4 Some Hydrogeological Methods for Determining Groundwater Recharge and Groundwater Flow

4.1 Introduction

The occurrence of groundwater, groundwater flow and the chemical composition of groundwater are of central importance for the siting and design of underground rock facilities, especially for the disposal of spent nuclear fuel. A high hydraulic conductivity makes rock engineering and disposal difficult. The groundwater can also attack barriers and waste containers, especially if the salinity is high, and can dissolve and transport hazardous components. The aim of this chapter is to present a few *hydrogeological investigation methods* used for determining groundwater recharge (quantity, spatial and temporal distribution) and its impact on groundwater chemistry as well as for studying groundwater flowpaths and their transport properties. Hydrological, hydraulical and chemical investigation methods and modelling methodology are not discussed here.

4.2 Hydrometeorological and Hydrological Data

Purpose

Hydrometeorological data are important in order to correctly calculate groundwater recharge in the ground and rock and to thereby provide general input data for flow potentials, for

example, for numerical flow models. Hydrochemical data are also important for providing a basis for the calculation of chemical equilibrium reactions, mixing, groundwater age and flow patterns. In particular, isotope determination can be of importance for tracer studies, see Section 4.5. Hydrometeorological and hydrological data provide boundary conditions for modelling based on present-day conditions. For long-term, retrospective climate trends, geological and biological studies are required, for example dendrochronological studies (studies of tree rings), sediment studies with pollen and diatom analysis as well as studies of natural isotopes (for example, oxygen) in polar ice. These paleoclimatic studies can also provide valuable information on natural climate variations which provide input data for climate forecasts. Advanced computer models are currently used to calculate future climate conditions where anthropogenic effects (human impact) are of particularly great significance.

Data Access and Measurement Techniques

Hydrometeorological data series comprise temperature, precipitation, precipitation chemistry, relative moisture content, air pressure, wind direction, wind spred and global radiation. There are a large number of meteorological stations operating in Sweden from which data can be obtained. Most of these stations are run by the Swedish Meteorological and Hydrological Institute (SMHI). Furthermore, weather stations exist at airports, military air bases and other military facilities as well as along public roads for the purpose of road maintenance control. In addition, measurements (of precipitation, temperature and wind etc.) are conducted at nuclear facilities, for example, at Forsmark and Simpevarp, as well as at the Äspö Hard Rock Laboratory, southeastern Sweden. The frequency of measurement data collection and the parameters registered vary considerably. Major weather stations at SMHI are currently often completely automated. Information on suitable climate stations

for regional and local investigations is provided by SMHI where data is currently stored digitally in several different large databases, *Svenskt klimatarkiv (KLAR)*, *Svenskt vattenarkiv (SVAR)* and for sea and oceanographic data, *Svenskt Havsarkiv (SHARK)*. Hydrometeorological data for Östhammar, Tierp and Oskarshamn have been compiled by SMHI on behalf of SKB (Larsson-McCann *et al.* 2002a, 2002b).

The *air temperature*, which is important for the calculation of evapotranspiration, is measured by mercury or resistance thermometers; the latter is preferable from the environmental standpoint. They are positioned protected from solar radiation, often about 1.5 metre above ground and at a distance from surrounding objects. The measurements are usually presented as weighted average values at different times of the day (Alexandersson 2002). In SMHI's assessment, error sources are small.

One of the most important and most common parameters which is necessary to provide input data for balance calculations and flow modelling is *precipitation*. The measurements are often conducted using a wind-protected precipitation gauge with a collection surface of 200 cm^2, placed 1.5 metres above the ground. In general, SMHI's stations perform measurements 1 to 2 times a day (at 07^{00} h and 19^{00} h, respectively). Precipitation collection is associated with significant uncertainty that is mainly due to turbulence around the gauge which causes the precipitation to miss the gauge. Significant measurement problems are associated with snowfall since the precipitation also has to melt. The losses vary with the wind strength and wind direction as well as with evaporation and adsorption on the walls of the vessel (Eriksson 1983). The measurements are often 10 to 25 % lower than the actual figures. Therefore, it is important for the precipitation values to be adjusted before use in, for example, water balance calculations. Statistical processing of long series of precipitation data is required to provide knowledge of the frequency of dry years and wet years. Since precipitation quantities can vary locally, it is important that several

representative measurement stations are located in the areas under investigation.

Wind direction and velocity are measured and specified as a matter of principle at a height of 10 metres. Since the height and speed constantly vary, an average value is given as a rule, such as during 10 minutes. The wind is used to correct other data, including precipitation, although it also has considerable significance in other contexts, for example, for the calculation of airborne pollutants, including the spreading of salt to the environment around roads (Blomqvist 2001).

Air pressure is measured using different types of barometers and this is conducted at a large number of SMHI's weather stations as well as at airports and military air bases. The air pressure is important for the interpretation of surface and groundwater levels and other parameters and should therefore be taken into account in accurate calculations of small level changes. The combined effects of air pressure and wind can often have a considerable impact on surface water levels in lakes and seas. The effects can also be reproduced in the form of distinct level changes in groundwater levels where hydraulic connections exist. This should be taken into account in connection with groundwater level measurements in coastal areas.

Evapotranspiration is an important factor for the calculation of groundwater recharge. In practice, it is very difficult to measure, since it is dependent on many different factors, such as radiation balance, air temperature, air humidity, wind, type of ground, soil water and type of vegetation. *Potential evapotranspiration* can be calculated on the basis of climate parameters using Penman's formula or can be measured as evaporation from an open, water-filled vessel. However, since actual evapotranspiration is considerably less and is strongly affected by soil water and vegetation, it is difficult to measure. It should therefore be calculated, either as a loss item, if measurements of surface water runoff and precipitation are conducted, or be based on potential evapotranspiration and soil water content (Brandt *et al.* 1994).

Runoff is generally determined on the basis of data from the runoff stations operated by SMHI, among others. The mainland of Sweden is divided into 119 main catchment areas which, in turn, are divided into more than 13,000 sub-catchment areas (SMHI 2004). The water level in large lakes and runoff into many large watercourses are measured manually one or more times per day or, which is more common today, are continuously registered. On the other hand, information on runoff into minor watercourses is often lacking. Therefore, it is necessary to start measurements, as early as possible, of representative, small catchment areas in order to obtain a basis for local water-balance studies. The flow in watercourses can generally be calculated directly from the water level in a *measuring weir*, for example a V-shaped Thomson overflow.

Measurements of *precipitation* and *atmospheric chemistry* are conducted by SMHI and IVL Swedish Environmental Research Institute Ltd. Together with Statistics Sweden (SCB), they have formed a consortium for the collection of emission data and for the development of a national database. Deposition data are very important for groundwater chemistry modelling and can also be used to study infiltration and water transport to the ground-water (percolation). Previously, isotopes in the water were also determined in precipitation samples from several sites in the country. Since the isotope laboratory at the Department of Hydrology, Uppsala University, was closed down, such measurements are no longer conducted, which is a major dis-advantage for studies of groundwater recharge (see Section 4.4).

4.3   Measurement of Surface and Groundwater Levels

Purpose

The measurement of surface and groundwater levels is an important part of hydrogeological investigations. The measure-

ments can have many different purposes, including long-term measurements to determine long-term trends and seasonal patterns in the level fluctuations. They can also be conducted as general difference measurements to determine flow potentials and flow directions or as specific difference measurements to determine hydraulic relationships, for example, in connection with pump tests and other investigations that aim at determining the hydraulic properties of the ground. The measurements are often used within an environmental control programme, for example, in connection with underground construction in order to prevent environmental effects in the form of ground settlement and damage to constructions, groundwater supply and vegetation. The measurements are sometimes conducted for several purposes and this involves different requirements with respect to measurement frequency, accuracy and the length of the measurement series. Prior to the construction of a repository for spent nuclear fuel, level measurements that fill many simultaneous purposes are necessary. It is important that regular measurements in different types of geology and in different terrains are started as early as possible in the site investigation areas, in order to obtain long time series and to describe undisturbed conditions. Regular level measurements in observation tubes and boreholes are going on at Forsmark and in the region of Oskarshamn.

