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Abstract

Groundwater flow measurements with the point dilution method have been carried out within various SKB field investigations in Swedish bedrock since the beginning of the 1980´s. Knowledge of groundwater flow under natural conditions is an important part of the overall understanding of hydrogeological and hydrochemical conditions at investigated sites and for the function of engineered barriers /SKB 2001, 2003/. Flow measurements have also been made during pumping tests to provide indications of hydraulic connections between various bedrock features. Another frequent use of groundwater flow data from dilution measurements is for identifying suitable injection sections for cross-hole tracer experiments.

This report presents an overview of groundwater flow measurements made in boreholes during various SKB investigation programmes. The main purpose is to provide a summary of dilution measurements intended to characterise natural flow conditions within the SKB site investigations at Forsmark and Oskarshamn, and to analyse data on a site basis. In addition, general overviews of earlier investigations at Finnsjön, Ävrö and Äspö are presented as well as more recent measurements in connection with cross-hole experiments in Forsmark and Oskarshamn.

The measured groundwater flow rates in Forsmark and Oskarshamn are approximately log-normally distributed with a median of about 10^{-8} m^3/s. Flow rates show no systematic depth-dependence, high or low flow rates may occur at any depth. The only exception to this is that there appears to be a tendency for high flow rates in shallow borehole sections at Forsmark.

Another main variable that is analysed is the hydraulic gradient, derived from borehole flow rates, a transmissivity estimate and assumptions about the flow convergence due to the borehole. This data shows very large variation from extremely low gradients to in several cases seemingly unrealistically high gradients. Most of the calculated gradients are within the interval of 0.01–0.1 m/m.

There is an overall impression that the magnitudes of the calculated hydraulic gradient values tend to be too high relative to reasonable topographically-based estimates of the regional hydraulic gradient. An examination of possible sources of error for the gradient estimation indicates that it is likely that gradients tend to be over-estimated. One possible reason for this is that the flow convergence correction factor might often be larger than the commonly assumed value of two, due to fracture orientation and artificially increased hydraulic conductivity (negative skin) around the borehole. Of particular importance is the transmissivity values used for estimation of hydraulic gradients and this may be one of the largest sources of uncertainty.

Sammanfattning

Mätningar av grundvattenflöde med hjälp av utspädningsmetoden har gjorts inom SKB:s olika undersökningsprogram sedan tidigt 1980-tal. Kunskap om flödesförhållanden under naturliga förhållanden är en viktig del i den översiktliga förståelsen av hydrogeologi och hydrogeologi inom undersökta områden. Mätningar under störda förhållanden (t.ex. under provpumpningar) kan även ge indikationer på hydraulisk konnektivitet.

Denna rapport utgör en översiktlig beskrivning av mätningar av grundvattenflöde med utspädningsmätningar inom SKB:s undersökningar. Fokus ligger på analys av mätningar under naturliga förhållanden inom platsundersökningsprogrammen i Forsmark och Oskarshamn. Dessutom ges en mer översiktlig beskrivning av övriga mätningar med utspädningsmetoden.

Uppmätta grundvattenflöden i undersökta borrhålssektioner i Forsmark och Oskarshamn är i stora drag log-normalfördelade med ett medianvärde på cirka 10^{-8} m^3/s. Det finns inget tydligt djupberoende utan höga respektive låga flöden återfinns på alla djup. Undantaget från detta är en tendens att finna höga flöden i relativt ytnära borrhålssektioner i Forsmark.

Skattningar av den hydrauliska gradienten, med hjälp av bl.a. skattade transmissivitetsvärden från hydrauliska enhålstester, görs rutinmässigt i samband med att utspädningsmätningar utvärderas. Denna analys visar generellt på en stor variation från mycket låga gradienter till i många fall mycket höga värden. Flertalet skattade värden på den hydrauliska gradienten ligger dock inom intervallet 0.01–0.1 m/m.

Det kan konstateras att storleken på den skattade hydrauliska gradienten i många fall är alltför hög jämfört med rimliga skattningar enbart baserade på topografiska förhållanden. En genomgång av möjliga felkällor visar att framförallt två faktorer kan bidra till att gradienten tenderar att överskattas. En orsak är att den faktor som används för korrigering av konvergens av flödet runt en borrhålssektion ofta kan vara större än det vanligen antagna värdet två. Den kanske största felkällan är dock hur representativa antagna värden för transmissivitet (från hydrauliska enhålsförsök) är för de naturliga flödesvägar som utspädningsmätningar appliceras på.

Contents

1 Introduction

Groundwater flow measurements have been conducted within various SKB investigations in Swedish bedrock since the beginning of the 1980´s. The measurements have been carried out using the point dilution method, where dilution of an added tracer within an isolated borehole section is measured.

Knowledge of groundwater flow under natural conditions is an important part of the overall understanding of hydrogeological and hydrochemical conditions at investigated sites and for the function of engineered barriers /SKB 2001, 2003/. Flow measurements have also been made during pumping tests to provide indications of hydraulic connections between various bedrock features. Another frequent use of groundwater flow data from dilution measurements is for identifying suitable injection sections for cross-hole tracer experiments.

This report presents an overview of groundwater flow measurements made in boreholes during various SKB investigation programmes. The main purpose is to provide a summary of dilution measurements intended to characterise natural flow conditions within the SKB site investigations at Forsmark and Oskarshamn, and to analyse data on a site basis. In addition, general overviews of earlier investigations at Finnsjön, Ävrö and Äspö are presented.

2 History of groundwater flow measurements within SKB investigations

The SKB site investigations have involved investigations down to more than 1,000 m depth and have included fractures and fracture zones with a wide range of hydraulic conductivity values. For purposes of performance assessment and construction engineering, SKB has developed tools to make in-situ determination of groundwater flow by the dilution method. The equipment has been designed for a wide range of borehole conditions and physical and chemical conditions in fractured hard rock.

Prior to the current on-going site investigations at Forsmark and Oskarshamn, which is the main focus of this report, three major experimental episodes may be identified. These are:

- Measurements in surface boreholes at the Finnsjön site.
- Measurements in surface borehole at Äspö and Ävrö prior to the construction of the Äspö HRL (Hard Rock Laboratory).
- Measurements in tunnel boreholes within the Äspö HRL.

A general outline is given below to each of these. A more detailed discussion of performance and results of the dilution measurements is given in Chapter 4.

2.1 Finnsjön

The first groundwater measurements within SKB investigations were carried out at the Finnsjön site in north-eastern Uppland. The focus was here initially on development of the dilution probe. The dilution method was subsequently employed in two boreholes within the so called Fracture Zone project, with the purpose of characterizing natural flow conditions at different depths. Also, during a large scale tracer test, dilution measurements were utilized to confirm hydraulic connectivity between injection and pumping sections.

2.2 Äspö and Ävrö

Following the Finnsjön projects, dilution measurements were on a more routine basis used during various stages of the pre-investigation and subsequent tunnel construction prior to the Äspö HRL. Of particular interest here is that the utility of the dilution method was here expanded to groundwater flow measurements in combination with a large scale hydraulic interference test.

2.3 Tunnel boreholes at the Äspö HRL

Dilution measurements were frequently used within a series of flow and transport experiments in the Äspö HRL. Measurements were used for interpretation of flow connectivity during hydraulic interference tests and a valuable aid for hydro-structural interpretation. Prior to the tracers tests performed within the various experimental phases, dilution measurements were routinely used to identify suitable tracer injection sections and for design of tracer injection procedures. Among other applications can also be mentioned measurements in connections with the Prototype Repository project and the LTDE (Long Term Diffusion Experiment) project.

3 Groundwater flow measurements – equipment and methods

3.1 The dilution method – general principles

The dilution method is 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 within an isolated borehole section. The tracer is subsequently diluted by the ambient groundwater flow through the borehole test section. The dilution of the tracer is proportional to the water flow through the borehole section, Figure 3-1.

