In-situ groundwater flow measurements as a tool for hardrock site characterisation within the SKB programme

ERIK GUSTAFSSON & MANSUETO MOROSINI

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In many cases, groundwater flow governs hydrochemical conditions and transport of contaminants. Groundwater flow rates are also a very essential input to risk assessments and a general understanding of the hydraulic system, and Swedish Nuclear Fuel and Waste Management Co (SKB) has undertaken a considerable amount of technical development for in-situ groundwater flow measurements by the dilution method. In order to meet the requirements for performance assessment and construction engineering, equipment has been developed that make in-situ groundwater flow measurements possible for a range of borehole diameters and site conditions in fractured hard rock. The latter include surface boreholes down to 1000 m depth and high-pressure conditions in boreholes drilled from deep underground constructions. Results from more than ten years of development and measurements in Swedish hardrock sites show that in-situ groundwater flow measurements are a valuable tool for site characterisation in fractured hard rock, preferably combined with other hydraulic and chemical investigation methods. The dilution method is also well suited for collection of basic groundwater flow data, which may be used for development and calibration of hydraulic models. If groundwater flow is measured both under natural conditions as well as during disturbances to the system, the result will contribute significantly to the conceptual hydraulic understanding of the site.

Erik Gustafsson, Geosigma AB, Box 894, S-751 08 Uppsala, Sweden
Mansueto Morosini, SKB Äspölaboratoriet, Pl 300, S-570 95 Figeholm, Sweden

Introduction

Environmental and engineering problems in fractured hard rock typically concern the potential risks of contaminant transport, groundwater flow and drainage by underground constructions. The interest is focused on flow in the connected system of fractures and fracture zones, and not on average groundwater flow in the entire rock volume. Because groundwater flow in many cases governs hydrochemical conditions and transport of contaminants, groundwater flow rates are also a very essential input to risk assessments and our general understanding of the hydraulic system. Knowledge of groundwater flow rates is also of interest at well sites for geothermal energy in hard rock.

Groundwater flow rates can be obtained indirectly from estimates of hydraulic conductivity values and hydraulic gradients, or determined directly by in-situ measurements. Swedish Nuclear Fuel and Waste Management Co (SKB) has employed both approaches for flow determination for site characterisation. In particular, a considerable amount of technical development has been undertaken for in-situ groundwater flow measurements by the dilution method.

The dilution method

The dilution method has been used for groundwater flow measurements in porous media and open boreholes since the beginning of the 20th century. With the proper equipment, the dilution method is also an excellent tool for in-situ determination of flow rates in fractures and fracture zones.

In the dilution method, a tracer is introduced and homogeneously distributed into a borehole test section. The tracer is subsequently diluted by the ambient groundwater, flowing through the borehole test section. The dilution of the tracer is proportional to the water flow through the borehole section (Fig.1).

The dilution in a well-mixed borehole section, starting at time t = 0, is given by:

$$1n(C/C_0) = -\frac{Q_w}{V}t \qquad (1)$$

where C is the concentration at time t (s), C_0 is the initial concentration, V is the water volume (m^3) in the test section and Qw is the volumetric flow rate (m^{3}s^{-1}). Since V is known, the flow rate may then be determined from the slope of the line in a plot of ln (C/C_0), or ln C, versus t; see Fig. 1.

The reliability of the flow rate determination generally benefits from longer measurement times, because the uncertainty of the estimate of the slope (by linear regression of ln (C/C_0) vs. t data) decreases. However, three main stages of dilution rate are usually observable and the part of the dilution curve that may be used for evaluation is restricted. In the first stage, mixing is observed when the injected tracer is homogeneously distributed in the borehole test

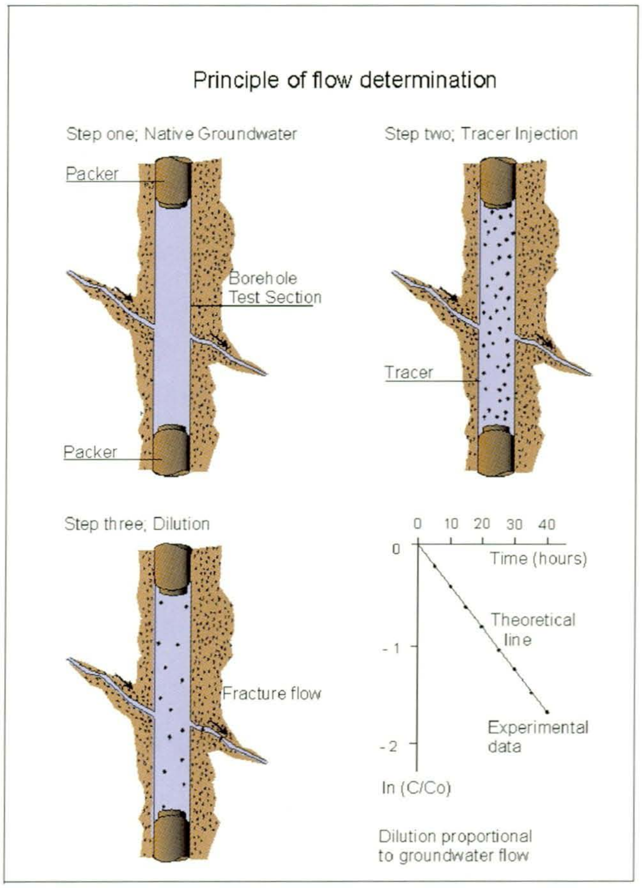

Fig 1. Principle of flow determination by the dilution method.

section by an artificial mixing device. In the second measurement stage, the dilution is due only to the ambient groundwater flow. In the third stage, dilution has progressed so far that natural background concentrations become significant and affect the ideal dilution curve (Halevy et al. 1967). For calculation of groundwater flow rates the second stage data should be used, but corrections for background concentration still have to be applied.

An important interpretation issue is to relate the measured groundwater flow rate through the borehole test section to the rate of groundwater flow in the fracture/fracture zone straddled by the packers. The flow-field distortion must be taken into consideration, i.e., the degree to which the groundwater flow converges and diverges in the vicinity of the borehole test section. With a correction factor, α, which accounts for the distortion of the flow lines due to the presence of the borehole, it is possible to determine the cross-sectional area perpendicular to groundwater flow by:

$$A = 2\,r\,L\,\alpha \qquad (2)$$

where A is the cross-sectional area (m^2) perpendicular to groundwater flow, r is borehole radius (m), L is the length (m) of the borehole test section and α is the correction factor. Fig. 2 schematically shows the cross-sectional area, A, and how flow lines converge and diverge in the vicinity of the borehole test section.

Assuming laminar flow in a plane-parallel fissure or a homogeneous porous medium, the correction factor α is calculated according to Eqn. (3), which is often called the formula of Ogilvi (1958). Here it is assumed that the disturbed zone, created by the presence of the borehole, has an axisymmetrical and circular form.

$$\alpha = \frac{4}{1 + (r/r_d) + (K_2/K_1)(1-(r/r_d)^2)} \qquad (3)$$

where r_d is the outer radius (m) of the disturbed zone, K1 is the hydraulic conductivity (ms^{-1}) of the disturbed zone, and K_2 is the hydraulic conductivity of the aquifer. If the drilling has not caused any disturbances outside the borehole radius, then $K_1 = K_2$ and $r_d = r$ which will result in $\alpha = 2$. With $\alpha = 2$, the groundwater flow within twice the borehole radius will converge through the borehole test section, as illustrated in Fig. 2.