Data Access and Measurement Techniques

Long-term measurements of the groundwater level are regularly conducted within the Geological Survey of Sweden's (SGU) groundwater network, which comprises about twenty-five measurement areas spread over Sweden. In each measurement area, there are one or more specific measurement points that represent different aquifers, both tubes in soil as well as boreholes in rock. For groundwater monitoring, 82 areas with 120 stations also exist in the form of tubes, boreholes and springs for

controlling groundwater quality. The size of the groundwater fluctuation and its temporal variation provide good information on the aquifers' properties, limitations, heterogeneity and hydraulic relationships. SGU's level measurements are generally conducted twice a month, and this is considered to be the minimum to obtain a clear reflection of the seasonal variations. High-resolution level measurements at som stations can be used to calculate the size of the groundwater recharge, see Section 4.4 (Johansson 1987, Healy & Cook 2002). Therefore, the evaluation requires a sufficiently high measurement frequency and, for aquifers with a small variation (for example, large aquifers or groundwater discharge areas), a high measurement accuracy is necessary.

In connection with major construction projects, separate control programmes are conducted for existing as well as newly installed measurement points. For example, major tunnel projects, such as the Bolmen tunnel which, during construction, involved measurements in more than 400 wells, tubes and boreholes as well as the Hallandsås tunnel, where the number of measurement points was close to 1,000 (Banverket 2000). However, for many of these measurement points, the measurements have only been conducted very occasionally or the measurement series are very short. Furthermore, in major cities, such as Stockholm and Gothenburg, specific monitoring programmes exist with a very large number of measurement points (almost 1,000 in Stockholm) which are, however, only measured a few times a year.

It has quite often been found that the *length of the measurement series* before the start of an underground construction project has been far too short for reliable assessments of groundwater impact to be made. The Swedish Environmental Protection Agency (1999) specifies an absolute minimum period of 6 months of measurement before construction start. Studies of *non-equivalent measurement series* (=unequal measurement frequencies) show that the measurement series should preferably be 15 to 18 months (Lundmark & Olofsson 2002) in order to

determine minor deviations (<1 dm) from natural fluctuations. The length of the measurement series over several hydrological years and the use of equidistant measurements allow statistical *time-series analyses* to be used. If measurement points are used where groundwater abstraction occurs, for example, dug and drilled wells, the size of the groundwater abstraction must also be taken into account when evaluating the measurement series.

The measurements are either performed manually through sounding or continuously through, for example, pressure sensors and data logs. Continuous measurements are naturally preferable although they often result in large data sets. At present, there is a possibility of automating measurements from many points and of sending information via links to a data processing centre through which information can be obtained in real time from the measurement points. There is a considerable value in obtaining real-time information during the construction phase in order to allow for rapid measures and thereby prevent damage to buildings and vegetation. This approach has been successfully used in connection with underground construction in Norway in order to determine the need for leakage-mitigation measures in the underground facility (Randolph-Lund *et al.* 2003). It is also important that methods for analysis of groundwater level data are available in order to distinguish construction-related effects on the levels from natural variations. Systems for such statistical computer processing have been developed (such as *GCP – Groundwater Control Programme*) and have been used in connection with different underground projects, for example the Ormen tunnel in Stockholm (Cesano & Olofsson 1997), the Bolmen tunnel and the Hallandsås tunnel (Banverket 2000), see examples in *Figure 4.1*. Groundwater data are routinely collected in many construction projects, although this is often done without a structured analysis methodology. In this way, deviations have not been observed at all or have been detected at such a late stage that it has not been possible to prevent effects on the soil and vegetation.
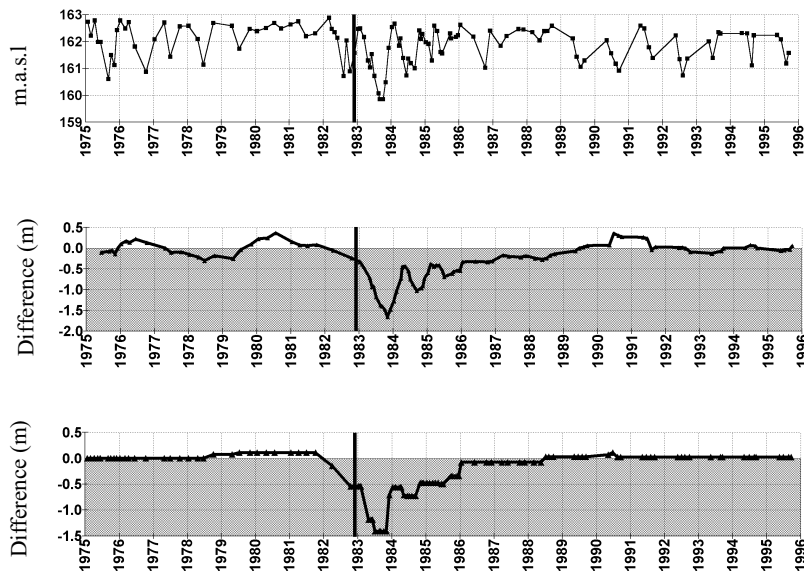
Figure 4.1. *Examples of how statistical calculations can be conducted on groundwater levels in order to obtain deviations from natural level variations in connection with underground construction. The uppermost diagram shows unprocessed groundwater level measurements. The middle curve shows deviations from natural level variations obtained using stepwise regression and the last curve shows deviations calculated using a modified double mass analysis. The vertical line shows the time when a tunnel was constructed close to the measurement point (taken from Olofsson in Knutsson & Morfeldt, 2002).*

The number of measurement points and their position are naturally very important for the usability of the groundwater data. Existing wells in rock and soil as well as springs are

naturally used as measurement points which is particularly important in the initial stage as well as to investigate possible impacts during a later construction phase. The determination of the number of boreholes in rock that is necessary and the positioning of these boreholes in connection with construction projects, for example, during the construction of the Hallandsås tunnel and prior to the construction of the repository, is generally conducted on the basis of geological and geophysical investigations as well as the tectonic and geological models which are set up on the basis of these investigations. The borehole configuration is therefore highly dependent on the heterogeneity of the rock and the need to investigate specific geological rock structures. The number and positioning of soil tubes for investigation are similarly determined by the variation of the soil cover and topographical conditions. In order to capture the typical long-term level variations in an investigation area, soil tubes and boreholes must be located in different geological and topographical environments and the levels must be registered in recharge and discharge areas for different groundwater systems and at different depths (if the stratification involves several groundwater systems). Therefore, this is different from the siting of control and investigation holes that primarily aim at providing construction-related data or at investigating specific structures. In order to design a long-term control programme for groundwater levels, a good knowledge of the geology of the area is required. The more heterogeneous and geologically fragmented an area is, the more observation points are required for a good control of the level changes. It is very difficult to obtain an adequate control in crystalline bedrock, since two adjacent boreholes can demonstrate completely different or temporally displaced level variations. In construction projects, it is usual to underestimate the area of impact, especially along major conductive zones in the rock (Olofsson 1991, Banverket 2000). Existing measurement programmes can be made more efficient as measurement data are obtained, through different statistical methods, for example principal

component analysis (PCA, Pearson 1901), from which the co-variation between different points can be determined. The methodology is independent of the spatial distribution of the points and only explores linear trends in the data set. For points with hydraulic connections, different variations of geostatistic methodology can be used, for example, kriging, in order to render the position and number of measurement points more efficient (Ackerberg 2002).

The measurement of surface water levels is important, as has been described above, for the determination of runoff in small watercourses and for the calculation of water balances and the interaction between the surface water and groundwater. In many cases, high-resolution registration is of considerable importance, with respect to time and level, and this can provide knowledge of the lake's or watercourse's hydraulic conditions. High-resolution pressure and temperature registration have been conducted in a few lakes in the Forsmark area and show that lakes in the same area can function very differently in hydrodynamic terms with respect to recharge and discharge conditions as well as with respect to hydraulic connections with the surrounding groundwater (Widén 2001).

4.4   Groundwater Recharge – Measurement Methods and Calculations

Background and Problems

Groundwater is the underground part of the water cycle and, thereby, the most difficult part to measure and investigate. Groundwater recharge is defined as the downward water flow that reaches the groundwater system in question. Knowledge of the quantity of the recharge and of its spatial and temporal distribution is of greatest importance, for example, in connection with siting, design and construction of underground facilities below the groundwater table as well as in connection

with the siting and design of waste deposits and water supply wells. The impact of groundwater recharge on the groundwater chemistry (for example, through acid rain or pollutants) must also be taken into account, for example, by conducting a vulnerability analysis for existing or planned water supply wells.