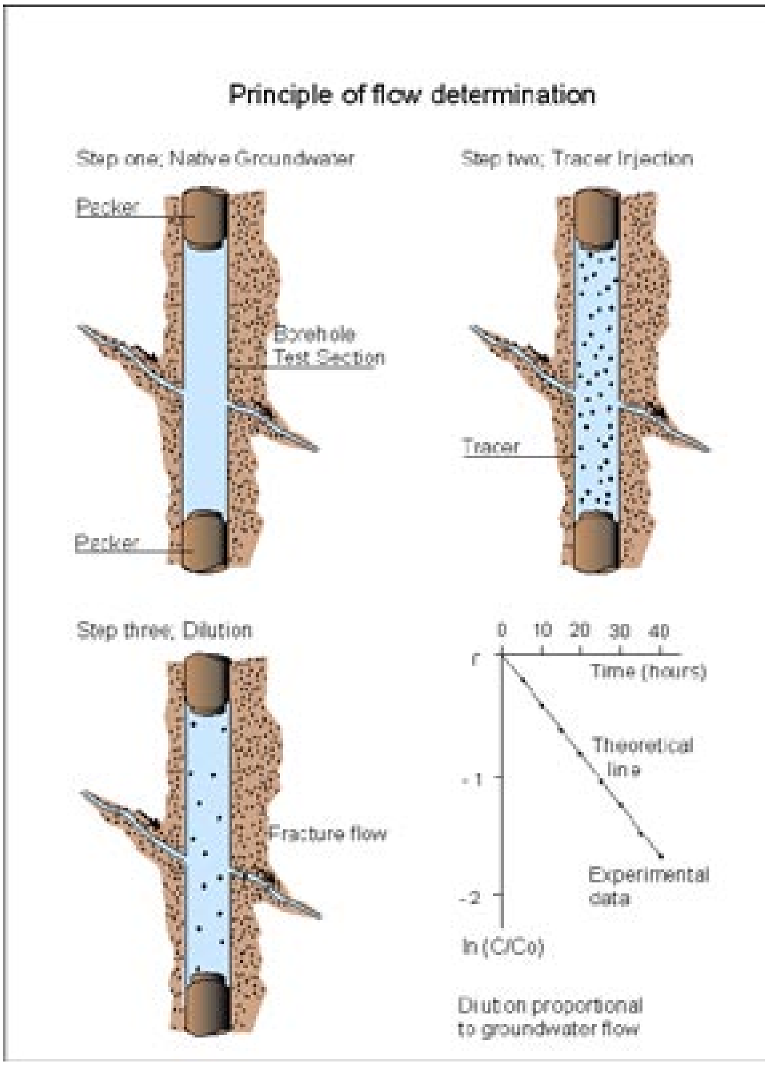


Figure 3-1. *General principles of dilution and flow determination.*

Assuming that the background concentration is negligible, the dilution in a well-mixed borehole section, starting at time t=0, is given by:

$$\ln(C/C_0) = -\frac{Q_w}{V} \cdot t \qquad \text{(Equation 3-1)}$$

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 Q_w is the volumetric flow rate (m^3/s) through the borehole section. Since V is known, the flow rate may be determined from the slope of the line in a plot of ln (C/C_0), or ln C, versus t.

If the background concentration, C_b, of the diluted tracer is significant, the dilution equation becomes:

$$\ln[C(t) - C_b] = -\frac{Q_w}{V} t + \ln(C_0 - C_b) \qquad \text{(Equation 3-2)}$$

Thus, plotting ln[C(t) – C_b] vs. t gives a linear slope equal to $-Q_w/V$. High background concentrations may occur, for example, if Uranine is used as a tracer and there is remaining Uranine from the drilling fluid around the borehole section.

A typical result from a tracer dilution experiment is illustrated in 3-2.

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

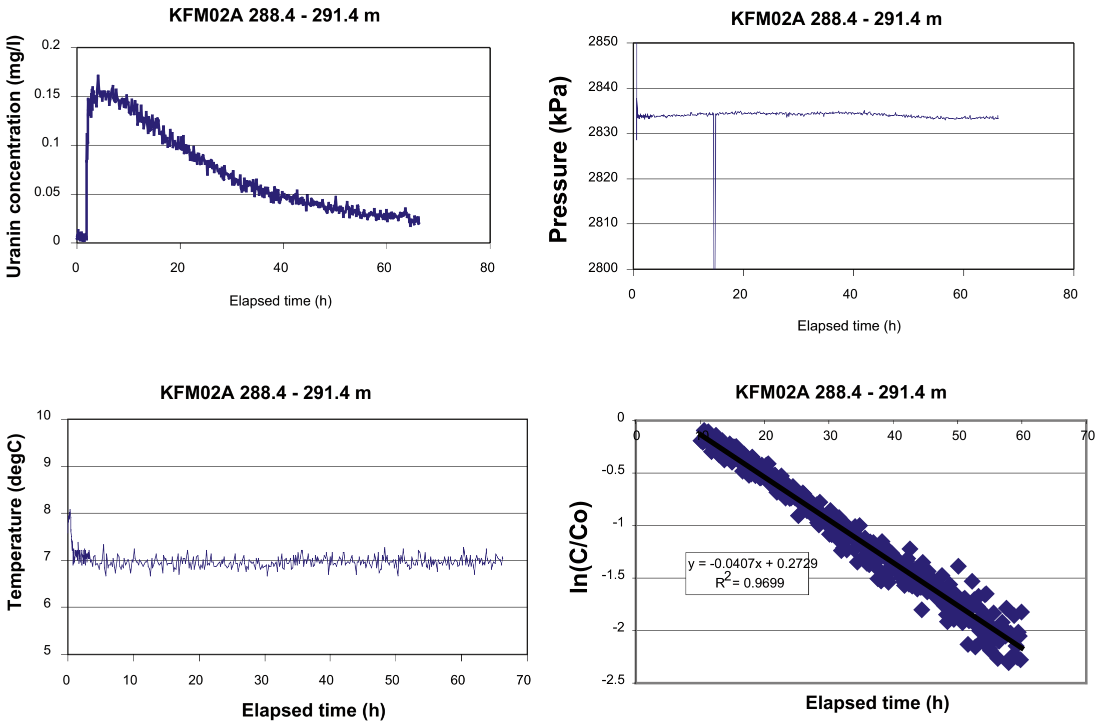


Figure 3-2. *Typical example from a field experiment of a dilution curve with supporting measurements of pressure and temperature. The lower right diagram shows evaluation of flow from a straight-line fit in a semi-log plot. From dilution measurements with the dilution probe in Forsmark, borehole KFM02A /Gustafsson et al. 2005/.*

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:

$$A = 2 \cdot r \cdot L \cdot \alpha \qquad \text{(Equation 3-3)}$$

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. The definition of L is not obvious because flow in fractured rock may in most cases not be expected to be evenly distributed along the entire borehole section. Instead, the flow is concentrated to one or several individual fractures or a group of fractures that may be defined as a fracture zone. Thus, it might be possible to define L, for example, as the width of some flowing zone in the borehole section, rather than the entire length of the section. Figure 3-3 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 may be calculated according to Equation (3-4), which often is called the formula of Ogilvi (Halevy et al. 1967). Here it is assumed that the disturbed zone, created by the presence of the borehole, has an axi-symmetrical and circular form.

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

where r_d is the outer radius (m) of the disturbed zone, K_1 is the hydraulic conductivity (m/s) 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 a channel with a total width of twice the borehole diameter, will converge through the borehole test section, as illustrated in Figures 3-3 and 3-4.

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. positive skin due to drilling debris and clogging, the correction factor α 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 conductivity around the borehole and thus affect α. In Figure 3-4, the correction factor, α, is given as a function of K_2/K_1 at different normalized radial extents of the disturbed zone (r/r_d).

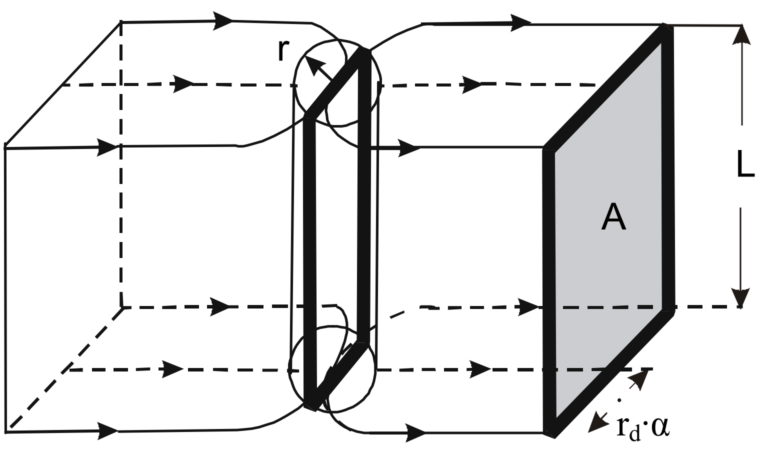


Figure 3-3. *Diversion and convergence of flow lines in the vicinity of a borehole test section.*

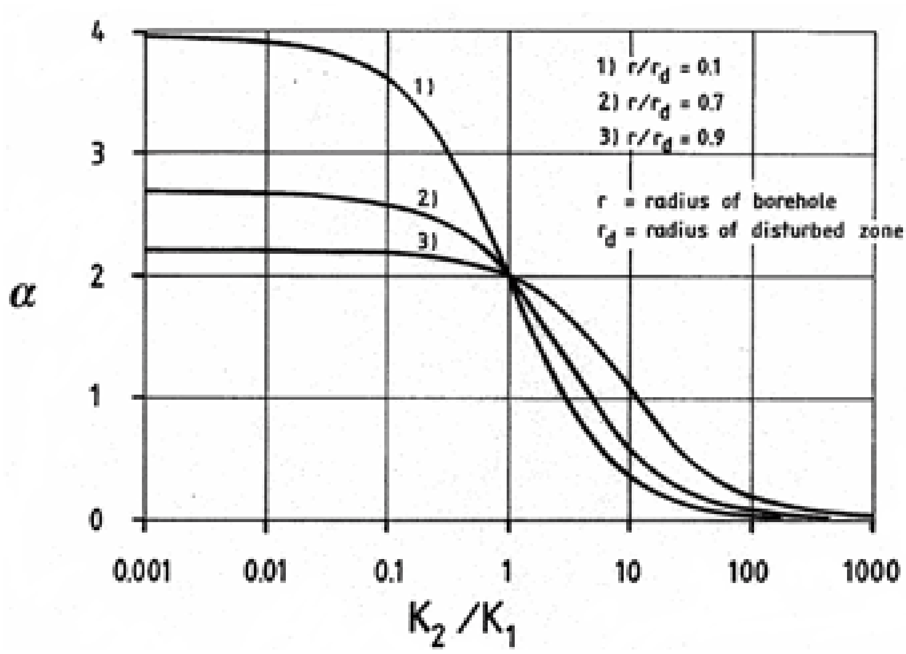


Figure 3-4. *The correction factor, α, as a function of K_2/K_1 at different radial extent (r/r_d) of the disturbed zone (skin zone) around the borehole.*

If the fracture/fracture zone and groundwater flow are 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 α will be about 41% larger than in the case of perpendicular flow. This is further discussed in /Gustafsson 2002b/.