If there is a disturbed zone around the borehole, the correction factor α is given by the radial extent and hydraulic conductivity of the disturbed zone. If the drilling has caused a zone with a lower hydraulic conductivity in the vicinity of the borehole than in the fracture zone, e.g., a positive skin due to drilling debris and clogging, the correction factor _ will decrease. A zone of higher hydraulic conductivity around the borehole will increase α. Rock stress redistribution, when new boundary conditions are created by the drilling of the borehole, may also change the hydraulic con-

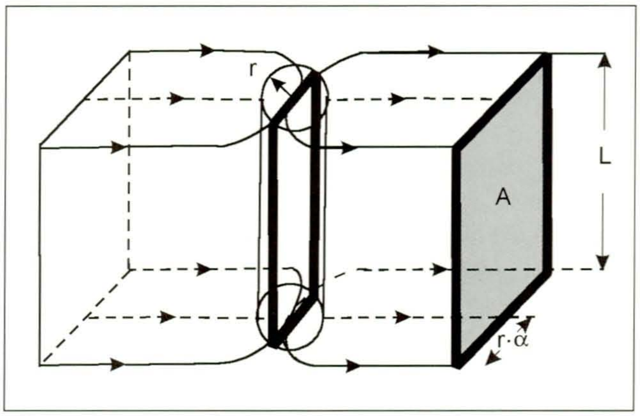

Fig. 2. Flow lines in the vicinity of the borehole test section in the ideal case.

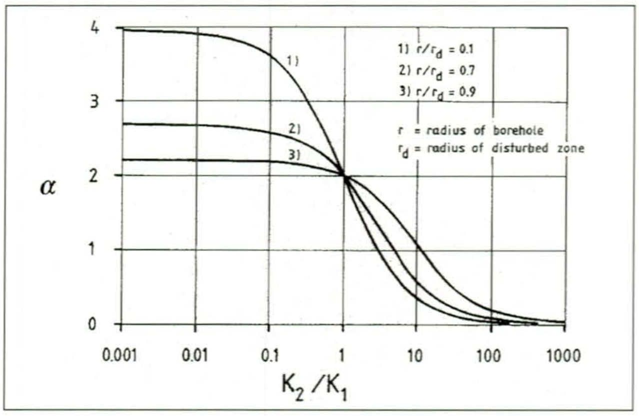

Fig. 3. The correction factor, a, as a function of K2/K1 at different radial extent (r/rd) of the disturbed zone (skin zone) around the borehole.

ductivity around the borehole and thus affect α. In Fig. 3, the correction factor, α, is given as a function of K_2/K_1 at different normalised radial extents of the disturbed zone (r/r_d). If the fracture/fracture zone and groundwater flow is not perpendicular to the borehole axis, this also has to be accounted for. At a 45 degree angle to the borehole axis, the value of a will be about 41% larger than in the case of perpendicular flow. This is further discussed in Gustafsson (2002b) and Rhén et al. (1991).

The groundwater flow in the rock formation is expressed as specific discharge (Darcy velocity), defined as the flow per unit cross-sectional area perpendicular to the groundwater flow direction. The specific discharge is denoted by v_f (ms^{-1}) and given by Eqn. (4). The specific discharge may also be expressed as a volumetric flux density, Q_{fr} ($m^3m^{-2}year^{-1}$).

$$V_f = -\frac{Q_w}{A} \qquad (4)$$

Equipment developed by SKB

The site characterisations carried out by SKB so far have involved investigations down to more than 1000 m depth and included fractures and fracture zones with a wide range of hydraulic conductivity values. In order to meet the requirements for performance assessment and construction engineering, SKB has developed tools that make in-situ groundwater flow measurements by the dilution method possible for a range of borehole diameters (56 – 140 mm) and site conditions in fractured hard rock. The latter include surface boreholes down to 1000 m depth and high-pressure conditions in boreholes drilled from deep underground constructions. The equipment has been designed with special consideration given to high accuracy and a wide range of possible flow rates. This requires:

- accurate determination of test section volume
- complete mixing in test section
- no excess pressure in the test section, relative to the aquifer
- tracer concentration measured accurately and with high resolution
- non-sorbing tracers
- ensure that the test section straddles the hydraulic unit of interest

Measurement range and accuracy

Molecular diffusion of the tracer into the fractures always exists, and has to be considered at low groundwater flow rates. The lower limit of groundwater flow measurement is set by the dilution caused by molecular diffusion of the tracer into the fractured/porous aquifer, relative to the dilution of the tracer due to advective groundwater flow through the test section. In a normally fractured granite, the lower limit of groundwater flow measurements is approximately at a hydraulic conductivity value between $6{\cdot}10^{-9}$ and $4{\cdot}10^{-8}$ ms^{-1}, if the hydraulic gradient, I, is 0.01. This corresponds to a flux value (Darcy velocity) in the range of $6{\cdot}10^{-11}$ to $4{\cdot}10^{-10}$ ms^{-1}, which in turn may be transformed into groundwater flow rates corresponding to 0.05 – 0.3 ml/hour through a 2 m test section in a 56 mm diameter borehole. In a fracture zone with high porosity, and thus a higher rate of molecular diffusion from the test section into the fractures, the lower limit is about $K = 4{\cdot}10^{-7}$ ms^{-1} if $I = 0.01$. The corresponding flux value is in this case $4{\cdot}10^{-9}$ m/s. The lower limit of flow measurements is, however, in most cases constrained by the time available for the dilution test. The required time frame for an accurate flow determination from a dilution test is within 7-60 hours at hydraulic conductivity values greater than about $1{\cdot}10^{-7}$ ms^{-1}. At conductivity values below$1{\cdot}10^{-8}$ ms^{-1}, measurement times should be at least 70 hours for natural, undisturbed, hydraulic gradient conditions.

The upper limit of groundwater flow measurements is determined by the capability of maintaining a homogeneous mix of tracer in the borehole test section. This limit is determined by several factors, such as length of the test section, volume, distribution of the water-conducting fractures, and how the circulation pump inlet and outlet are designed. The practical upper measurement limit is about 6000 ml/hour for the equipment developed by SKB.

The accuracy of determined flow rates through the borehole test section is affected by various measurement errors related to, for example, the accuracy of the calculated test section volume and determination of tracer concentration. The overall accuracy when determining flow rates through the borehole test section is about ± 8%, based on theoretical calculations and laboratory measurements in artificial borehole test sections.

The groundwater flow rates in the rock formation are determined from the calculated groundwater flow rates through the borehole test section and by using some assumption about the flow field around the borehole test section. This flow field depends on the hydraulic properties close to the borehole and is given by the correction factor α, as discussed above. The value of α will, at least, vary within $\alpha = 2 \pm 1.5$ in fractured rock (Gustafsson 2002b). Hence, the groundwater flow in the rock formation is calculated with an accuracy of about ± 75 %, depending on the flow-field distortion.