Groundwater recharge can be *direct*, namely, the precipitation directly infiltrates through the ground to an open aquifer (aquifer=a permeable geological formation capable of yielding groundwater to wells and springs) or *indirect* through the inflow of water from surrounding elevated areas to a closed aquifer or through contact with other aquifers. Another indirect process is induced infiltration, namely leakage from adjacent lakes or watercourses to an open aquifer as well as infiltration in dry river beds which is common in arid climate areas after heavy rain. The infiltration conditions are very different in different rock and soil strata depending on their permeability and moisture content. The size of the infiltration naturally also depends on the weather conditions, primarily the nature, quantity and temporal distribution of the precipitation as well as the size of the evapotranspiration. In this way, the conditions for groundwater recharge are very different from year to year or from time-period to time-period depending on the changes in weather and climate, especially in an arid climate (Knutsson 1988). Therefore, it is very important to collect and process hydrometeorological and hydrological data (see above), also statistically, so that the frequency of "dry" years and "wet" years is determined as well as more long-term climate changes.

In connection with direct groundwater recharge, infiltration into the ground takes place within the elevated areas of the terrain, also known as *recharge areas*, from which the water flows all the way from small, superficial, local systems to large, deep regional systems (*Figure 4.2*). Through topographical variations as well as variations in the geology, such as the occurrence of horizontal or flat structures with considerable water permeability, such as sand and gravel layers in till, superficial, open fractures in the bedrock (such as in Forsmark, see *Figure 3.11* in

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Chapter 3) or fracture zones at greater depths (such as at Finnsjön in Uppland, Sweden), the groundwater is then step by step linked to springs, wetlands, surface watercourses and lakes, also known as *discharge areas* at different levels in the landscape. In this way, only a small part of the water reaches deeper parts of the bedrock and flows to the regional systems. The small-scale topography which dominates both southeastern Sweden and northeastern Uppland is favourable for the occurrence of local flow systems and superficial groundwater recharge, although not for regional systems and groundwater recharge at deeper levels (Follin & Svensson 2003, SKB 2003). One difficult complication is if human intrusion should disturb the natural groundwater recharge, for example, by leading water away in connection with tunnel construction. This causes the groundwater levels to sink and the recharge area changes and this can lead to increased recharge, faster turnover and changes in the groundwater chemistry. In agricultural areas with irrigation, a small addition of (surplus) infiltrating water can be expected, as is the case in densely populated areas with leaking sewage and clean water pipes followed by subsequent changes in groundwater chemistry.
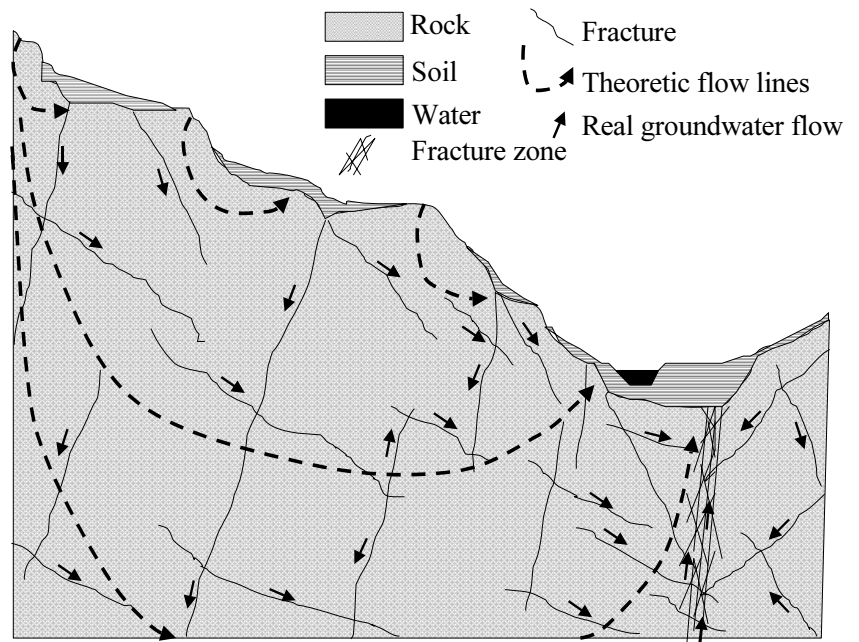
Figure 4.2. Recharge and discharge areas as well as groundwater flow patterns in a valley with varying topography and thin soil cover on fractured, hard rock. The actual flow pattern deviates considerably from the theoretical depending on fractures and fracture zones (Olofsson et al. 2001).

Important questions relating to groundwater recharge include the following:

- How and where does groundwater recharge occur? How is the chemistry affected?
- How great is the groundwater recharge in different aquifers and at different depths and what kind of hydraulic connection occurs with the surface water and between different aquifers?

- How does groundwater recharge occur in time with different weather conditions and climate changes?
- What kind of human intrusion can disturb groundwater recharge and change the chemistry?

Methods and Calculations

Overall assessments of groundwater recharge in a large area can be conducted in the form of a water-balance study based on precipitation and evapotranspiration data and taking into account geology, hydrology, topography and vegetation. The amount of groundwater recharge in a certain aquifer can be calculated using infiltration coefficients (the relationship between the quantity of infiltrated water and precipitation in a recharge area) for different rock types and soils if the geological and topographical conditions are very homogeneous and large-scale. However, this is seldom the case in Swedish terrain and consequently the method cannot be recommended.

Area and site-specific information on the size of groundwater recharge, its spatial distribution and temporal evolution requires detailed knowledge of geology, hydrogeology, land use and topography in the area as well as extensive measurements and calculations. Up-to-date information on precipitation and evapotranspiration is needed in the form of long series of or forecastes of climate data.

Different methods, based on different principles, exist for measuring and calculating groundwater recharge. Method selection should be conducted taking into account the purpose, time-scale, type of information desired (point or area data) as well as access to background information and resources. The use of the different methods must be based on good knowledge of the groundwater recharge processes and the existing geological and hydrogeological conditions. Therefore, it is important to initiate the study by setting up a *conceptual model* of the area of investigation. This entails a simplified, generalised description

with a principle diagram (block diagram, cross section) of how the entire groundwater system functions as a whole *(Figure 4.3)*. The conceptual model is based on the water-balance calculations and on existing data on the geology, size and limits of the groundwater system as well as on where and how groundwater recharge occurs and flows and on whether human intrusion can be expected to disturb the natural processes. Based on the model and the criteria specified above, the most suitable investigation methods and computer models can be selected. However, remarkably few good examples exist of conceptual models that are openly described in the literature, especially for groundwater conditions in hard rock.

In principle, the methods can be classified according to where in the system the movement and quantity of the water is being studied:

- Recharge, for example, using tracers.
- Response within the system, for example using groundwater level analysis.
- Discharge, for example runoff measurements.

Preferably, several independent methods should be tested. The uncertainties in the calculations must be specified for each specific method.
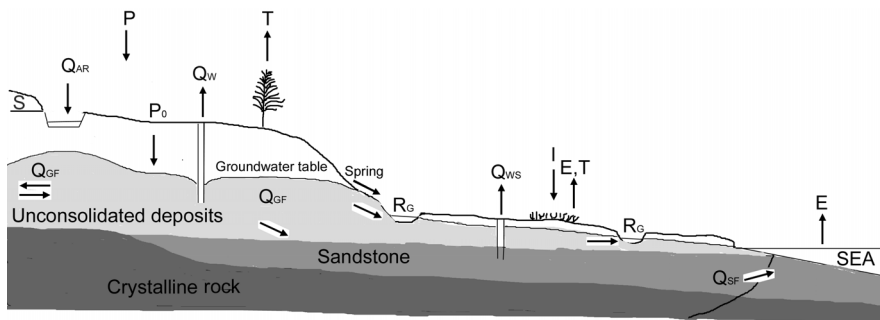
Figure 4.3. Conceptual model for the groundwater conditions in the Nybro esker and its surroundings in a profile from the esker to the sea. E=Evaporation + T=Transpiration (350 mm/year), I=Irrigation, P=Precipitation (510 mm/year), P_0=Natural groundwater recharge (160 mm/year), Q_{AR}=Artificial recharge from basins (40 mm/year), Q_{GF}=Groundwater inflow and outflow, Q_{SF}=Outflow of groundwater from sandstone aquifer to the Baltic Sea. Q_W=Abstraction wells (60 mm/year), Q_{WS}=Abstraction of water from sandstone aquifer, R_G=Runoff in streams and drainage from groundwater, S=Sublimation and infiltration from snow. Note that the diagram is not to scale. The length of the profile is about 5 km and the maximum thickness is about 50 m (from Eliasson 2001).