The measured flow through the borehole section may be used to estimate the hydraulic gradient that governs the flow thorough the borehole, if the transmissivity T (m^2/s) of the section is known. For the flow geometry shown in Figure 3-3, the gradient *i* (expressed with a positive sign) is given by:

$$i = \frac{Q_w}{T 2 r_w \alpha} \qquad \text{(Equation 3-5)}$$

Thus, the hydraulic gradient may be estimated without any assumptions about the vertical extent of the flowing feature(s). However, this also implies the assumption that the used transmissivity value is representative for the natural flow geometry through the borehole. The T-value is typically obtained from hydraulic testing involving either pumping or injection of water and is thus obtained under different hydraulic conditions than for the groundwater flow measurement.

The Darcy velocity, v_d, which is not an actual velocity but flow per unit cross-sectional area, and also called the specific discharge, is obtained from:

$$v_d = \frac{Q_w}{A} \qquad \text{(Equation 3-6)}$$

Thus, it is necessary to make assumptions about the cross-sectional flow area when calculating the Darcy velocity. For borehole flow measurements within SKB investigations, the flow area is routinely assumed to be distributed along the entire borehole section. Thus, the calculated Darcy velocity is an average specific flow for the rock within the borehole section interval. It is conceivable that other assumptions may be made about the flow distribution within or around the borehole section, which then would result in different (larger) values of the Darcy velocity.

3.2 Equipment

3.2.1 The borehole dilution probe

The borehole dilution probe is a mobile system for groundwater flow measurements, Figure 3-5. Measurements can be made in boreholes with 76–77 mm diameter or larger and the test section length can be arranged for 1, 2, 3, 4 or 5 m with an optimised special packer/dummy system for 76–77 mm diameter boreholes and section lengths between 1 and 10 m with standard packers. The maximum measurement depth is at 1,030 m borehole length. The vital part of the equipment is the probe which measures the tracer concentration in the test section down hole and in-situ. The probe is equipped with two different measurement devices. One is the Optic device, which is 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 and is used for detection/analysis of saline tracers. The probe and the packers that straddle the test section are lowered down

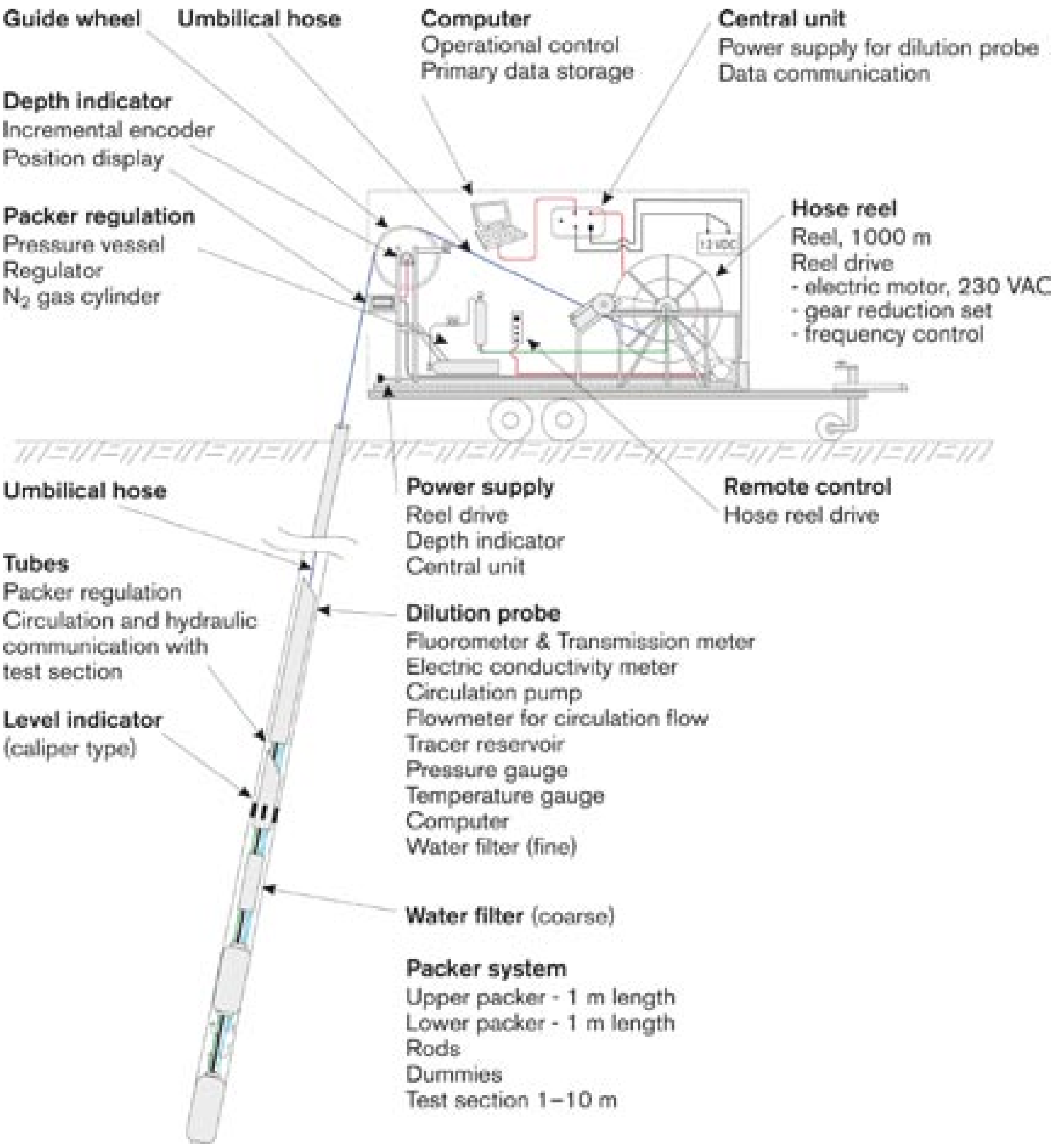


***Figure 3-5.** The SKB borehole dilution probe.*

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 detection, the absolute pressure and temperature are measured. 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. The pressure gauge and the temperature gauge are both positioned in the dilution probe, about seven metres from top of test section. This bias is not corrected for as only changes and trends relative to the start value are of great importance for the dilution measurement. Since the dilution method requires homogenous distribution of the tracer in the test section, a circulation pump is also installed and circulation flow rate measured.

A caliper log, attached to the dilution probe, is used to position the probe and test section at the pre-selected borehole length. The caliper detects reference marks previously made by a drill bit at exact length along the borehole, approximately every 50 m. This method makes it possible to position the test section with an accuracy of c. ± 0.10 m.

3.2.2 Measurements in permanently installed monitoring sections

The boreholes involved in the tests are instrumented with 1–9 inflatable packers isolating 2–10 borehole sections each. In Figure 3-6 drawings of the instrumentation in core and percussion boreholes are presented.

All isolated borehole sections are connected to the HMS (Hydro Monitoring System) for pressure monitoring. In general, the sections planned to be used for tracer tests are equipped with three polyamide tubes. Two are used for injection, sampling and circulation in the borehole section and one is used for pressure monitoring.