The borehole probe dilution equipment

The Borehole Probe Dilution Equipment is the result of more than 10 years of development and improvement of dilution equipment and measurements. In the first borehole dilution probe, a light-transmission meter was used for the measurement of light-absorbing tracers. It was thoroughly tested in laboratory and field measurements (Gustafsson 2002a). Improvements to the equipment allowed measurements to greater depth (500 m) and within smaller borehole diameters (76 mm). In addition, more theoretical work and field measurements were conducted (Gustafsson 2002b). Further improvement and development of the Borehole Probe

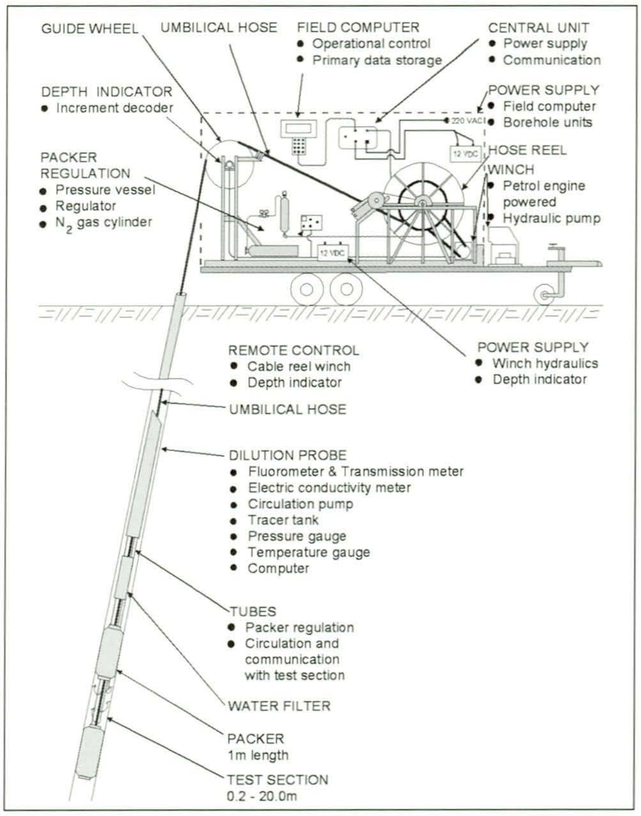

Fig. 4. The Borehole Probe Dilution Equipment.

Dilution Equipment in the period 1991–98 resulted in mobile equipment that can be handled and operated by one person (Fig. 4). Measurements can be made in boreholes with 56 mm diameter or larger and the test section length can be between 0.2 and 20 m. The maximum borehole length is 1030 m. The main part of the equipment is the probe which measures in-situ the tracer concentration in the test section. There are two different measurement devices. One is the Optic device, which is equipped with a combined fluorometer and light-transmission meter. Several fluorescent and light absorbing tracers can be used with this device. The other device is the Electrical Conductivity device, which measures the electrical conductivity of the water. This is used for detection/analysis of saline tracers. The probe and the packers that straddle the test section are lowered in the borehole with an umbilical hose. The hose contains a tube for hydraulic inflation/deflation of the packers and electrical wires for power supply and communication/data transfer. Besides tracer dilution, the absolute pressure and temperature are also measured in the test section. The absolute pressure is measured during the process of dilution because a change in pressure indicates that the hydraulic gradient, and thus the groundwater flow, may have changed.

Surface sampling dilution equipment

The Surface Sampling Dilution Equipment was developed within the SKB Fracture Zone Project, where a gently dipping major fracture zone in granodiorite was studied by means of borehole investigations (Gustafsson & Andersson 1991). The principle of the surface sampling dilution equipment is basically the same as the borehole probe dilution equipment. However, it has a simpler construction with all the electronic equipment, pumps, etc., located on the ground surface. This system has both advantages and drawbacks compared with the borehole probe dilution equipment. Borehole sections longer than 20 m can be tested, but there are no built-in facilities for measurements of hydraulic head or temperature in the test section. The maximum depth to the groundwater table is restricted to about 8 m due to the location of the circulation pump at the ground surface. Tracer dilution versus time is measured by analysis of samples taken from the circulating water with an automatic sampler. This enables the use of any type of tracer, since any analysing method for tracer content can be applied at the ground surface. As water is lost from the test section when samples are collected, sampling will in itself cause a dilution of the tracer, which is not due to the groundwater flow through the test section. This is compensated for at low flow rates.

The multipacker system

The Multipacker System for Dilution Measurements was developed for groundwater flow measurements in permanently instrumented observation boreholes at the Äspö

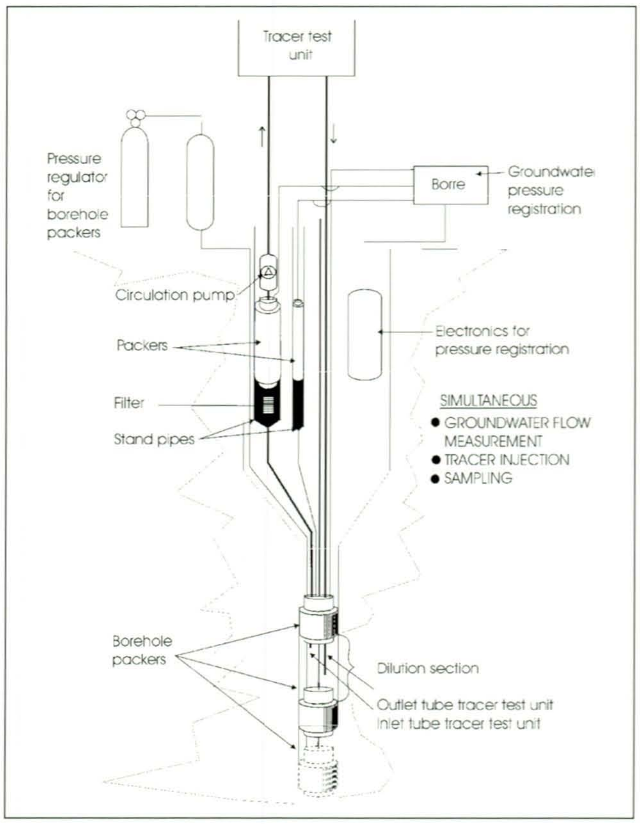

Fig. 5. Principle of the Multipacker system, equipped for groundwater flow measurements by the dilution method.

Hard Rock Laboratory (Ittner et al. 1992). The multipacker system is designed for telescope boreholes with borehole diameters in the uppermost 100 m widened to 150 mm or larger (Fig. 5). Up to eight test sections may be isolated for hydraulic head monitoring and two of these sections can also be equipped for dilution measurements. The circulation pump is placed down-hole in a standpipe enabling measurements even at depths greater than 8 metres to the groundwater table. The tracer test unit gives the choice of intermittent sampling or using a flow-through cell for continuous measurements. Tracer injection is carried out using a dosage pump. The tracer test unit is mounted to the down-hole equipment with quick couplings, thus making it possible to serve several multipacker systems with a single surface tracer unit.

The tunnel equipment

The tunnel equipment is basically the same as the Surface Sampling Equipment. However, all components, such as the circulation pump and sampling and injection devices, have been designed to withstand the high differential pressure in tunnels down to 500 m depth (Fig. 6).

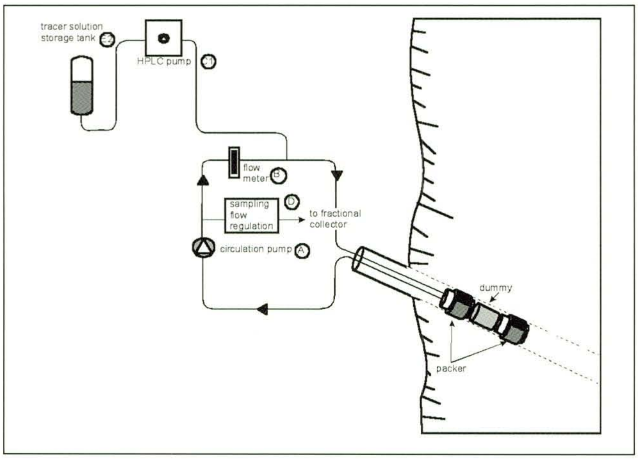

Fig. 6. Dilution equipment for application in tunnels.