Recharge Methods

Groundwater recharge can be studied with the help of tracers and through modelling. Added tracers and natural tracers (see Section 4.5) have both been used to follow the path of the precipitation, such as snow melt water with a certain oxygen isotope composition through the unsaturated zone down to

different depths below the groundwater surface for a couple or several years. Based on the average velocity of the water particles and the water content in an observed stretch, the size of the groundwater recharge is determined at 280 mm/year in sandy soil in the Uppsala district, south central Sweden (Saxena 1987). In Scania, south Sweden, and Denmark, tritium pulses have been followed for several years down through the thick soil cover to considerable depths in the bedrock. This has made it possible to determine parameters such as the time sequence for groundwater recharge to limestone at a depth of 150 metres on the Kristianstad plain to about 5 years (Engqvist 1991, see Section 4.5). Isotope data (deuterium, oxygen-18, carbon-14 and tritium) on the water from different depths at the Äspö Hard Rock Laboratory have provided important information on the origin of different types of groundwater, for example, that a low oxygen-18 content indicates that water from land ice melting has contributed to groundwater recharge deep in the bedrock (Laaksoharju 1999). These methods are of great interest for the development and evaluation of possible future scenarios for how a repository for spent nuclear fuel can be affected in connection with deglaciation after an expected, future ice age (see SKB 2003). It has also been possible to follow the changes in the original composition of the groundwater during the construction of the access tunnel to the Äspö Hard Rock Laboratory (see SKB 2003).

Experiments with added tracers result in pointwise measurements which can be difficult to transfer to larger areas or deeper levels. Furthermore, several of the mathematic models used are not suitable for determining groundwater recharge at depths since they have been developed for soil water studies. One complication in the use of recharge methods is if infiltration is affected by particularly permeable zones, for example, macropores in the soil cover or fracture zones in the rock. However, the results provide information on the quantity of water that is added to the surface groundwater system, namely the greatest possible groundwater recharge, which is of

interest for further calculations using groundwater models (Olsson 2000). What are needed are methods to determine the groundwater flow from the soil cover to the bedrock on the basis of existing hydraulic heterogeneity, for example, for the determination of the flow from till to underlying fractured rock. This could be achieved using a combination of geophysical measurements for mapping conductive soil and rock structures as well as measurements of groundwater pressure levels and groundwater chemistry (including isotope analysis) in different geological environments.

Response Methods

The methods involve studies of how different parts of the groundwater system, for example groundwater levels, groundwater flow and groundwater chemistry, react to changes in the form of added water and chemical substances, in this case, through groundwater recharge or discharge/abstraction of water, which is compensated for by subsequent recharge. The latter continuous abstraction method has been tested at water supply wells with long-term abstraction, which often entails a change in natural groundwater recharge. The response methods provide information on the actual groundwater recharge to the system or to the level in question.

The analysis of groundwater level changes is the most immediately suitable method since groundwater levels are easy to measure and are often included in long measurement series, such as with respect to many municipal water supply wells, and in different control programmes and as a reference in similar groundwater environments in SGU's groundwater network since the mid-sixties. A detailed description of the method with its different variations, for example, to calculate reservoir changes, is provided by Fealy & Cook (2002). The most common analysis involves transforming the groundwater level fluctuations in a number of representative observation tubes, wells or boreholes

in an open groundwater reservoir to corresponding water quantities with the help of a value for the storage coefficient, also known as the specific yield of water. The storage coefficient is the quantity of water that is removed or added to the reservoir per unit area (for example, 1 m^2) in connection with the lowering or the raising of the groundwater level by one unit (for example 1 m). It is primarily determined by pump tests but can also be established on soil or rock samples in the laboratory. It should be known for different parts of the groundwater reservoir, which can be a demanding task, especially in fractured, hard rock. The groundwater level analysis method is otherwise best suited to groundwater levels that are fast-reacting and relatively deeply located, such as in the bedrock, where the level fluctuations are not affected by capillary transport and evapotranspiration (Johansson 1987) or ground frost. Important information which is also obtained through this method, includes knowledge of the temporal processes in groundwater recharge in relation to precipitation and climate changes and the effects of different activities that affect groundwater recharge.

The chloride balance or chloride concentration method is based on the relationship between wet and dry precipitation of chloride from the atmosphere and the chloride content in the groundwater. The chloride content usually increases with the infiltration of the water due to evapotranspiration but is then not changed in the groundwater zone. The method appears to be simple and inexpensive but has been found to contain significant uncertainties, particulary in the determination of dry precipitation and through the fact that the chloride content in the groundwater can be affected by both relict saltwater and pollutants. It is probably most suitable for rough estimates of groundwater recharge in large areas and over long periods of time. Gustafson (1988) has carried out such a calculation for crystalline bedrock in Sweden, divided into six regions with the support of existing data from SGU and SMHI. The results are interesting and show regional differences which appear to be reasonable, namely low values (24-28 mm/year) in eastern

Götaland and Svealand with a low net precipitation and high values in Scania (114 mm/year, compare with Hallandsås below) and in western Sweden (250 mm/year). The values correspond to groundwater recharge in relatively superficial parts of the bedrock since the calculation is based on data from local water supply wells which are usually 100 m deep, at most. The method has been much used in dry areas, where it is expected to be a useable supplement to other methods (Lloyd 1999).

The groundwater flow method is a more demanding method which applies both to input data on hydraulic parameters and boundary conditions and to calculations with analytical and numerical solutions, or nowadays, primarily with numerical modelling. An early use of a finite element model for two-dimensional flow was conducted in the sedimentary bedrock on Gotland in the Water Planning Official Report (Berggren *et al.* 1980). The groundwater recharge was calculated at between 10 mm/year in an area with low hydraulic conductivity and 80 mm/year in another area with higher hydraulic conductivity. The development of mathematical models has since then been extensive, including three-dimensional (3-D) flow, at the same time that increased computer capacity has speeded up calculations. In a 3-D model of northeastern Uppland, groundwater recharge at a depth of 500 m in crystalline rock is estimated at between 1.6 mm/year and 5.7 mm/year for different cases with a net precipitation of 250 mm/year (Holmén *et al.* 2003). In this case, it would be suitable to attempt to calibrate this modelling by measurements and calculations with other methods. Previously, groundwater recharge at Äspö has been estimated at 150 mm/year on the surface and 5 mm/year at great depth. In general, it is stated that a turnover of only 1-2 % of the surface groundwater recharge occurs in the deeper parts of the bedrock (SKB 2003). However, a disturbance in the form of construction work with subsequent groundwater lowering can essentially increase groundwater recharge. On the tunnel level in Hallands-åsen, the increase has been calculated at 25 % in connection with

a maximum groundwater lowering of 100 metres (Anderberg 2000).

Discharge Methods

The methods are based on obtaining data on the quantity of water leaving the groundwater system either by direct measurements or by model calculations. The most simple method is *flow measurements from springs* on condition that the catchment area for the spring is well-defined and that no water passes by or below the spring. The method has been tested with great success in superficial systems, for example, springs in moraine areas (Johansson 1987) and is useable in sedimentary bedrock, above all in karst formations. On the other hand, it is difficult to apply to deep groundwater systems in fractured rock. Runoff measurements in surface water which drain a certain area and at the same time *isotope analysis* of oxygen-18 and deuterium in rainwater, groundwater and surface water from the same area have, however, been found to provide very valuable information, above all that the amount of groundwater in the runoff is much greater than previously assumed also at flood peaks in connection with snow melting or heavy rain (Rodhe 1987, *Figure 4.4*). However, the quantity of groundwater is probably dominated by superficial groundwater and it should be an important task to investigate, through additional isotope determination, whether the groundwater supplied from greater depths, for example from well-defined bedrock areas, can be separated.