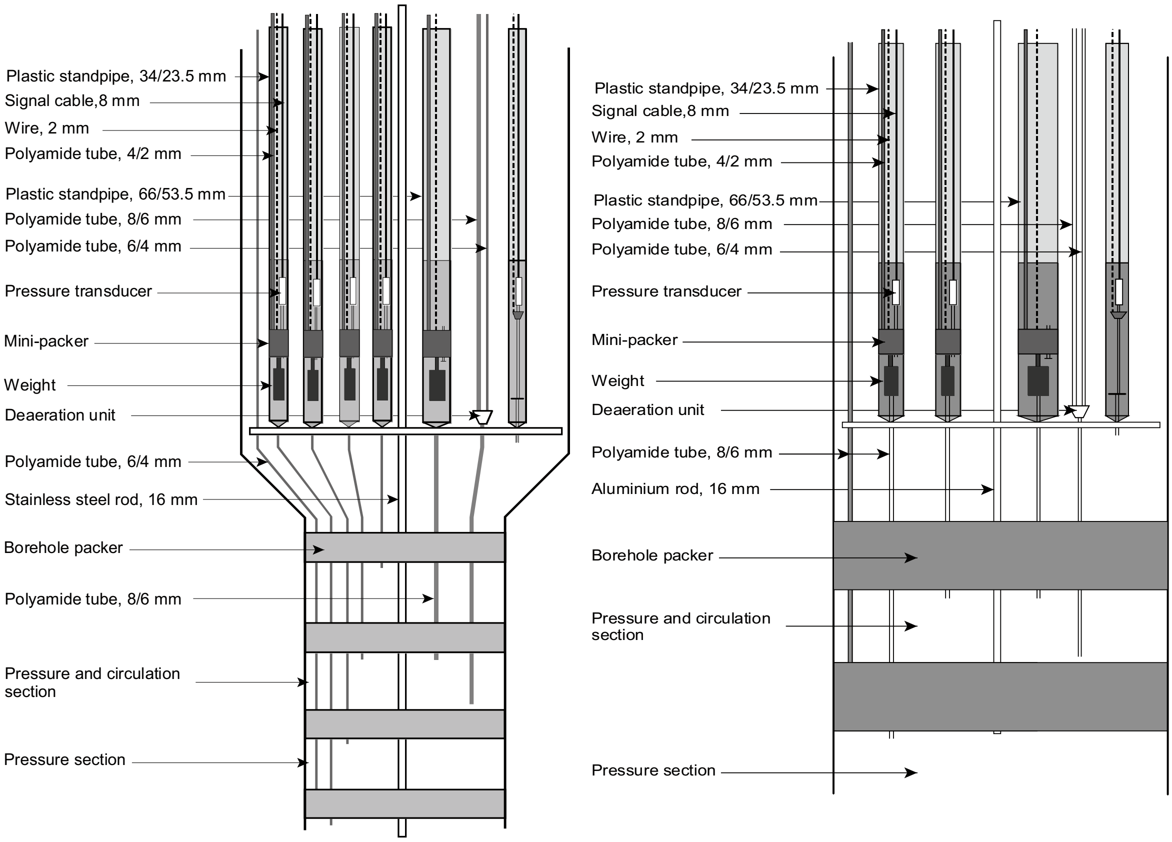


Figure 3-6. *Example of permanent instrumentation in core boreholes (left) and percussion boreholes (right) with circulation sections.*

The tracer dilution tests were performed using five identical equipment set-ups, i.e. allowing five sections to be measured simultaneously. A schematic drawing of the tracer test equipment is shown in Figure 3-7. The basic idea is to cause an internal circulation in the borehole section. The circulation makes it possible to obtain a homogeneous tracer concentration in the borehole section and to sample the tracer concentration outside the borehole in order to monitor the dilution of the tracer with time.

Circulation is controlled by a down-hole pump with variable speed and measured by a flow meter. Tracer injections are made with a peristaltic pump and sampling is made by continuously extracting a small volume of water from the system through another peristaltic pump (constant leak) to a fractional sampler. The equipment and test procedure is described in detail in SKB MD 368.010, SKB Internal document.

The tracers used were two fluorescent dye tracers, Uranine (Sodium Fluorescein), from Merck (purum quality) and Amino-G Acid from Aldrich (techn. quality).

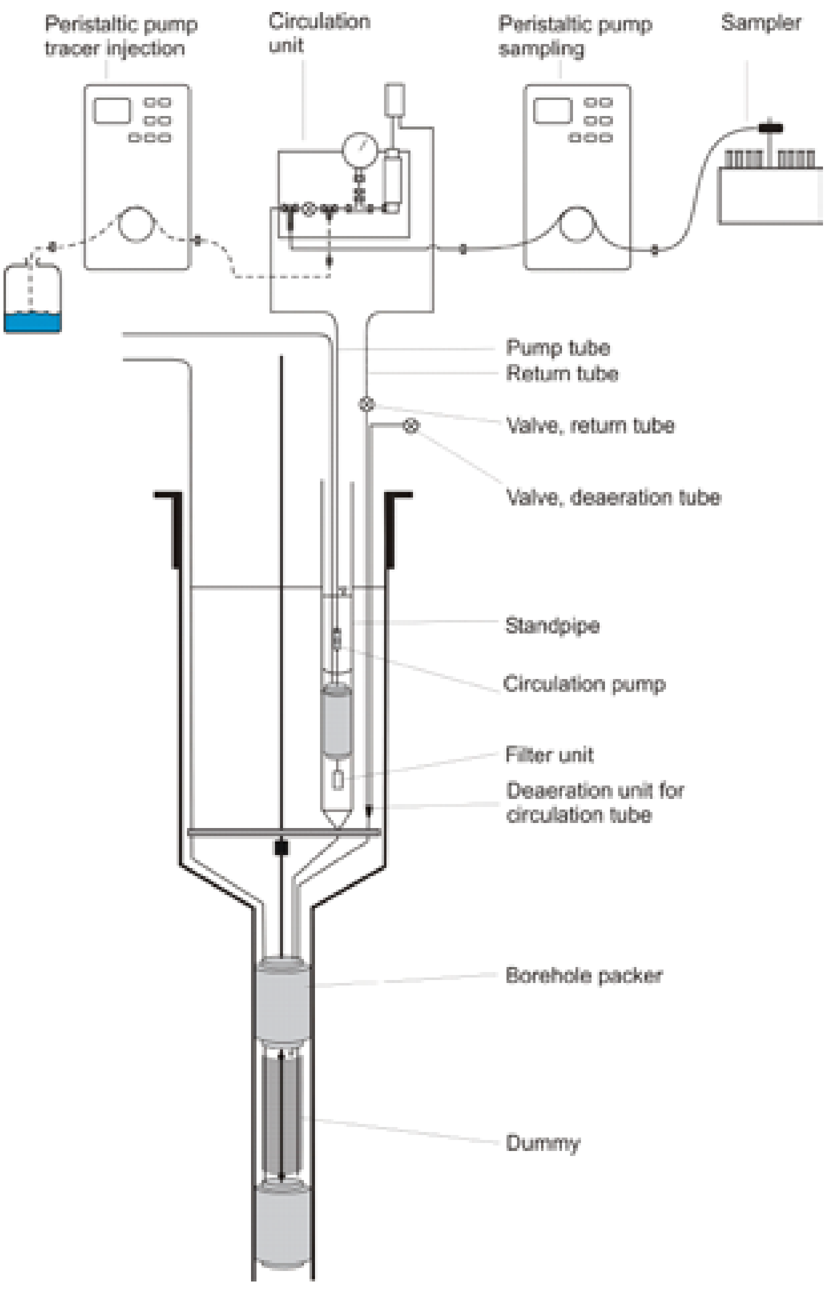


***Figure 3-7.** Schematic drawing of the equipment used in tracer dilution measurements.*

3.3 Measurement range and accuracy

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 a groundwater flow measurement is approximately at a hydraulic conductivity, K, between $6\cdot10^{-9}$ and $4\cdot10^{-8}$ m/s, if the hydraulic gradient, i, is 0.01. This corresponds to a groundwater flux (Darcy velocity), v_d, in the range of $6\cdot10^{-11}$ to $4\cdot10^{-10}$ m/s, which in turn may be transformed into groundwater flow rates, Q_w, corresponding to 0.03–0.2 ml/hour through a one m test section in a 76 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 $K = 4\cdot10^{-7}$ m/s if i = 0.01. The corresponding flux value is in this case $v_d = 4\cdot10^{-9}$ m/s and flow rate $Q_w = 2.2$ ml/hour. 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 $1\cdot10^{-7}$ m/s. At conductivity values below $1\cdot10^{-8}$ m/s, 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 2,000 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 better than ± 30%, based on 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 in section 3.1. 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.

4 Dilution measurements during earlier SKB field investigations and tracer experiments within the site investigation programmes

4.1 Finnsjön

The first borehole point dilution experiments were carried out in the Finnsjön area, a research site within the SKB program in northern Uppland. A field test of the method, preceded by laboratory tests, was performed in a previously identified fracture zone in the Gåvastbo area /Gustafsson and Klockars 1981/. Initially, three dilution experiments were performed in borehole G2 /Gustafsson 2002a/, a percussion-drilled borehole with a borehole diameter of 110 mm, using the large-molecule Blue Dextran 2000 as a tracer. Two of the experiments were performed in a borehole section with relatively high transmissivity and one in a section with relatively low transmissivity.

Additional follow-up point dilution measurements were performed in boreholes G8 and G9 /Gustafsson 2002b/.

These dilution measurements were not made under natural conditions; an artificial flow field across the site was created by continuous pumping in another borehole (G1) throughout the duration of the dilution tests. This enabled comparison of results with other hydraulic and tracer experiments within the area.

The flow rates estimated from the dilution curves ranged between approximately 5×10^{-10} to 10^{-7} m^3/s. The relative magnitudes of the flow rates among the borehole sections were, at least qualitatively, related to the transmissivity in the borehole section. In one of the sections in borehole G8 it was found that the flow rate varied considerably over time (total experimental time was about 1,200 hours), with the highest measured dilution rate value being about seven times the lowest measured rate. The changes in dilution rates roughly coincided with changes in precipitation and hydraulic gradients and, thus, it is possible that the temporal variations in dilution rates are correlated to variability in hydraulic conditions.

Subsequent investigations within the Finnsjön area was focussed on a large sub-horizontal fracture zone called Zone 2 /Andersson et al. 1991, Andersson 1993/. The project, called The Fracture Zone Project, was aimed at characterising flow and transport characteristics, as well as other properties, of large fracture zones. The low-angle Zone 2 is considered to be about 100 m thick, with a well-defined, almost planar, upper boundary while the lower boundary of the zone is less distinct. The top of the zone is highly permeable and is also a distinct boundary between non-saline water above the zone and saline water below.