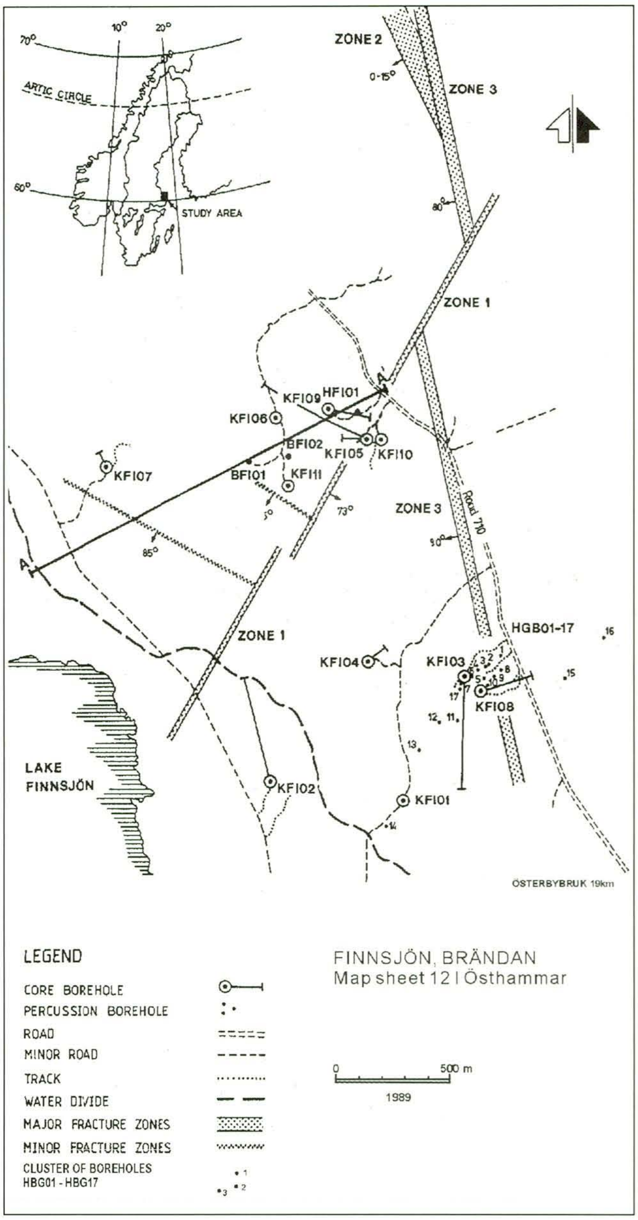

Fig. 7. Map of the Finnsjön site showing borehole locations and major fracture zones. Section A-Á illustrated in Fig. 9 is also marked.

Groundwater flow at the Finnsjön site

At the Finnsjön site, located in the central eastern part of Sweden, groundwater flow measurements were performed in the granite rock in core-drilled 56 mm boreholes and percussion-drilled 115 and 170 mm diameter boreholes. Measurement depths ranged from 9 to 356 m and test section lengths were 1.3, 1.5, 2, 41 and 180 metres. In the shorter sections, the borehole probe dilution equipment was used and in the longer sections the surface sampling equipment was used.

In boreholes HGB02, HGB08 and HGB09 (Fig. 7), measurements were carried out with the objective to test the equipment and to investigate the capability of the dilution method for groundwater flow measurements and site characterisation. The results from these tests were in agreement with groundwater flow rates and velocities determined from two cross-hole well tracer tests and hydraulic tests. Two of the tests were continued for up to 50 days and the changes of groundwater flow rates due to changes in hydraulic gradient were monitored successfully. The results indicated that groundwater flow measurements by the dilution method are well suited for the collection of basic groundwater flow data. Measurement depths ranged from 32 to 90 metres and test section lengths were 1.3 and 1.5 m. Hydraulic conductivity ranged from about $1{\cdot}10^{-8}$ to $3.3{\cdot}10^{-6}$ ms^{-1}. Groundwater flow rates ranged from 2 to 435 ml per hour and Darcy velocity from $1.3{\cdot}10^{-9}$ to $3.0{\cdot}10^{-4}$ ms^{-1}.

The fracture zone project at the Finnsjön site was conducted during the years 1984–1990, and included an integrated approach with the objective of characterising the

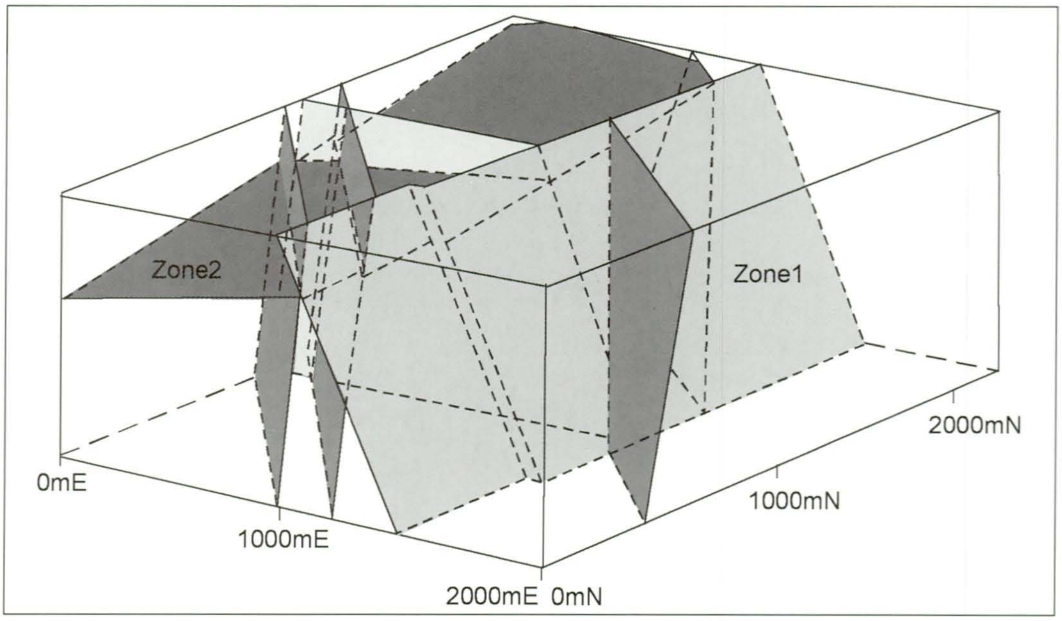

Fig. 8. Conceptual model of the fracture zones in the Brändan area, Finnsjön site.

hydraulic, hydrochemical and flow conditions in a low-angle, major, granodiorite fracture zone (Zone 2). The 100 m-thick, gently dipping Zone 2 was studied by means of borehole investigations. Measurements with the dilution method of the groundwater flow under natural groundwater conditions in sealed-off borehole sections were very valuable for the development of a conceptual hydraulic model for Zone 2 and the surrounding rock. Measurements were performed in boreholes BFI01 and HFI01. A simplified map of the Finnsjön site is presented in Fig. 7, a 3-D view of Zone 2 in Fig. 8 and a transverse hydrogeological section of Zone 2 in Fig. 9. The results of the dilution measurements in borehole BFI01, penetrating Zone 2, are presented in Table 1 and Fig. 10. Groundwater flow is concentrated to the upper highly conductive part of Zone 2 (242-246 m), where the flow rate is considerable. In the lower, highly conductive part, no advective flow was observed, i.e., only apparent flow due to molecular diffusion of the tracer into the fractures (about $9{\cdot}10^{-4}$ $m^3m^{-2}yr^{-1}$) occurred. This shows that the driving force for groundwater flow in the lower region of Zone 2 is very low, which supports conclusions from hydrochemical investigations carried out in the area, indicating the presence of stagnant groundwater in the deeper parts of Zone 2 with a high salinity and uniform composition. Above Zone 2, the

