar i kristallin berggrund har metodologiskt intresse, och effekterna av ytbelastningsförändringar, såväl som modelleringsresultaten rörande hög heterogenitet, har betydelse för grundvattenmodellering.

De viktigaste slutsatserna var:

- CFC-datering är inte pålitlig i skogsmiljöer med finkornig jord, där snabb nedbrytning av åtminstone CFC-11 är sannolik.
- En avsevärd del av observerade grundvattennivåförändringar i kristallin berggrund kan vara momentana belastningseffekter som inte beror på någon magasinförändring eller något vattenflöde. Detta förklarar observerat snabbt svar på nederbörd på avsevärda djup.
- Grundvattennivån i den studerade bergakviferen kunde simuleras med en enkel begreppsmässig modell som beskriver den vertikala vattenflödet från det överliggande jordtäcket. För att beskriva enskilda grundvattenbildningstillfällen på bästa sätt var det nödvändigt att ta hänsyn till effekten av ytbelastningen.
- Modelleringsresultaten antyder att lokala omättade zoner kan utvecklas i heterogent berg vid stora hydrauliska gradienter, vilket minskar den effektiva hydrauliska konduktiviteten. Det är därför särskilt viktigt att ta hänsyn till heterogenitetseffekter när den hydrauliska gradienten är stor.

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