The borehole investigations with the dilution method in Zone 2 can be regarded as the first regular field determination of groundwater flow in fractured rock in Sweden; the earlier measurements described above were more aimed at testing and development of the method. Two boreholes, called HFI01 and BFI01, were utilised for dilution measurements. Flow rates under natural conditions were determined within as well as outside Zone 2.

During the investigations in Zone 2, a variation of dilution measurement was introduced, in addition to the so far used down-hole equipment. This entailed circulation of tracer between the ground surface and the borehole section, with sampling at the surface and subsequent laboratory analysis. The latter method also included dilution measurements in a 180 m long section. Both measurement concepts were used successfully and established dilution measurements as a routine method for determination of groundwater flow rates in situ.

Figure 4-1 shows some of the more striking results from the dilution measurements in borehole BFI01. It shows that high natural flow occurs at the top of the fracture zone (about 1–3 × 10^{-6} m^3/s thorough the borehole section) but that flow is below the lower measurement limit of the equipment (estimated to be about 3 × 10^{-12} m^3/s) at the bottom of the zone, despite the high hydraulic conductivity (obtained from hydraulic injection tests) of the lower section. This result showed that the driving force for flow, e.g. the hydraulic gradient, is very low in the lower parts of the zone. The determination of in situ groundwater flow rates was in this case very important, together with other investigations, for the development of the conceptual model of flow and transport within Zone 2. For example, groundwater flow rates estimated from piezometric measurements and hydraulic injection tests were at least four orders of magnitude higher compared with those determined from dilution measurements.

Dilution measurements were also extensively employed in conjunction with two tracer tests, i.e. under induced hydraulic flow fields. During a radially converging tracer experiment /Gustafsson and Nordqvist 1993/ with nine tracer injection locations, dilution measurements were used to confirm hydraulic connectivity between injection and pumping sections. The dilution measurements were repeated during the tracer experiment and indicated that flow rates through the injection sections were decreasing. This was interpreted as possible clogging effects in the borehole injection intervals. The use of dilution measurements during the tracer experiments showed that such measurements in conjunction with other experiments could be very valuable.

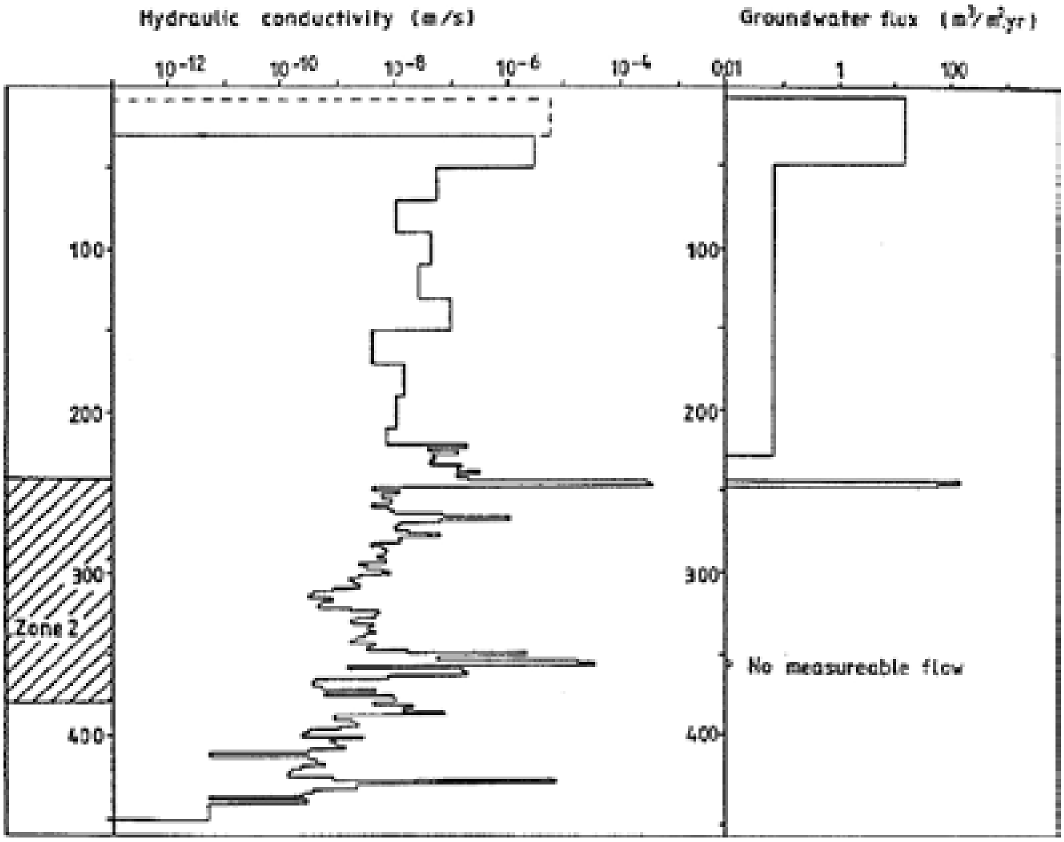


__Figure 4-1.__ Estimated natural groundwater flow and hydraulic conductivity along borehole BFI01 in Zone 2 at the Finnsjön site. Groundwater flux ($m^3/m^2/year$) is the flow rate through the section normalised to the section length and an assumed flow convergence factor of 2.0. (Reproduced from /Gustafsson and Andersson 1989/).

4.2 Äspö surface borehole investigations

At the SKB HRL (Hard Rock Laboratory) on the island of Äspö, south-eastern Sweden, dilution measurements were performed during the pre-investigation as well as during the tunnel construction phase /Gustafsson and Morosini 2002/. For these investigations, a multi-packer system was developed for groundwater flow determinations in permanently instrumented observation boreholes. This system is basically the same as the one used in the current monitoring program, described in section 3.2.2.

During the pre-investigation and construction phases, a total of 64 dilution measurements in 22 borehole sections were carried out. Measurement depths ranged from 47 to 854 metres, test section lengths from 7 to 145 metres and the hydraulic transmissivity ranged from 2.3×10^{-6} to 6.4×10^{-4} m^2/s.

The dilution measurements were made both during ambient conditions as well as during two long-term pumping tests. One of the pumping tests was also combined with a large-scaled tracer experiment called LTP-2 /Ittner et al. 1991/. The combination of measurements during natural conditions and pumped conditions gave information not only about actual flow rates but also about the hydraulic connectivity within and between various fracture zones. The dilution measurements were used in the development of the conceptual model of conductive structures at Äspö. The dilution measurements also showed that there was no simple correlation between natural groundwater flow rates and transmissivity, although larger transmissivity tended to be associated with higher flow rates. Further, during pumped conditions, there was no correlation with the distance to the pumped section. Figure 4-2 shows groundwater flow rates in boreholes at Äspö as well as the impact on flow rates during a large-scale pumping test. This shows that groundwater flow during the large-scale pumping tests increased considerably in most of the measured sections. In one single case, on the other hand, there is a small decrease in groundwater flow, which may either indicate a flow reversal or simply a result of natural variations.

Dilution measurement campaigns also took place at four different times during tunnel construction /Ittner 1994/. The tunnel construction was found to clearly affect groundwater flow and chemical conditions in the studied borehole sections /Ittner and Gustafsson 1995/.

Further development and testing of the dilution probe was also carried on at the neighbouring island of Ävrö in the core-drilled borehole KAV01 /Gustafsson 1999/.

4.3 Tunnel boreholes at Äspö HRL – experimental phase

At the Äspö Hard Rock Laboratory (HRL), an extensive test programme was initiated called the Tracer Retention Understanding Experiment (TRUE). The overall objectives of the project were to /Winberg et al. 2000/:

- Develop the understanding of radionuclide migration and retention in fractured rock.
- Evaluate to what extent concepts used in models are based on realistic descriptions of fractured rock and if data can be collected in site characterisation.
- Evaluate the usefulness and feasibility of different approaches to model radionuclide migration and retention.
- Provide in situ data on radionuclide migration and retention.

The TRUE programme initially focussed on studying a single fracture in a detailed scale /Winberg et al. 2000/ and this was followed by a fracture network study called the TRUE Block Scale project /Andersson et al. 2002/.