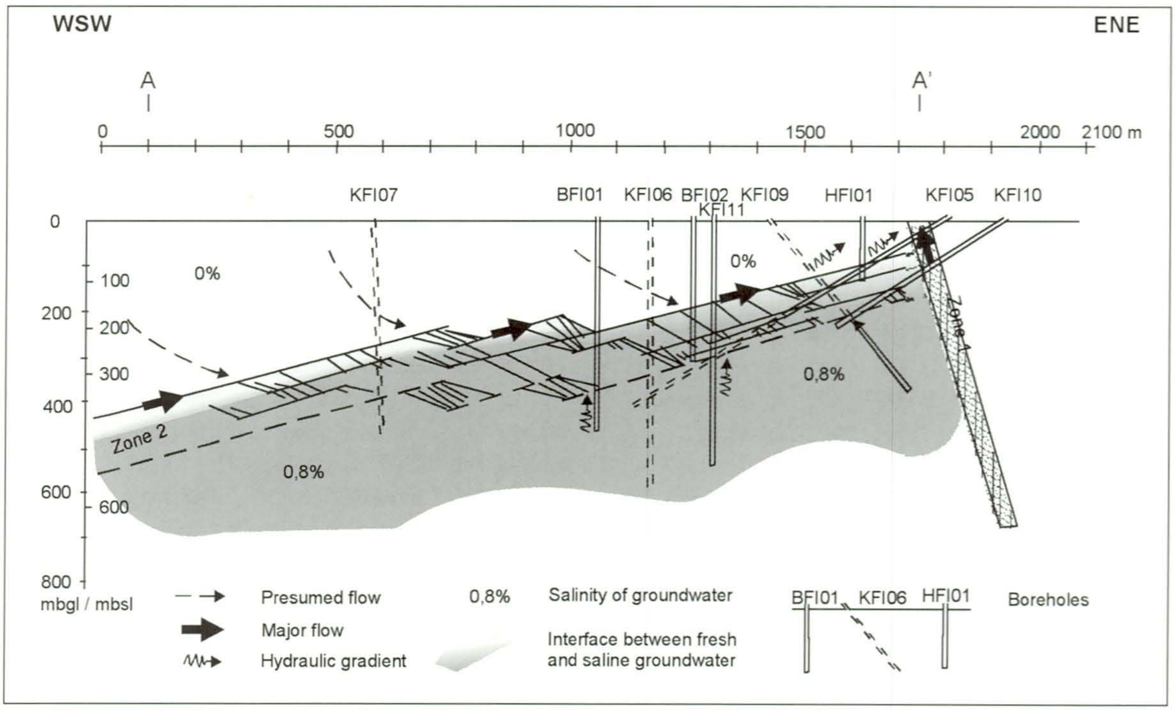

Fig. 9. Transverse hydrogeological section A-Á (see Fig. 7 for location).

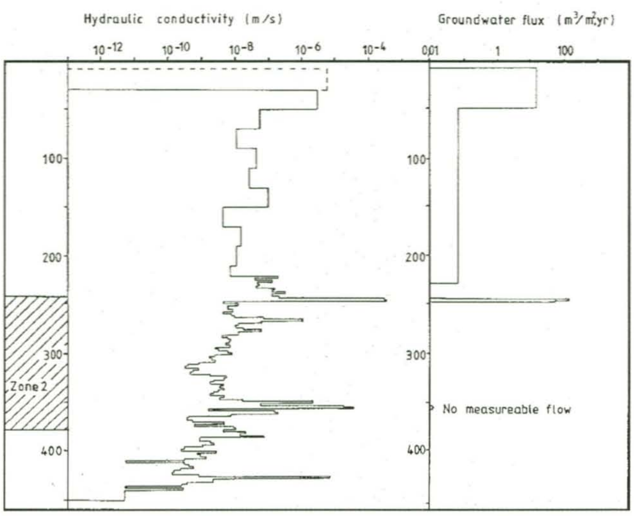

Fig. 10. Results of groundwater flow measurements by the dilution method in borehole BFI01 compared with the hydraulic conductivity, determined from hydraulic injection tests.

groundwater flow is high in the uppermost 50 metres of fractured and highly conductive rock. Below this there is almost 200 m of medium- to low-conductivity rock where the groundwater circulation is low. Measurements performed in borehole HFI01, which penetrates only the upper part of Zone 2 and the overlying rock, also showed a high groundwater flow rate in the upper part of Zone 2, 106.4 ml/min, which is comparable to the rate in BFI01. From the dilution measurements and the hydrochemical investigations, it is concluded that under natural gradient conditions, groundwater flow of considerable rate only takes place in the upper highly conductive part of Zone 2. Nearly stagnant flow conditions prevail in the lower part of Zone 2, in spite of the very high hydraulic conductivity, due to flow dynamics that causes the hydraulic gradient to be very small.

The successful performance of groundwater flow measurements encouraged further development and the dilution method was subsequently used in conjunction with a radially converging tracer test in Zone 2 (Gustafsson & Nordqvist 1993). The groundwater flow measurements were performed in the boreholes BFI01, KFI06 and KFI11 under induced gradients created by pumping in borehole BFI02. The aim was to obtain information about groundwater flow rates through nine borehole sections before the start of tracer injections. The results were used to verify that the borehole sections, which were selected for tracer injection, belonged to a hydraulically active, flowing part of the fracture zone.

Table 1. Results of groundwater flow measurements in borehole BFI01.

Section (m)	K ($m\ s^{-1}$)	T ($m^2\ s^{-1}$)	Q_w ($ml\ min^{-1}$)	Q_f ($m^3\ m^{-2}\ year^{-1}$)	v_f ($m\ s^{-1}$)	($m\ d^{-1}$)
9- 50	8.0E-6	3.2E-4	381.2	14.2	4.5E-7	0.039
50-230	3.1E-8	5.6E-6	7.9	0.07	2.2E-9	0.0002
242-244	3.0E-4	6.0E-4	169.4	131.7	4.2E-6	0.361
244-246	3.4E-4	6.8E-4	61.9	48.3	1.5E-6	0.132
352-354	1.7E-5	3.4E-5	no advective flow		<3E-11	
354-356	3.5E-5	7.0E-5	no advective flow		<3E-11	

ÄSPÖ Hard Rock Laboratory

On the island of Äspö, on the Swedish southeast coast, groundwater flow has been measured in-situ by the dilution method at the SKB Hard Rock Laboratory (Fig. 11). Measurements have been conducted during the pre-investigation programme, under the construction phase and also under the experimental phase. For the experimental phase, more measurements are still being planned.

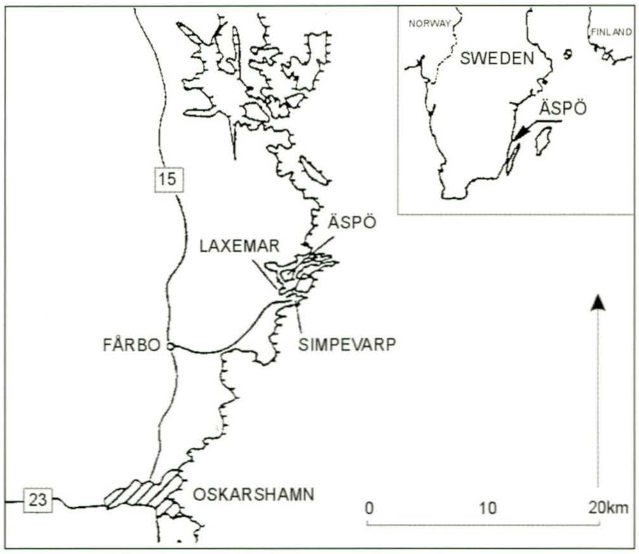

Fig. 11. Location of the Äspö Hard Rock Laboratory (HRL). The island of Ävrö is situated close by and southeast of Äspö.