Runoff models have been used to determine groundwater recharge in areas with consistent geology, such as the moraine areas and large glaciofluvial deposits in southeastern Sweden (Johansson 1987 and Eliasson 2001). In the first study, several different models and methods were compared. In both studies, different variations of the HBV model, developed by SMHI, which is based on easily available weather data, were used. The model gave reasonable results on the average, annual ground-

water recharge for each area. In the second study, it was also possible to obtain a value for groundwater recharge in the sandstone aquifer situated below the glaciofluvial deposits (15 mm/year compared with 160 mm/year in the superficial layers, see *Figure 4.3*). Unfortunately, the study did not include the underlying hard rock, although the groundwater recharge can be estimated at only a few mm/year.
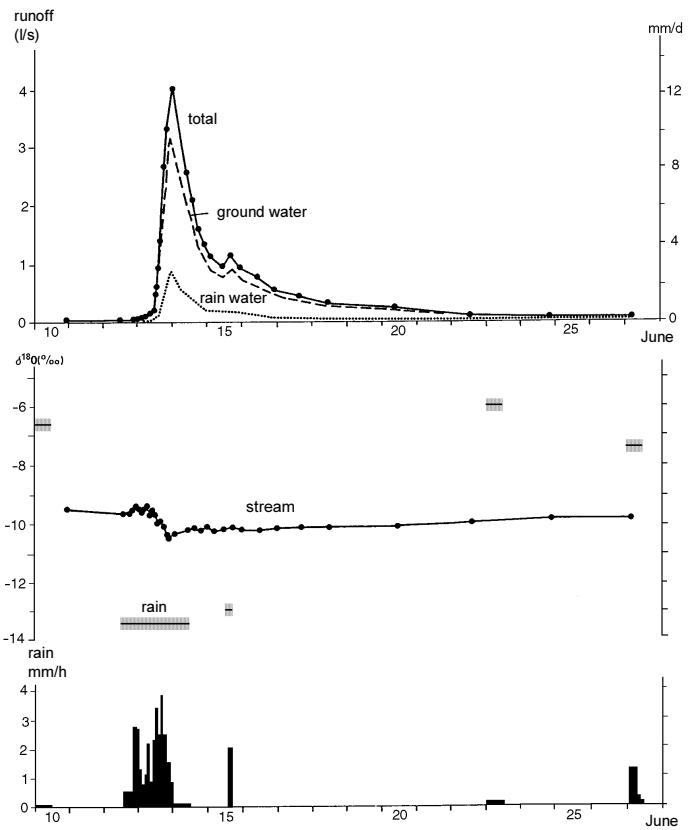
Figure 4.4. *Diagram of runoff in a stream, the rain intensity and oxygen-18 content in rainwater at different precipitation times and in the stream water for the entire period. The low oxygen-18 content in the heavy rain does not have any particular impact on the oxygen-18 content in the stream water due to the fact that most of the runoff comprises "old" groundwater with a higher oxygen-18 content. It is forced out of the discharge areas near the stream of the infiltrating water upstream through the piston flow principle (based on Grip & Rodhe 1988 in Knutsson & Morfeldt 2002).*

4.5   Tracer Methods and Isotope Techniques

Background and Problems

It is often of great interest to study groundwater flowpaths, flow velocities and transport pathways for pollutants or sorption of pollutants in the groundwater zone in connection with different types of groundwater investigations. The least controversial method to do so is to follow the path of the groundwater or pollutant through experiments and measurements of very small quantities of specific substances or isotopes that occur naturally or that are added to the soil and groundwater, namely, to conduct a tracer experiment. The results can then be used to determine hydraulic contexts and safety distances to sources of pollutants as well as to evaluate the results of modelling of for example, the transport and sorption of different radioactive substances. The usual problems that are studied are:

A. The groundwater
- flow between boreholes and wells, in boreholes in connection with packer tests and sampling or, for example, between sink holes and springs in a karst system
- flow direction and flow patterns in the bedrock fracture system or in soil layers
- flow rate between two points or, for example, within a protection area of a water supply well
- recharge, origin and age

B. The soil and ground
- dispersion properties, such as the dispersion plume of a pollutant
- hydraulic properties, primarily permeability/hydraulic conductivity
- sorption and ion-exchange properties, such as sorption of a pollutant

Requirements on Artificial Tracers

It is not difficult to find suitable tracers for investigations to determine a hydraulic connection between two points, since the behaviour of the tracer in the ground is not of decisive importance for the interpretation of results. The only important factor is to be able to detect the arrival of the tracer. In order to determine the flow direction of the groundwater, tracers, that to a certain extent are retained in the bedrock, can be used. The sorption of certain pollutants or ion-exchange in different rock or soil types, for example, fractured rock, can also be studied. This is the concept for a series of tracer experiments that are conducted in different parts of the world, such as at the Äspö Hard Rock Laboratory, prior to the disposal of spent nuclear waste.

For investigations to determine the actual flow rate of the groundwater and to determine hydraulic properties, there are major difficulties in finding suitable tracers. The ideal artificial tracer must fulfil certain requirements:

- It should follow the groundwater movement without being sorbed or delayed in the ground by ion-exchange.
- It may not react, for example, with microorganisms, or be affected by pH changes.
- It should be possible to detect the tracer in very low concentrations so that the physical and chemical conditions of the water are not changed.
- It may not be hazardous or damage plant or animal life, for example, in discharge areas and springs.
- It should be easy to acquire at a reasonable cost and should not entail high analysis and measurement costs.

The first two requirements mean that the difficulty of finding an ideal tracer is greatest in porous rock and soil types, where the contact surfaces between the particles in the rock or soil types and tracers are very large and, thereby, the sorption and ion-

exchange processes are very active. The more fine-grained the rock or soil type, the greater is the effective contact surface for these processes. The mineral composition in the rock or soil types also play an important role for the scope of the processes as does the content of organic material as well as precipitation and weathering on particle or fracture surfaces. Quartz particles have the least impact, clay minerals and organic minerals have the greatest impact. This means that in the "cleanest" sandstones and sand deposits and in open fractures and channels in the bedrock, certain types of tracers are slightly or not at all affected, while the impact is great, for example in humus and clayey soil types, in clay-weathered zones and in fractures with precipitation in the bedrock (Knutsson 1971). The occurrence and role of the microorganism can have considerable importance for the decomposition of organic dyes, some of which are also sensitive to pH- and temperature changes as well as light.

The third requirement means that a tracer which must be added in large quantities to be detectable cannot be selected. Large quantities of sodium chloride have, for example, been added in karst areas, and a heavy saltwater stream has penetrated into deep cavities and thereby not participated in the natural flow process. In porous rock and soil layers, density stratification can occur. However, the problem has decreased as analysis techniques have evolved, which has also had a favourable impact on the fourth requirement which, during a period when radioactive tracers were preferable from the detection standpoint entails considerable limitations near to water supply wells. The fifth requirement can usually be fulfilled, even if the analysis costs for isotope determination are considerable. However, the dominant costs are often the experiment costs themselves since extensive drilling, measurements and sampling at the experiment site are required. Groundwater level measurements on a large number of points are therefore necessary both for the planning and performance of tracer experiments and for the interpretation of the results.

Different Types of Tracers

The following tracers have been used:

- Organic dyes with fluorescence, for example, Rhodamine, Sulforhodamine B, C, WT and Uranine.
- Salts, above all anions such as bromide, iodide, chloride and nitrate.
- Complex compounds such as fluorinated benzoates and stable metal complexes such as chromium-EDTA.
- Radioactive isotopes, primarily tritium and radioactive isotopes of anions and metal complexes (see above).
- Organisms, primarily bacteria, bacteriophagues and spores.
- Diverse chemical substances in the form of pollutants such as detergents, pesticides and chlororganic compounds (such as CFCs).