In the first TRUE stage (TRUE-1), dilution measurements were performed at two occasions in the experimental target fracture with the main objective to monitor changes in the natural groundwater flow during the TRUE-1 tracer test programme. A general conclusion of these

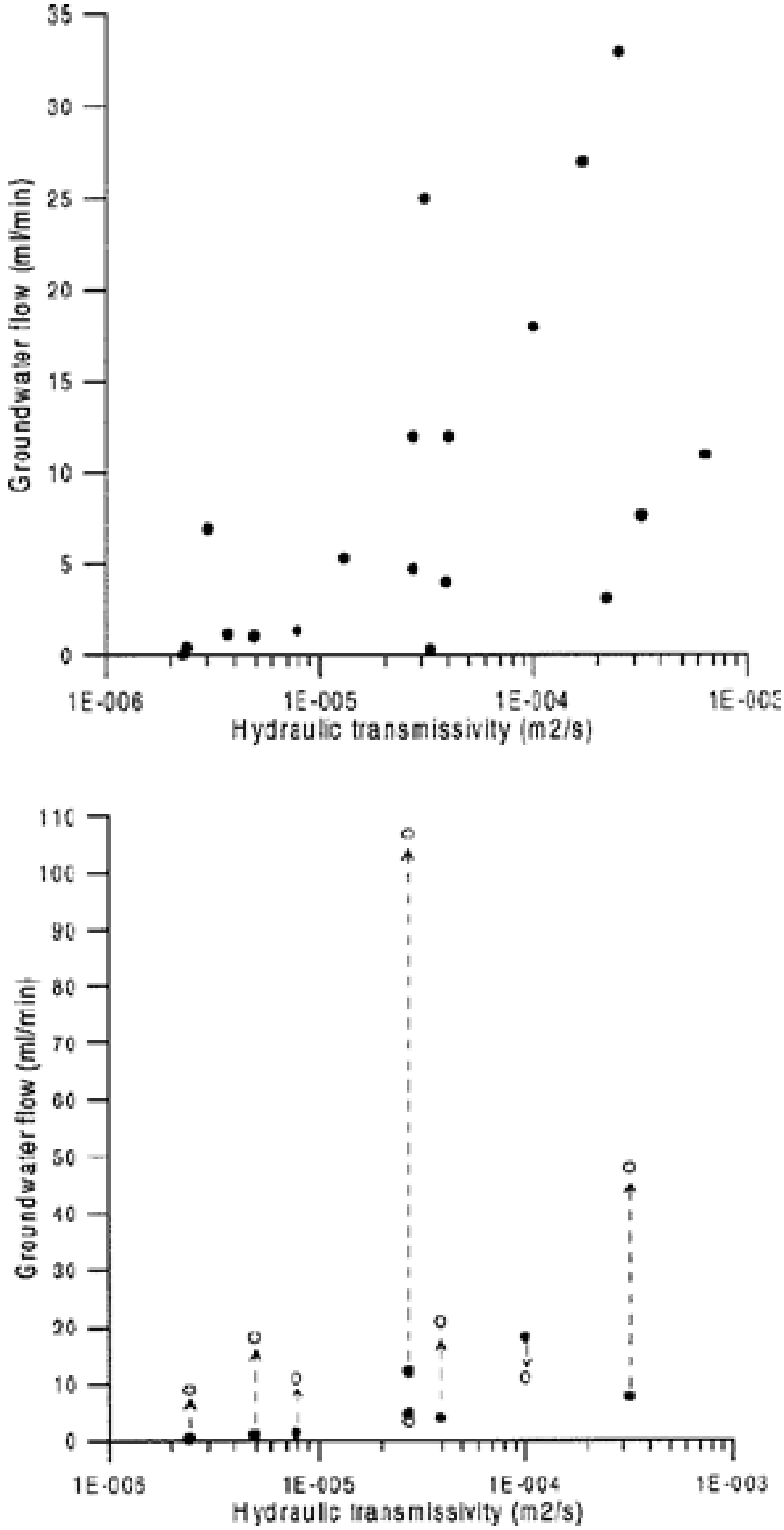


Figure 4-2. *Groundwater flow vs. hydraulic transmissivity in boreholes at Äspö; (top) all boreholes sections during natural conditions, (bottom) comparison between flow under natural conditions and flow during a large-scale pumping test (LPT-2). (Reproduced from /Gustafsson and Morosini 2002/).*

measurements was that only small flow rate changes were observed and that the magnitudes of the flow rates were consistent with the local transmissivities and the hydraulic gradients within the tested rock feature.

In the TRUE Block Scale project dilution tests were used extensively throughout all phases. The tests were used to determine ambient background flow and for identification of connected flow paths in connection with hydraulic interference tests. In addition, results from the dilution tests were used to identify suitable injection sections for the tracer tests. Four hydraulic interference tests and multiple-hole tracer tests were performed in combination with dilution measurements. A total of 109 measurements were conducted in 53 sections in boreholes drilled from the tunnel at a depth of around 400 meters. The flow rates generally varied substantially within the Block Scale volume and there were also variations in ambient flow rates with time. Estimated hydraulic gradients were generally high, in the range of 0.3–3 m/m, which may be expected in the proximity of a tunnel.

For the analysis of flow and transport connectivity within the tested site, the tracer dilution tests were very valuable. Changes in groundwater flow rate in response to pumping provided very clear indications of connectivity. An example of such a response in shown in Figure 4-3.

Similar use of the tracer dilution method was also employed in subsequent hydraulic and tracer tests in the TRUE Block Scale Continuation project /Andersson et al. 2004/. Further, dilution measurements were performed during the Prototype Repository project /Gokall-Norman and Andersson 2007/ during two campaigns in order to compare groundwater flow conditions during drained tunnel conditions and after closing of the repository. As expected, it was clearly confirmed that groundwater flow rates decreased significantly after closing of the repository.

Tracer dilution measurements were also used in combination with hydraulic and tracer tests to characterise groundwater flow conditions around the site for the LTDE (Long Term Diffusion Experiment) experiment /Wass 2005/.

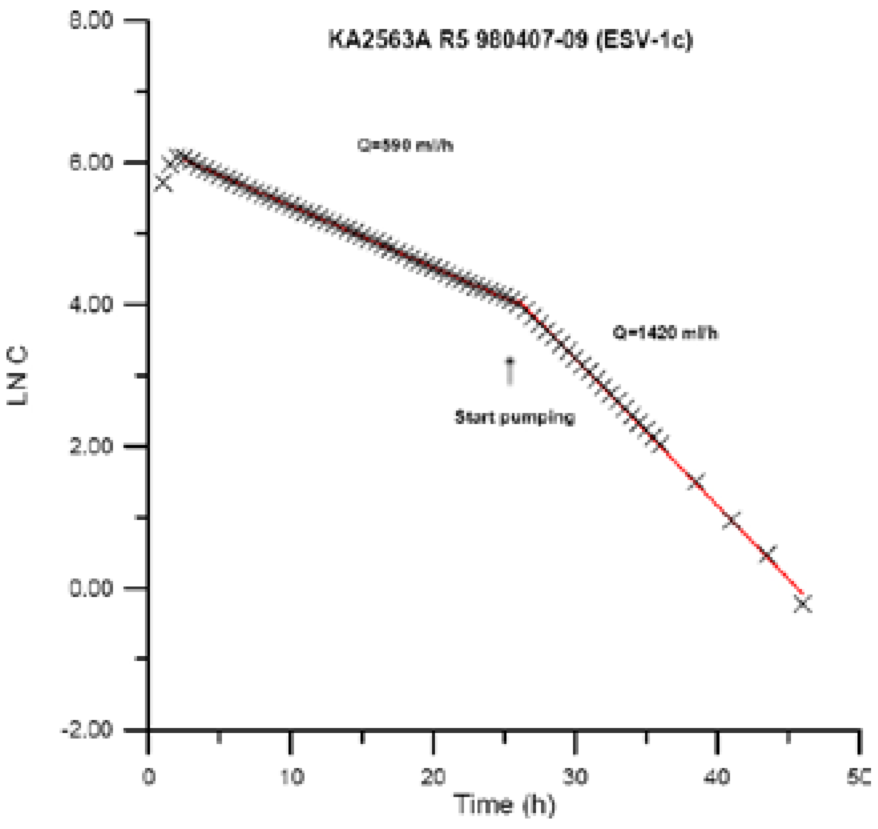


Figure 4-3. Illustration of change in groundwater flow rate due to pumping in another borehole section during a hydraulic interference test within the TRUE Block Scale project /from Andersson et al. 2001/.

4.4 Dilution measurements in connection with tracer experiments within the site investigations in Forsmark and Oskarshamn

In recent cross-hole tracer experiments within the site investigations at Forsmark and Oskarshamn, dilution measurements were employed as a fully integrated tool for experimental design and tracer test evaluation.

In a large-scale cross-hole tracer test in Forsmark /Lindquist et al. 2008a/, with the objective of verifying hydraulic connectivity of structures, dilution tests were used as an indicator of hydraulic connectivity during a hydraulic interference test prior to the tracer experiment. Dilution tests were carried out in 10 borehole sections, providing candidates for tracer injection sections. Six sections were selected for tracer injection for the cross-hole tracer experiment and dilution measurements were repeated in those sections both before and after the main pumping started. The results showed a clear groundwater flow rate response in most injection sections. Flow rates for natural (un-pumped) conditions varied between 1 and 13 ml/min, while rates for stressed conditions varied between 2 to 85 ml/min.

An interesting illustration of a combined change in flow direction and flow rate increase is shown in Figure 4-4. When pumping starts in the tracer sampling section, the flow rate does not instantaneously decrease (as in the example in Figure 4-3). Instead, there is a small plateau of approximately constant concentration before the concentration start decreasing again. The interpretation of this is that the pumping induces a reversed flow direction through the injection borehole so that tracer that already has been carried away by the ambient groundwater flow re-enters the borehole section.