Pre-investigation and construction phase

At the Äspö Hard Rock Laboratory (HRL), 13 deep cored boreholes have been drilled from the ground surface (Fig. 12). They are equipped with the Multipacker system mentioned above which has made it possible to install about 70 packed-off sections in the boreholes for the monitoring of hydraulic head. In 22 of these sections (straddling hydraulic conductive fracture zones), it is also possible to conduct groundwater flow measurements and water sampling. Groundwater flow, hydraulic head and water chemistry were monitored in the borehole sections during undisturbed natural gradient conditions before the start of excavation of the HRL access tunnel, and also during successive intervals as the tunnel approached the HRL target area in a spiral beneath Äspö island. The total length of the excavated tunnel reached 3600 m and the maximum depth of the HRL 450 m (Fig.13). A total of 64 measurements of groundwater flow were performed during the pre-investigation and construction phases. Depth ranged from 47 to 854 m, test section length 7 to 145 m and hydraulic transmissivity of the structures involved ranged from $2.3 \cdot 10^{-6}$ to $6.4 \cdot 10^{-4}$ m^2s^{-1} (Andersson 1992).

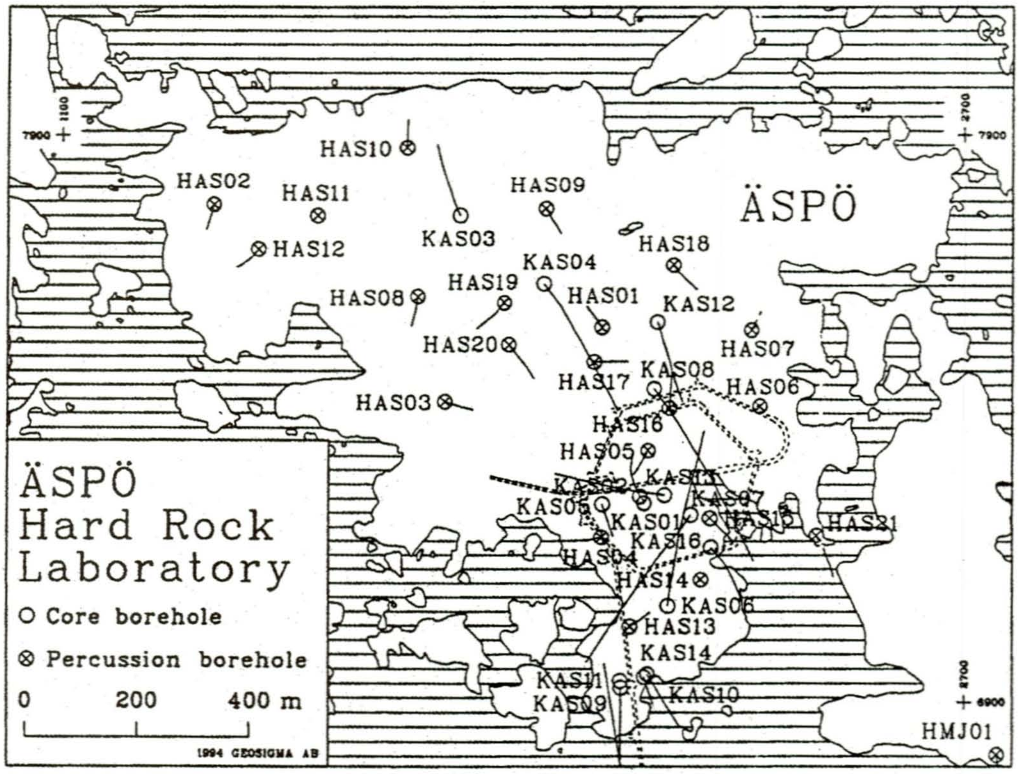

Fig. 12. Äspö with borehole locations. Circles represent the intersections of the boreholes with the ground surface, the lines represents the projection on the ground surface of the borehole. The HRL tunnel excavation is also indicated (dotted lines).

The results are presented in Table 2. The measurements during natural gradient conditions (NG1 and NG2) and pumping tests (LPT-1 and LPT-2) gave information not only about the actual flow rates but also about the hydraulic connections between different zones (Ittner et al. 1992). The measurements were used in the development of the conceptual model of the conductive structures at Äspö, and the flow measurements verified hydraulic connections in the conceptual model suggested by Wikberg et al. (1991). The results also showed that groundwater flow rates varied significantly during natural undisturbed conditions, and that in fracture zones considerable groundwater flow rates may occur even at depths of a few hundred metres (Fig. 14a). The highest flow rates at depth were found in the vertical NNW-SSE oriented fracture zones NNW, NNW-1 and NNW-2 (Fig 14b), but measurable flow rates also occurred in the NE-SW oriented fracture zone NE-1, dipping at about 70°NW (Fig. 14c). In the E-W orientated fracture zone EW-5 dipping at about 35°N, low flow rates were found in both the shallower and the deeper parts (Fig.14d). Comparison of groundwater flow rates under natural gradient and long-term pumping tests (LPT1 and LPT2) showed no simple correlation between

Table 2. Results of groundwater flow measurements on Äspö during the pre-investigation programme and construction phase.

Borehole	Section	Flow (ml/min)									T
	(m)	LPT-1	NG1	NG2	LPT-2	SNE	TP1	TP2	TP3	TP4	(m2/s)
KAS02	309-345	1.1	-	-	2	-	1.0	0.5	105	-	2.0E-5
	800-854	-	-	-	4	-	3.0	2.5	40-80	-	4.0E-5
KAS03	107-252	-	-	6.9	-	-	-	-	-	103	3.0E-6
	533-626	-	-	-	-	-	-	-	-	76	4.0E-6
KAS04	332-392	28	-	12	-	-	4.7	4.3	-	-	4.0E-5
KAS05	320-380	6.5	-	0.4	9	-	-	-	-	15	2.4E-6
	440-549	40	1.8	1.3	11	-	-	-	-	60	7.8E-6
KAS06	191-249	197	25	27	ph	-	3.0	2.5	-	-	1.7E-4
	431-500	79	52	25	ph	-	96	119	93	-	3.1E-5
KAS07	191-290	ph	-	1.0	18	-	-	-	-	-	4.9E-6
	501-604	ph	-	5.3	-	-	-	-	-	118	>1.3E-5
KAS08	140-200	4.3	-	4.0	21	-	-	-	-	-	3.9E-5
	503-601	20	5.5	7.6	48	-	-	-	-	250	3.2E-4
KAS09	116-150	nd	nd	11	-	>273	-	-	-	-	6.4E-4
KAS11	47- 64	nd	nd	0.3	-	-	-	-	-	-	3.3E-5
	153-183			33	-	-	-	-	-	-	2.5E-4
KAS12	235-278	nd	nd	0	-	-	-	-	-	-	2.3E-6
	279-330			12	107	-	-	-	-	-	2.7E-5
KAS13	151-190	nd	nd	1,1	-	-	-	-	-	-	3.7E-6
	191-220			4.7	3.3	-	-	-	-	-	2.7E-5
KAS14	131-138	nd	nd	3.1	-	-	-	-	-	20	2.2E-4
	147-175			18	11	>238	-	-	-	>300	1.0E-4

ph = pumped borehole nd = borehole not yet drilled - = no or failed measurement
LPT-1 August 1989, NG1 September 1989, NG2 June-August 1990, LPT-2 October 1990, SNE February 1992, TP1 February 1992, TP2 September 1992, TP3 March 1993, TP4 April-May 1994