Organic dyes have been successfully used for a long time in karst areas and, recently, also in fractured crystalline bedrock, especially in connection with tracer experiments in the TRUE programme in the Äspö Hard Rock Laboratory (SKB 2001). In spite of the occurrence of both weathered feldspar on the fracture surfaces and mylonite, Uranine had the same transport rate as the anions, bromide and iodide as well as tritiated water, which indicates open fractures. However, the transport paths in this initial experiment were very moderate, about 5 m (SKB 2001). Therefore, it was not surprising that, in connection with the continued block-scale experiments on a 100-metre scale, which corresponds to the safety distance from a nuclear waste landfill to a major fracture zone, Uranine was significantly retarded in relation to bromide when in contact with different sorbing materials (Andersson *et al.* 2002). Similar results were obtained in connection with tracer experiments in a large fracture zone in hard rock in Germany in connection with a 295-metre flow path (Maloszewski *et al.* 1999). Normally since dye tracers undergo sorption and degradation in the soil cover, they

cannot be recommended in such environments. Furthermore, they can probably not be recommended in porous sediment rock types. According to *Table 4.1*, it is on the whole difficult to identify a dye tracer which is not adsorbed, degraded or changed. It is remarkable that SKB has considered Uranine to be a tracer that is conservative (that cannot be affected), since it is pH and temperature-dependent and is easily adsorbed on humus and clay minerals.

Table 4.1. *Comparison between the properties of different fluorescing dyes (based on Tilly et al. 1999).*

	Detection limit, µg/1	Tempe-rature dependent	pH-dependent pH 6–8	Photo-chemical degradation	Adsorption on humus	Adsorption on kaolinite	Cost
BLUE							
Amino G Acid	0,51	little	little	moderate	big	relative little	high
Photine CU	0,36	little	yes	strong	very big	relative little	high
GREEN							
Uranine	0,29	moderate	yes	strong	very big	rather big	high
Lissamine FF	0,29	little	no	little	big	rather big	very high
Pyranine	0,087	little	yes	strong	big	relative little	high
ORANGE							
Rhodamine B	0,010	big	no	little	extremely big	extremely big	low
Rhodamine WT	0,013	big	no	little	very big	big	rather high
Sulpho Rhodamine	0,061	big	no	little	big	very big	rather high
BLUE-GREEN							
Na-Naphthionate			no	strong			

As far as *salts* are concerned, most cations can be excluded due to sorption and retardation by ion-exchange processes (although lithium has been used with a certain success). On the other hand, *anions* are only sorbed to a negligible extent or not at all, since the mineral particles are also negatively charged, as a rule. Bromide, iodide and chloride ions have been largely successfully used in a large number of experiments. Bromide and iodide have advantages since the natural concentrations are very low as a rule and, consequently, only very small quantities need to be added. However, they also have certain disadvantages, for example, the risk of sorption at low pH values, when the mineral particles are positively charged. Similarly, problems can occur in contact with iron precipitation in the B-horizon and below the groundwater table at low pH values (Tilly *et al.* 1999). Chloride appears to have given the consistently best results and is considered to be a conservative tracer which follows the water flow without being retarded. It has been used in a large number of experiments at municipal water supply plants in Sweden in order to determine residence times for water between infiltration basins and abstraction wells. In these contexts, it is significant transport distances (up to 2,000 metres) and long residence times (weeks to months), although on the other hand, the deposits are often very coarse-grained (Hansson 2000). However, sometimes chloride is less suitable, bearing in mind the fact that chloride can occur in varying amounts in certain geological environments and in places due to pollutants, for example from landfills and roads. Therefore, chloride is directly unsuitable for use at great depths in the bedrock where the chloride concentrations are often high. The use of chloride is also dubious in low-lying areas, below the highest seawater-line in Sweden with relict salt, which requires that large quantities of salt have to be added to obtain reliable results. However, the disadvantages are most often outweighed by the fact that chloride in the form of common sodium chloride is inexpensive and easy to handle and through the fact that detection in the field is simple. The conductivity is measured directly in boreholes, wells or springs or even from the

ground surface using geoelectrical methods (see Section 3.4.8) as well as the fact that chloride analyses can be inexpensively conducted in laboratories.

Stable metal complexes have also been found to be very useful as tracers. Suitable complexes exist among the metal chelates, of which the best known is ethylenediaminetetraacetic acid (EDTA). A chromium-EDTA complex has been tested in a very large number of laboratory experiments with different mineral mixtures, including different clay minerals, as well as several field experiments in rock and in the soil (Knutsson & Forsberg 1967). The chromium complex in dilution down to 0.0001 ppm is not sorbed or retarded in common minerals or in rock and soil types made of these minerals if complexation is complete. However, in contact with high concentrations of iron-bearing minerals and precipitation, for example, goethite and the B-horizon, certain iron and manganese-bearing silicates as well as clay minerals and clay mineral-rich rock and soil types, a certain retardation of the chromium complex occurs (Knutsson 1971). Other EDTA complexes and metal complexes have also been tested with favourable results (Knutsson 1970).

However, *tritium*, the radioactive hydrogen isotope, is the least controversial tracer since a small quantity of tritium is included in ordinary water (HTO) and tritium must be considered to follow the path of the water without sorption or retardation in most situations. Tritium has therefore been used extensively in a large number of experiments, especially in the Äspö Hard Rock Laboratory, as well as a reference tracer in connection with the testing of other tracers. However, in connection with such testing, with a 10 % addition of water-saturated bentonite (with montmorillonite as the main component) in quartz sand, tritium was found to be absorbed to these swelling clay minerals and tritium was retarded in relation to chromium-51-EDTA. Similar effects were not obtained in experiments with other clay minerals or other mineral mixtures. Furthermore, this was not the case in field experiments in different rock and soil types (Knutsson 1970).

By adding tritium, or previously, through the fluctuations in tritium content which occurred through hydrogen bomb experiments, it has been possible to follow a "pulse" of tritium from infiltration by water through the soil layers down to deep rock layers. In this way, the transport velocity of the water, or the time that it takes for the groundwater to reach a certain level in the bedrock, can be demonstrated. This has been studied in deep bedrock aquifers in Scania, south Sweden (Engqvist 1991) as well as in connection with nuclear waste disposal investigations. However, investigations conducted at the same time with other tracers have shown that a mixture of water of various origins can occur at great depths. A new modelling concept has therefore been developed within projects at SKB, the M3 model, through which it is possible to investigate the proportions in water of various origins (Laaksoharju 1999, *Figure 4.5*).

Added tracers can primarily be used to determine the groundwater flow velocity between boreholes, in fracture zones or around water supply wells in order to determine the layout of the protection areas (particularly complicated in fractured bedrock) as well as to determine the residence time of the water in connection with artificial groundwater recharge as well as to map groundwater flowpaths from planned waste landfills. Investigations with added tracers are thus most suitable for small or medium scale experiments, where the residence times are moderate and the experiment times reasonable. On a regional scale, natural tracers should be used in the first instance or analyses of possible pollutants dispersed by man, such as freons and pesticides, should be tried, see below.
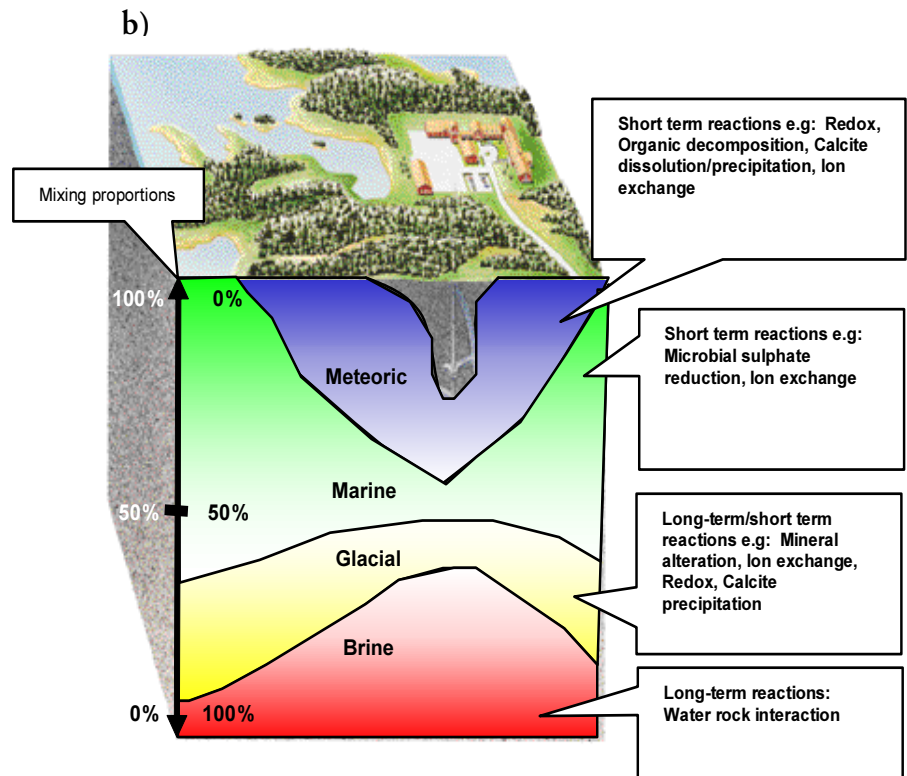
a)