Dilution measurements were also used during two-well radially converging tracer experiments over shorter distances with sorbing and non-sorbing tracers in Forsmark /Lindquist et al. 2008b/ as well as Oskarshamn /Lindquist et al. 2008c/. In Forsmark the flow increased from 0.65 during natural conditions to 15 ml/min during pumped conditions. In Oskarshamn, on the other hand, there was no clear increase in the flow rate, which may be an effect of changed flow direction. Such behaviour can be seen also in other sections in Forsmark and Oskarshamn.

Groundwater flow measurements under natural conditions have also been carried out in five soil wells within the Oskarshamn site investigations /Askling 2007/. The measurements were performed in open soil wells and measured flow rates varied between 20 and about 153 ml/min.

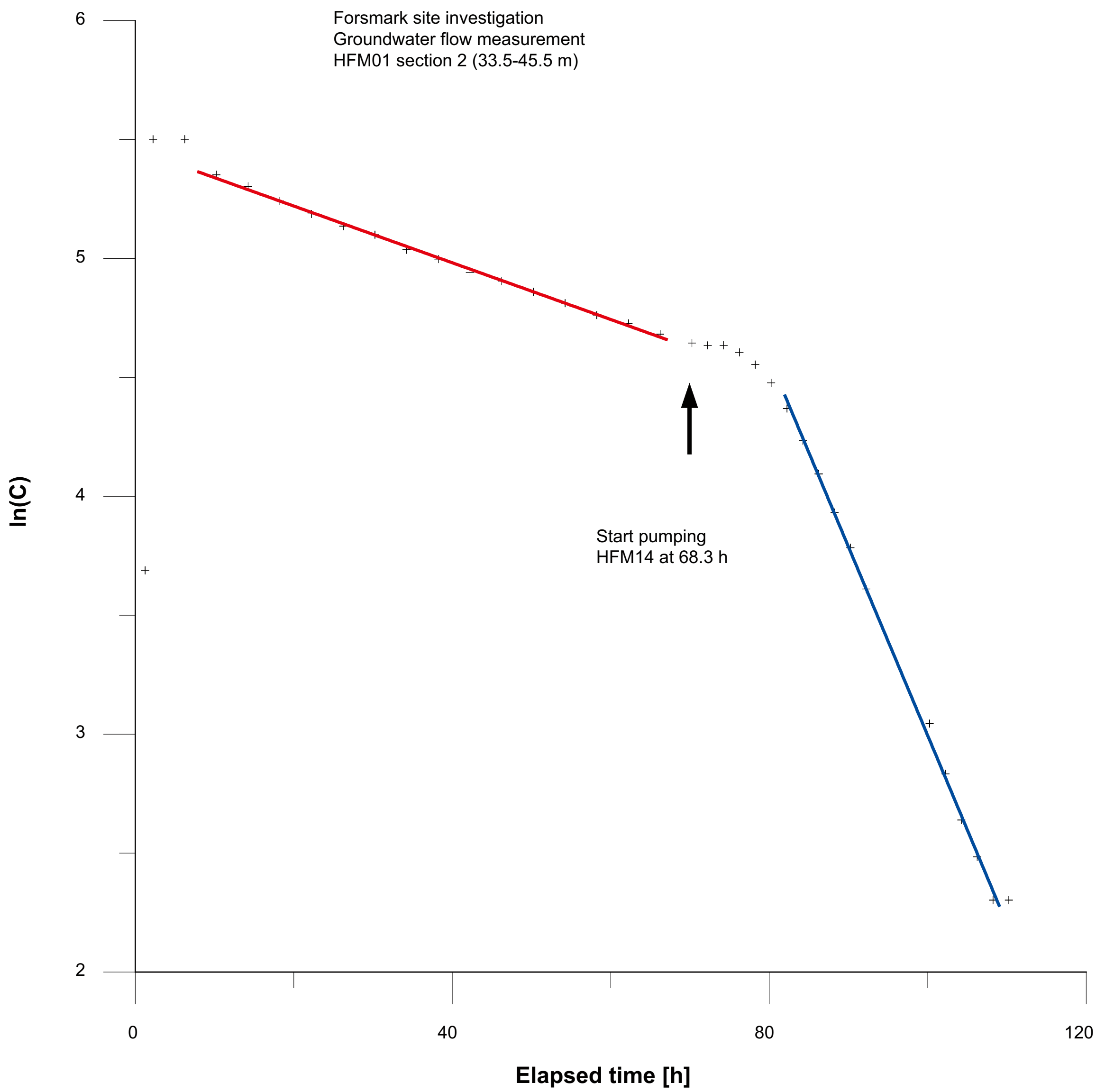


Figure 4-4. *Illustration of effect of flow direction change, induced by pumping in another borehole, on tracer dilution. The effect is seen as delayed response in the dilution curve. (Modified from /Lindquist et al. 2008a/).*

5 Dilution measurements under natural conditions in Forsmark and Oskarshamn – description of data

5.1 General

The primary focus in this report is on groundwater flow data from the site investigations at Forsmark and Oskarshamn. The data consist of dilution probe measurements during investigations of selected boreholes and of measurements in permanently installed monitoring sections (see section 3.2). These measurements are intended to represent natural flow conditions, i.e. without any major hydraulic disturbances. However, it should not be excluded that activities such as drilling or pumping occasionally might influence experimental results. All of the analysed data are available in the SICADA data base. The analyses in this report are generally made for each site separately. The analysed types of variables and other attributes include:

- *Groundwater flow through the borehole section* – obtained from dilution measurements in packed-off borehole sections. This is the primary result that may be used for subsequent interpretation of natural groundwater flow and hydraulic gradients in the fracture formation.
- *Darcy velocity (specific discharge)* – groundwater flow per cross-sectional area based on section length and on assumptions about convergence of flow lines. It may be pointed out that presented values for the Darcy velocity are based on the entire section length and does therefore not consider the specific distribution of the flowing features within or around each measurement section.
- *Transmissivity* – estimated from single-hole hydraulic testing. Groundwater flow rates and estimated gradients may be correlated with the transmissivity. The transmissivity values consist of values reported in the SICADA data base and are the values that were considered best available at the time for evaluating and reporting hydraulic gradients from the borehole dilution measurements. These values are in many cases preliminary and may have been modified in later analyses. Further, hydraulic testing for estimation of transmissivity has generally not been carried out in the exact same section intervals as for the dilution measurements. Estimates of the transmissivity for the dilution sections have in such cases been obtained by summation of transmissivities from smaller intervals or flow anomalies contained within the section for the dilution measurement.

Furthermore, the transmissivity values have been obtained using different methods with varying time frames and hydraulic conditions. The importance of these factors is further discussed in chapters 6 and 7.

- *Hydraulic gradient* – calculated from measured flow rates through the borehole section, transmissivity and assumptions about flow line convergence.
- *Section length* – the section length may be correlated with groundwater flow rates through the section because of possible increased number of flowing fractures in the sections. Long measurement sections may possibly also induce short-cut flow paths that are not connected under natural conditions.
- *Measurement elevation* – flow measurements and gradients may be correlated with depth.

The borehole sections in the monitoring programs at each site are intended for repeated (yearly) dilution measurements and for those sections up to five measurements are available to this date. For the main part of analysis in this report, the most recently obtained measurement in each section has been used. However, time series of dilution measurements in some of the monitoring sections are plotted and discussed briefly in section 6.4.

Measurement errors and uncertainties for groundwater flow rates and Darcy velocity (specific discharge) are previously discussed in section 3.3, which may be considered as general guidelines. Specific uncertainty estimates for each measurement have not been made. Estimates of the hydraulic gradient are further affected by uncertainties in the transmissivity values. The latter is discussed further in section 7.2.

5.2 Criteria for selection of borehole sections

The overall aim of the dilution measurements is to characterise natural groundwater flow conditions within the site investigations with measurements located to obtain good areal coverage. Another consideration is that selected borehole sections should include a variety of measurement depths and be distributed among important zones.

The borehole sections in the monitoring program have been selected with consideration of data needs for hydrogeochemistry, hydrogeology and transport properties. In some cases, the monitoring sections have been selected to approximately coincide with borehole sections selected for complete chemical characterisations or flow measurements with the dilution probe. The detailed positions of the packers are based on prior information about transmissivity along the borehole and other borehole data. The monitoring program sections are intended for regular measurements yearly.

For the dilution probe measurements, borehole sections are usually shorter than the monitoring sections, partly because the maximum section length for the dilution probe is 5 metres. Therefore the selection of measurement sections have been oriented towards parts of the borehole where there is one or several well defined flowing fractures in otherwise relatively impermeable rock. Another reason why the monitoring sections are longer than the sections for probe measurements is that those measurements are in many cases intended to encompass entire zones. The dilution probe measurements have to some extent been located at repository depth (400–700 m) because a number of SWIW (Single Well Injection -Withdrawal) experiments /e.g. Gustafsson et al. 2005/, which also are performed using the dilution probe, were carried out in conjunction with the dilution measurements.

5.3 Overview of groundwater flow measurements within the site investigation programmes at Forsmark and Oskarshamn

At each site, there are two main types of measurement. Measurements are either made using the dilution probe or with the equipment installed in monitoring boreholes (see section 3.2). Irrespective of measurement type, the intention is to measure groundwater flow rates under natural conditions. The total number of measurements at each site is:

- Forsmark: **64**; 34 with the dilution probe and 30 in monitoring sections.
- Oskarshamn: **72**: 38 with the dilution probe and 34 in monitoring sections.