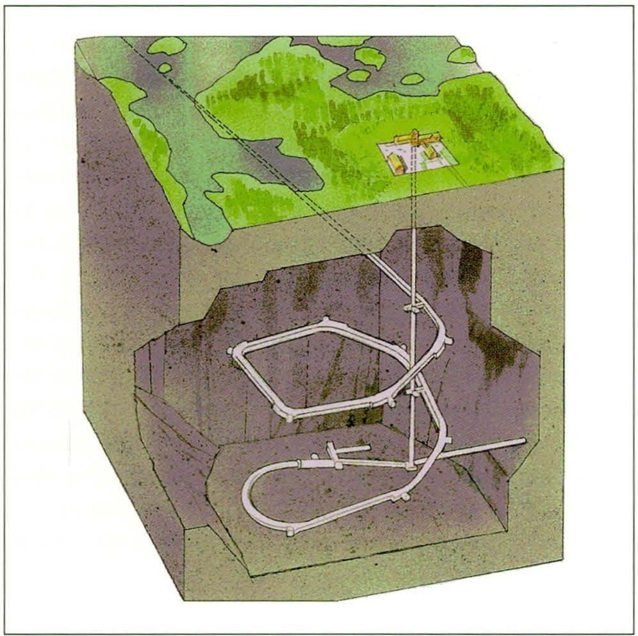

Fig. 13. General layout of the Äspö Hard Rock Laboratory, with a total tunnel length of 3600 m and maximum depth 450 m.

hydraulic transmissivity and groundwater flow, either under natural gradient conditions or induced gradients (Fig. 15a, b). Further, under induced gradient conditions there was no correlation with the distance to the pumped well. The dilution measurements indicated that, in fractured hard rock, the groundwater flow in fracture zones to a large extent is governed by the direction of the large-scale hydraulic gradient relative to the strike and dip of the conductive fracture zones. This relationship seems just as important as the capability of the zones to conduct water, i.e., their hydraulic conductivity.

The groundwater flow measurements presented in Table 2 as TP1, SNE, TP2, TP3 and TP4 were performed in successive intervals during the construction phase, at tunnel front positions 1210, 1240, 1620, 2195 and 3168 m, respectively. The presence of the tunnel was found to clearly affect the hydraulic head, groundwater flow and chemistry in the studied borehole sections (Ittner 1994, Ittner & Gustafsson 1995).

Experimental phase

An experiment from underground, phase A of the TRUE Block Scale experiment (Tracer Retention Understanding

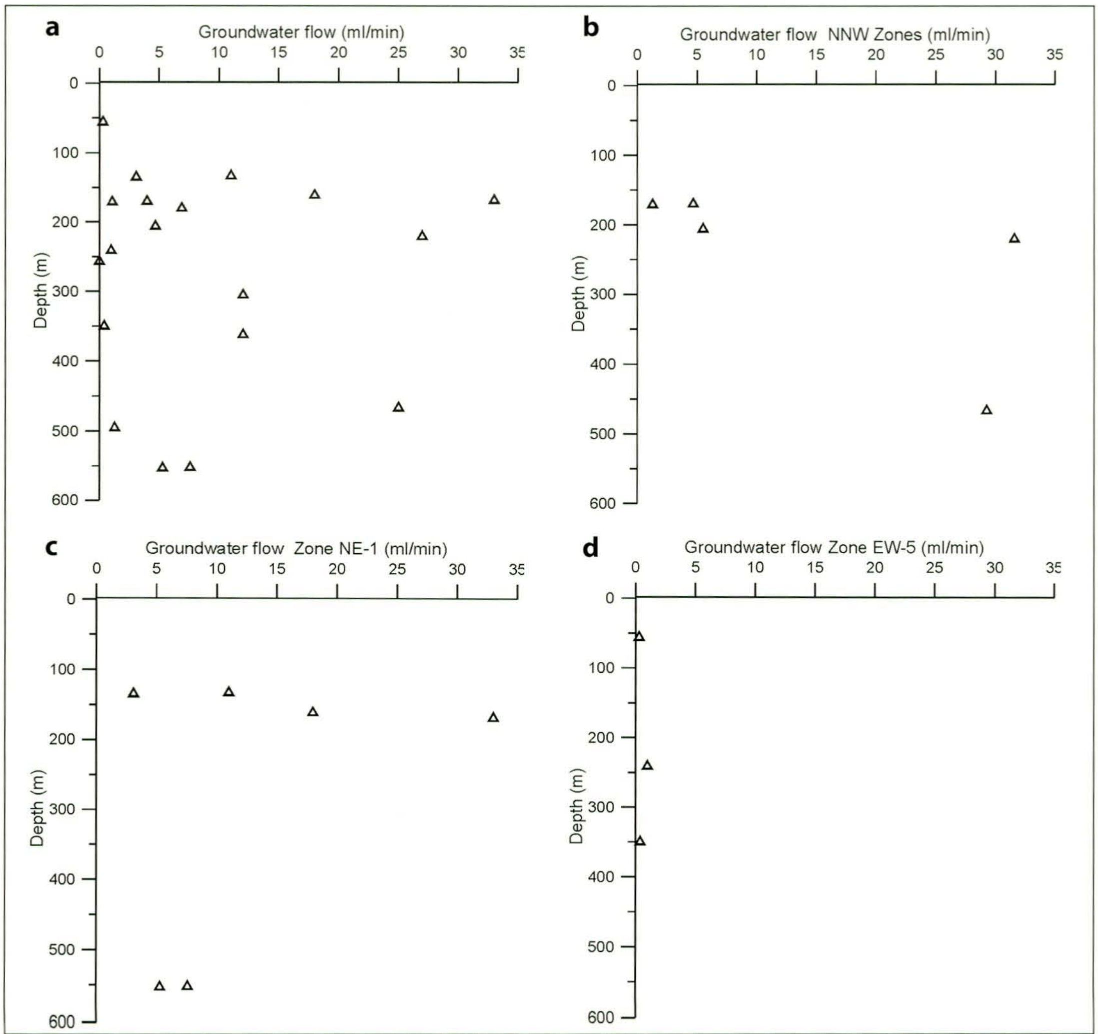

Fig. 14. Groundwater flow versus depth during undisturbed natural hydraulic gradient conditions; (a) All borehole sections measured. (b) Flow in the NNW-SSE orientated fracture zones NNW, NNW-1 and NNW-2. (c) Flow in the NE-SW orientated fracture zone NE-1. (d) Flow in the E-W orientated fracture zone EW-5.

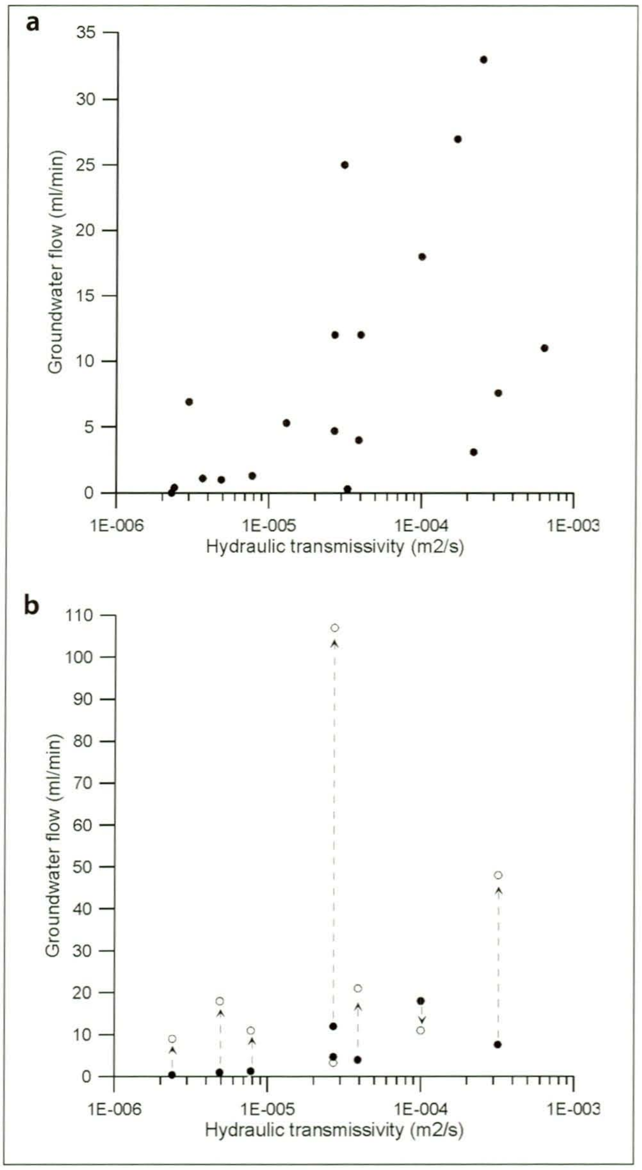

Fig. 15. Groundwater flow versus hydraulic transmissivity; (a) All borehole sections measured during undisturbed natural hydraulic gradient conditions. (b) Flow during a large-scale pumping test, LPT-2, (circles) compared to natural gradient conditions (dots).