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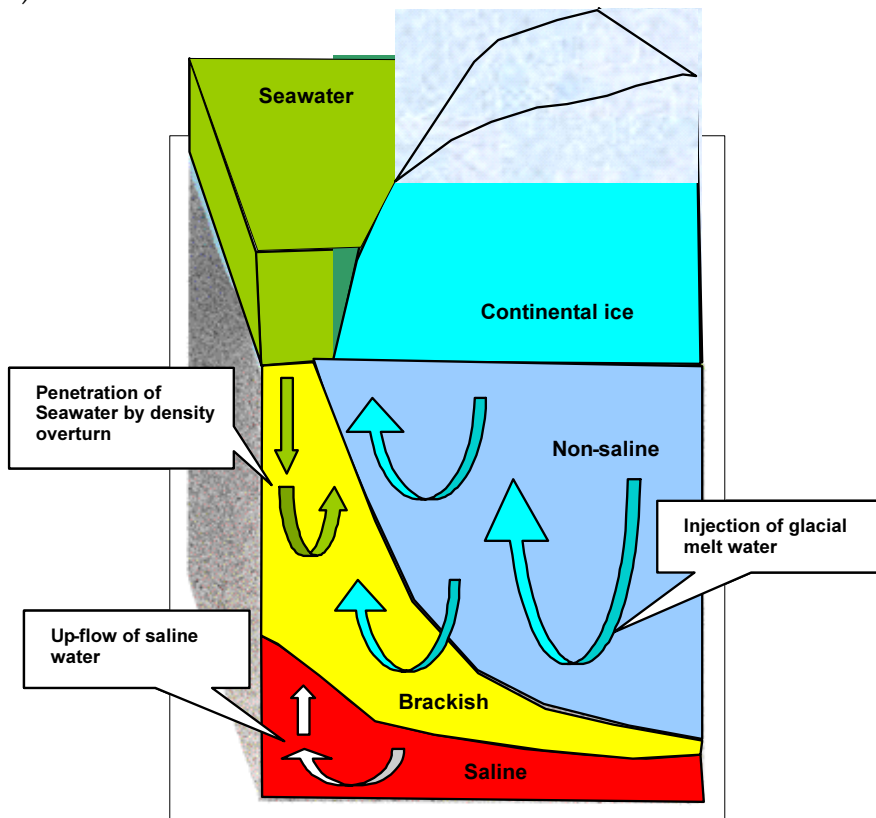
Figure 4.5. **a)** *Conceptual model of different events in geological evolution since the ice age, which have affected groundwater chemistry at Äspö.* **b)** *The calculation of mixing portions between different types of water at Äspö as well as dominant mass balance reactions with the help of the M3 model (from Laaksoharju, 1999).*

A special application of added tracers is to use the conservative tracer elements such as bromide, iodide and HTO together with a number of sorbing elements, common cations, such as sodium and calcium, and radioactive cations such as cesium and strontium. In this way, flow conditions and hydraulic parameters can be reliably determined through measurements of the

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conservative tracers and sorption and delay (through ion-exchange and diffusion) of different cations can be studied under controlled forms. The methodology has been tested in a large number of experiments conducted in a number of SKB projects, previously in Stripa and Finnsjön and, in recent years, at the Äspö Hard Rock Laboratory, where several tens of experiments have been conducted with highly interesting results (SKB 2001, *Figure 4.6*).

A new type of tracer which enables groundwater dating and groundwater recharge determination to be conducted is to measure the content of chemical products which started to be manufactured in recent years and which are used in liquid form, such as for agricultural purposes (pesticides) or released as gases in the atmosphere (freons, namely chlorofluorocarbons /CFCs/). The assumption is that they are not degraded or that the decomposition products can be measured. Freons appear to be the most useful. Freon manufacturing started in the 1940's and, since then, they have accumulated in the atmosphere. They are water soluble, are added through precipitation and act as tracers. The determination of the Freon content in groundwater at varying depths can therefore show with great accuracy when the water in question came into contact with the atmosphere. The method was developed in the USA in the 1970's and has been used in Germany and Denmark and other countries as well as on the Kristianstad plain and in southern Scania (Barmen 2001).

A group of researchers in Uppsala has started to use the method to determine the age of the groundwater in fractured rock (Bockgård 2000). The concentrations of CFC-12 and tritium at different depths in three boreholes at Finnsjön show an increasing age with depth and a mixture of water of different ages (Bockgård *et al*. 2004). As the use of freons ceases, the method will become less useful. Pesticides have been found in deep aquifers in Denmark as well as in some wells drilled in the rock in Sweden. The difficulty often lies in determining when the pesticides were brought to the surface.
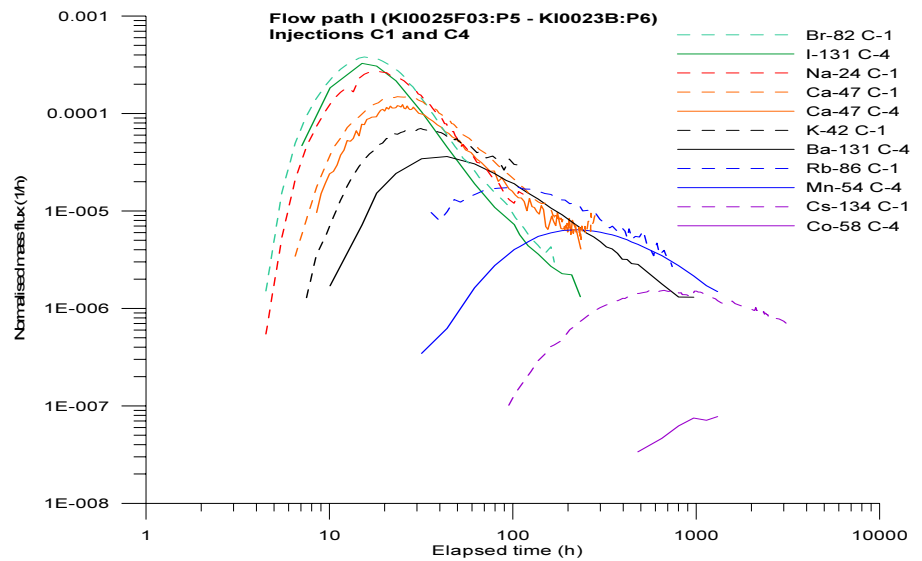
Figure 4.6. *Normalised breakthrough curves for all tracers in the C1 and C3 tests in the TRUE block-scale experiments at Äspö. Note the difference in recovery and transport time between the conservative tracers, Br-82 (bromide) and I-131 (iodide) and the sorbing tracers Cs-134 (cesium) and Co-58 (cobalt), which are retained and retarded to a large extent (from Andersson et al. 2002).*

Natural Tracers

The following natural tracers can be used:

- Radioactive isotopes, above all tritium, carbon-14 and chloride-36.
- Stable isotopes, above all deuterium, oxygen-18/oxygen-16 as well as sulphur-34/sulphur-32.
- Noble gases such as argon, helium and radon (primarily radon-222).

Tritium and *carbon-14,* which are produced in the atmosphere through cosmic radiation, are the most important radioactive isotopes for determining the age of the groundwater. This can vary from a few weeks to many thousands of years and is of interest to know in several practical contexts, for example, in order to determine whether groundwater at great depth is fossil-based and without turnover occurring in connection with present-day conditions which can be favourable for the disposal of hazardous pollutants but unfavourable if groundwater abstraction for water supply is planned. Before the first hydrogen bomb explosion, it was possible to determine the actual age of the groundwater to a certain level, although certain complications arose due to the mixture conditions between different types of groundwater. At that time, precipitation had a certain concentration of tritium (4 to 20 tritium units /TU/ depending on the season) and no additional tritium was supplied during infiltration. The knowledge that tritium has a half-life of 12.3 years meant that the age of the groundwater could be calculated fairly accurately. After the hydrogen bomb tests, the tritium concentrations in the precipitation increased very rapidly with the highest values at about 10,000 TU for 1963 and 1964 in certain locations in Europe. This was like an enormous tracer experiment in the whole of the northern hemisphere. Since then, the concentrations have successively decreased so that they are now at natural levels apart from in some fairly old groundwater with residues of bomb tritium and where local sources of pollutants occur (IAEA 2000). In spite of pollutants in the groundwater system, one way of determining the actual age is to determine the relationship between the concentrations of tritium and its daughter, helium-3. Helium starts to accumulate in the groundwater zone when tritium-bearing groundwater reaches the zone. The method is expensive and so far little used (Bockgård 2000).

Tritium determination can also be used to determine whether the groundwater at different depths is of the same origin and whether the groundwater at a certain depth is fed by ground-

water from another area or is connected to the surface water. This has been successfully utilised for practical purposes, in a large Swedish mine in order to trace the origin of large flows of mine water, partly in connection with tunnel engineering in the Gothenburg area to determine whether the water in lakes could be connected to the groundwater in bedrock where tunnels would be built (Knutsson & Morfeldt 2002).

The determination of the age of very old water can be conducted with the help of carbon-14 which has a half-life of 5,730 years or chlorine-36 with a half-life of about 300,000 years. The determination of carbon-14 in groundwater carbon dioxide has been used since the 1950's in many parts of the world, and very high ages have been measured in groundwater in deep aquifers, for example, in Florida and in Nubian sandstone beneath the Sahara desert as well as at great depths in Swedish crystalline bedrock within the SKB projects and at great depths in the Kristianstad plain where mineral water is abstracted which, according to the carbon-14 determination, was formed during the bronze age. However, the use of carbon-14 is problematic and complex due to the fact that the carbon dioxide content of groundwater can have different origins: from the atmosphere, from fossil organic material as well as from carbonate minerals. Major progress in resolving this problem has been made in a SKB project through the development of a method of measuring the carbon-14 concentration in groundwater in the very small occurrences of humus in groundwater at great depths by enrichment in ion-exchange columns (Petersson & Allard 1991). The deep groundwater ages calculated by previously used methods in Swedish crystalline bedrock were found to be too high.

Deuterium (D) and oxygen-18, which in very low concentrations are included in the water molecule, are of great interest in order to determine the residence time and origin of the water. The possibility of using these stable isotopes arises from the fact that an isotope fractionation (see Chapter 5) occurs in water through the fact that during each evaporation process, the

enrichment of the lighter oxygen-16 isotope occurs in relation to the remaining liquid phase. The vapour that forms over the sea therefore has a lower oxygen-18 content and deuterium content than the seawater. The fractionation process is affected to a high degree by the temperature conditions prevailing during evaporation and condensation which leads to seasonal variations in temperate climates and with increasing altitudes over the sea. Norwegian investigations have found very small variations on the coast but major seasonal variations in upland areas in the interior of the country. It has been possible to determine residence times for water infiltrating into different groundwater systems (Haldorsen 1994) as well as the amount of induced surface water in connection with the pumping of groundwater in crystalline bedrock (*Figure 4.7*). In Greece, the geographical origin of groundwater recharge for different springs and boreholes in a rock area is identified through differences in the oxygen-18 concentration due to the effect of altitude (Leontiades and Nikolau 1999). The method has also been used to obtain data for the previously mentioned modelling conducted at Äspö (*Figure 4.5*) as well as in connection with experiments with added tracers at Äspö.

Helium has started to be used to study diffusion in the bedrock matrix (Andersson *et al.* 2002).

Radon has been successfully tested to study the exchange between surface water and groundwater.

4.6   Conclusions and Recommendations

Hydrometeorological and hydrological data series are necessary for the calculation of the water balance and groundwater recharge in an area where underground facilities are to be sited in the rock. Statistical processing of long data series is necessary in order to obtain the frequency of, for example, "dry years", which is the design basis for the removal of groundwater, bearing in

mind the environmental consequences to fauna and flora as well as for the local water supply.
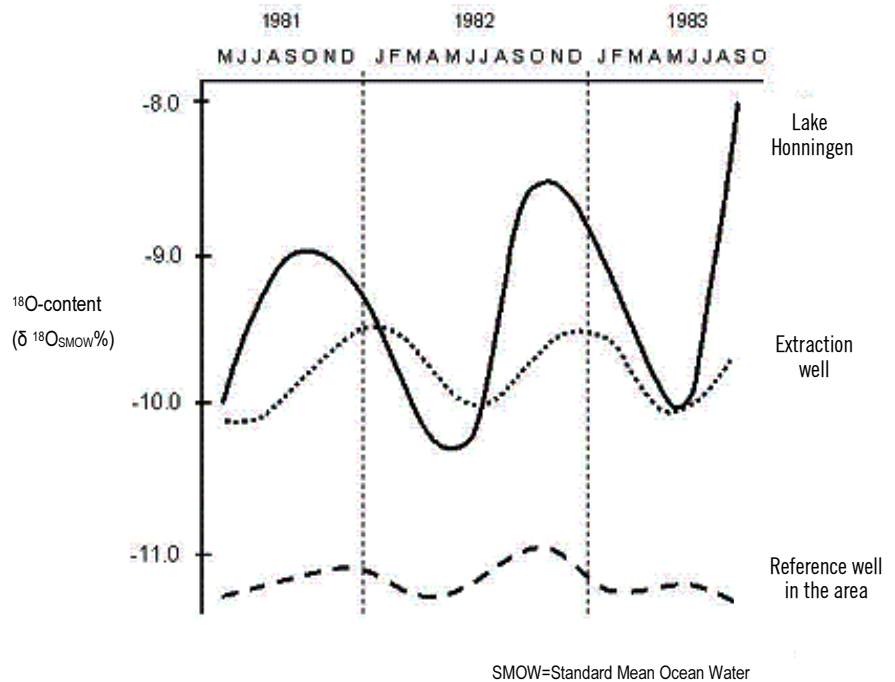

Figure 4.7. Variations in the concentration of oxygen-18 in a well in hard rock and in lake water in Rakkestad, Norway, which shows induced infiltration in rock with a residence time of 2.5 months and 77 % mixing of lake water (based on Hansson 2000).

The local variations in, for example, precipitation and temperature can, however, be considerably dependent on, for example, altitude effects and location, in relation to the coast. Therefore, it is necessary to supplement the national measurement stations by local and regional measurement stations for

hydrometeorology and hydrology as well as extensive networks of measurement stations for groundwater level/groundwater pressure and groundwater chemistry in different hydrogeological environments and at different depths. The data are successively processed statistically and correlated with the data series from the national measurement stations.

Conceptual models of the groundwater conditions on a regional and local scale must be set up and reported openly for each investigation area to provide a basis for method selection and for computer models. There are several investigation methods that can be used to determine groundwater recharge and considerable knowledge has been obtained in the past few decades, although unfortunately, not much has been obtained regarding the size of groundwater recharge at large depths in hard rock. Knowledge must therefore be improved by testing of several independent methods on the same area, for example, response methods in combination with natural isotopes and freons as well as computer models. By using different methods, results can be checked and compared and different types of information can be obtained on groundwater recharge in time and space. This has been found in an analysis of ten different methods which were tested at Yucca Mountain in the USA (Flint *et al.* 2002). It is also of great importance to develop methods for the measurement of the groundwater flow from the soil layer to the bedrock, which can, for example, be achieved by combinations of geophysics, the measurement of groundwater pressure and groundwater chemistry including isotopes. In this, and in most other contexts, it is a disadvantage that the determination of natural isotopes in the water and certain other isotopes is no longer conducted in Sweden. The use of natural isotopes has decreased in Sweden unlike, for example, Norway, with its "domestic" laboratory.

Large-scale tracer experiments (safety distance to regional fracture zone) with several different conservative tracers (not dyes) are necessary in order to characterise the groundwater flow, not only in fracture zones but also in the entire bedrock.

Experiments to determine the sorption and retardation of different radioactive substances should be conducted in parallel as should diffusion experiments.

Calculations using different computer models must naturally continue, in order to predict relevant groundwater recharge and groundwater chemistry conditions in the site investigations and to explore different future scenarios, such as different climate situations (greenhouse effect, glaciation) in these contexts during the repository construction phase and during long-term disposal.

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