Experiment in 10 –50 m block scale), included four hydraulic interference tests combined with groundwater flow measurements by the dilution method and multiple-hole tracer tests in two different well test configurations. The main objective of the tests was to investigate hydraulically the connectivity of the target area. A total of 109 flow measurements were conducted with the dilution method in 53 sections in boreholes drilled from the tunnel at a depth of about 400 m. Of these, 53 measurements were performed under ambient gradient conditions and 56 during pumping in different structures (fractures/zones). The hydraulic transmissivity in the structures involved ranged from $3.0 \cdot 10^{-8}$ to $1.5 \cdot 10^{-6}$ m^2s^{-1}. The groundwater flow measurements showed that the ambient flow varies substantially within the TRUE Block Scale rock volume. Groundwater flow rates typically were in the range of 0-300 ml/h. There were also variations in the ambient flow between the different tests, i.e., changes occurred with time in some sections (Andersson et al. 2000). The Darcy velocity was estimated from the measured flow rates according to Eqn.(4), and ranged from $8.0 \cdot 10^{-10}$ to $7.6 \cdot 10^{-7}$ ms^{-1}. Darcy velocity was further used together with estimated hydraulic conductivity values in the structures for calculation of hydraulic gradients in the TRUE rock block. The estimated gradients are typically in the order of 0.3-3. The tests verified previously interpreted hydraulic connections and generally confirmed the hydro-structural model of the target area (Doe 2001), as well as the conclusions from the short-term interference tests in borehole KI0025F03 (Gentzschein & Ludvigson 2001). The results of the groundwater flow measurements also served as input to the final choice of flow geometry to be used for the planned experiments with sorbing tracers during phase B and C of the TRUE Block Scale experiment.

Dilution tests at Ävrö

The latest version of the Borehole Probe Dilution Equipment (Fig. 4), which is still under development, was tested in borehole KAV01 (Fig. 16) on the island of Ävrö, situated close by

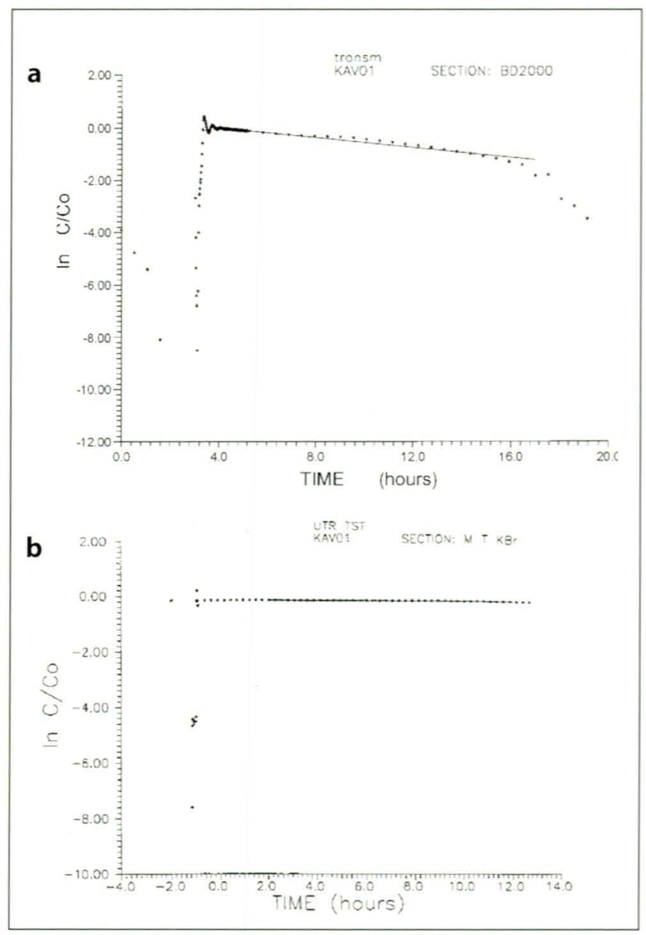

Fig. 17. Examples of dilution curves from measurements in borehole KAV01; (a) High groundwater flow rate (31.5 ml/min) in a shallow, highly conductive, fracture zone. (b) A low conductive fracture at depth with a low flow rate (0.008 ml/min).

Fig. 16. Field test of the Borehole Probe Dilution Equipment in borehole KAV01 on Ävrö.

and southeast of Äspö HRL (Fig. 11). Measurements were conducted in three 2 m and four 10 m test sections. Hydraulic conductivity ranged from very low values, $2.0 \cdot 10^{-11}$ ms^{-1}, which is below the limit of disturbance by molecular diffusion, to $8.7 \cdot 10^{-6}$ ms^{-1}. Depth ranged from 70 to 700 m. Fig. 17a exemplifies a dilution curve in a shallow, 70 – 80 m, highly conductive fracture zone K = $1.0 \cdot 10^{-6}$ ms^{-1}. Groundwater flow rate was determined at 31.5 ml/min and Darcy velocity $4.7 \cdot 10^{-7}$ ms^{-1} (0.04 m/d). Groundwater flow in a deep minor fracture, at depth 433.4 – 435.4 m and K = $1.0 \cdot 10^{-9}$ ms^{-1}, is exemplified in Fig. 17b, showing a dilution line of practically no slope and very low flow, 0.008 ml/min, and a corresponding Darcy velocity of $6.2 \cdot 10^{-10}$ ms^{-1} ($5.5 \cdot 10^{-5}$ m/d).

Concluding remarks

Research and development within the SKB programme has shown that it is possible to measure groundwater flow rates in-situ in hard rock using a single-well point dilution method. The dilution method is also the only available single-well method for in-situ flow measurements in fractured zones of hard rock.

Dilution test equipment can be built and operated in a wide range of borehole sizes, depths and site conditions (56–140 mm diameter, depth to 1000 m, surface and tunnel boreholes). In-situ groundwater flow measurements are a valuable tool for site characterisation in fractured hard rock, preferably combined with other hydraulic and chemical investigation methods. The dilution method is also well suited for collection of basic groundwater flow data, which may be used for development and calibration of hydraulic models, and thus provide additional constraints for modelling exercises besides hydraulic head.

The dilution method can be easily applied in boreholes at any stage of a subsurface investigation programme at a site. In the early stages, measurements can be made under natural hydraulic gradient conditions to serve as input data for hydraulic modelling, or for validation purposes. In later stages, measurements during hydraulic disturbances, such as pumping tests, shaft sinking and tunnel excavations, can provide valuable information about the nature of the hydraulic system studied. If groundwater flow is measured both under natural conditions and during disturbances to the system, the result will contribute significantly to the conceptual hydraulic understanding of the site.

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