Some of the basic data for the tested borehole sections are listed in Tables 5-1 to 5-4 and an areal overview of the sites with borehole locations are shown in Figure 5-1 and Figure 5-2.

Table 5-1. Borehole sections for tracer dilution measurements in the monitoring program at Forsmark.

Borehole	Section (m)	Section length (m)	Mid-section elevation (m.a.s.l)	T (m^2/s)	Q(m^3/s)
KFM01A	109.0–130.0	21.0	–115.8	1.00E–07	3.24E–09
KFM01D	429.0–438.0	9.0	–343.0	8.00E–07	4.43E–09
KFM01D	311.0–321.0	10.0	–252.5	2.00E–07	2.63E–09
KFM02A	490.0–518.0	28.0	–495.0	2.10E–06	1.39E–08
KFM02A	411.0–442.0	31.0	–417.8	2.50E–06	1.18E–08
KFM02B	491.0–506.0	15.0	–483.8	3.00E–05	7.69E–08
KFM02B	410.0–431.0	21.0	–407.1	2.00E–05	3.80E–07
KFM03A	633.5–650.0	16.5	–631.2	2.40E–06	1.03E–08
KFM04A	230.0–245.0	15.0	–199.8	2.00E–05	2.73E–07
KFM05A	254.0–272.0	18.0	–221.4	1.40E–08	2.14E–09
KFM06A	738.0–748.0	10.0	–622.8	1.20E–07	3.21E–09
KFM06A	341.0–362.0	21.0	–298.5	3.50E–06	9.48E–08
KFM06C	647.0–666.0	19.0	–527.0	5.30E–08	8.47E–10
KFM06C	531.0–540.0	9.0	–434.8	1.10E–06	3.35E–09
KFM08A	684.0–694.0	10.0	–550.6	2.00E–06	1.38E–08
KFM08A	265.0–280.0	15.0	–227.8	1.00E–06	2.92E–09
KFM08D	825.0–835.0	10.0	–662.6	2.00E–08	4.29E–08
KFM08D	660.0–680.0	20.0	–538.1	2.00E–07	1.51E–06
KFM10A	430.0–440.0	10.0	–299.8	3.00E–05	4.44E–08
KFM11A	690.0–710.0	20.0	–593.8	1.00E–06	4.16E–09
KFM11A	446.0–456.0	10.0	–398.6	6.00E–07	6.89E–10
KFM12A	270.0–280.0	10.0	–226.7	1.00E–06	5.23E–09
HFM01	33.5–45.5	12.0	–37.0	4.00E–05	1.31E–07
HFM02	38.0–48.0	10.0	–39.9	5.90E–04	5.49E–07
HFM04	58.0–66.0	8.0	–57.9	7.90E–05	1.26E–08
HFM13	159.0–173.0	14.0	–138.6	2.90E–04	2.11E–07
HFM15	85.0–95.0	10.0	–59.1	1.00E–04	1.42E–07
HFM16	54.0–67.0	13.0	–57.2	3.50E–04	1.73E–08
HFM19	168.0–182.0	14.0	–136.1	2.70E–04	4.05E–07
HFM21	22.0–32.0	10.0	–18.8	4.00E–05	3.20E–08
HFM27	46.0–58.0	12.0	–45.6	4.00E–05	8.55E–09
HFM32	26.0–31.0	5.0	–27.5	2.30E–04	7.96E–09
KFM03A	969.5–994.5	25.0	–969.1	5.50E–07	2.88E–08

Table 5-2. Borehole sections for tracer dilution measurements with the dilution probe at Forsmark.

Borehole	Section (m)	Section length (m)	Mid-section elevation (m.a.s.l)	T (m^2/s)	Q(m^3/s)
KFM01A	117.8–118.8	1.0	–114.6	5.35E–08	3.57E–10
KFM01A	177.8–178.8	1.0	–174.2	4.86E–08	3.27E–10
KFM01A	325.4–326.4	1.0	–320.7	2.71E–10	1.19E–10
KFM02A	109.9–112.9	3.0	–103.8	4.98E–05	3.89E–07
KFM02A	180.7–183.7	3.0	–174.4	3.56E–07	8.38E–10
KFM02A	216.0–219.0	3.0	–209.6	6.77E–07	4.79E–10
KFM02A	288.4–291.4	3.0	–281.7	5.04E–06	2.44E–08
KFM02A	414.7–417.7	3.0	–407.5	9.54E–07	4.79E–10
KFM02A	511.5–514.5	3.0	–503.9	3.87E–06	9.99E–09
KFM03A	129.7–130.7	1.0	–121.6	1.00E–07	3.21E–10
KFM03A	388.1–389.1	1.0	–379.2	9.21E–05	1.57E–09
KFM03A	450.5–451.5	1.0	–441.3	6.65E–06	1.38E–09
KFM03A	533.2–534.2	1.0	–523.6	2.25E–08	1.12E–09
KFM03A	643.5–644.5	1.0	–633.3	2.48E–06	2.92E–09
KFM03A	803.2–804.2	1.0	–792.1	1.40E–08	4.14E–09
KFM03A	986.0–987.0	1.0	–973.6	1.98E–07	2.25E–10
KFM03B	64.0–67.0	3.0	–56.8	2.07E–05	6.94E–09
KFM08A	188.5–191.5	3.0	–159.4	2.20E–06	3.69E–08
KFM08A	274.5–277.5	3.0	–230.7	1.29E–06	6.48E–09
KFM08A	410.5–413.5	3.0	–340.4	1.13E–08	1.65E–09
KFM08A	479.0–482.0	3.0	–394.3	6.93E–08	4.28E–10
KFM08A	685.5–688.5	3.0	–549.1	1.41E–06	4.22E–09
KFM04A	232.0–237.0	5.0	–197.2	5.50E–05	2.77E–07
KFM04A	296.5–297.5	1.0	–251.1	1.61E–07	7.06E–11
KFM04A	359.3–360.3	1.0	–304.6	1.26E–06	1.59E–08
KFM04A	417.0–422.0	5.0	–354.5	8.91E–09	2.72E–10
KFM01D	147.5–148.5	1.0	–118.1	5.32E–06	3.51E–10
KFM01D	316.4–317.4	1.0	–253.2	1.65E–05	3.51E–10
KFM01D	377.4–378.4	1.0	–300.4	3.15E–07	1.32E–09
KFM01D	431.0–432.0	1.0	–341.5	9.95E–07	2.88E–09
KFM01D	570.7–571.7	1.0	–446.6	1.27E–08	2.50E–10

Table 5-3. Borehole sections for tracer dilution measurements in the monitoring program at Oskarshamn.

Borehole	Section (m)	Section length (m)	Mid-section elevation (m.a.s.l)	T (m^2/s)	Q(m^3/s)
HLX20	71.0–80.0	9.0	–54.5	9.0E–06	9.41E–09
HLX27	153.0–165.0	12.0	–120.3	2.0E–06	4.33E–08
HLX28	70.0–90.0	20.0	–53.7	2.0E–05	1.87E–07
HLX32	20.0–30.0	10.0	–10.4	1.0E–06	2.45E–07
HLX35	120.0–130.0	10.0	–90.6	1.0E–05	1.22E–06
HLX37	95.0–110.0	15.0	–72.1	3.0E–07	2.02E–08
HLX39	187.0–199.0	12.0	–139.0	1.0E–05	2.34E–08
HLX43	135.0–146.0	11.0	–87.7	4.0E–06	1.38E–06
KAV01	391.0–434.0	43.0	–398.3	1.8E–05	1.13E–06
KLX01	171.0–190.0	19.0	–163.3	1.1E–05	8.05E–08
KLX02	1,145.0–1,164.0	19.0	–1,129.6	3.2E–07	1.19E–08
KLX02	452.0–494.0	42.0	–452.5	1.0E–07	2.67E–08
KLX03	965.0–971.0	6.0	–920.7	1.5E–09	3.40E–09
KLX03	729.0–751.0	22.0	–698.9	5.9E–06	6.58E–09
KLX04	870.0–897.0	27.0	–854.9	3.5E–08	9.37E–09
KLX04	507.0–530.0	23.0	–491.9	2.7E–06	1.17E–08
KLX05	241.0–255.0	14.0	–204.8	6.2E–07	3.58E–09
KLX06	554.0–570.0	16.0	–474.5	1.0E–05	1.36E–08
KLX06	256.0–275.0	19.0	–216.3	5.0E–05	2.79E–08
KLX07A	753.0–780.0	27.0	–569.7	3.5E–05	3.22E–07
KLX08	626.0–683.0	57.0	–539.4	2.9E–06	4.32E–07
KLX08	594.0–625.0	31.0	–500.9	2.5E–06	1.26E–08
KLX10A	689.0–710.0	21.0	–676.2	1.0E–07	9.88E–09
KLX10A	351.0–368.0	17.0	–338.4	1.0E–06	3.21E–07
KLX11A	573.0–586.0	13.0	–524.1	2.0E–05	5.26E–08
KLX11A	256.0–272.0	16.0	–225.3	2.0E–05	1.12E–08
KLX12A	535.0–545.0	10.0	–501.1	2.0E–07	2.67E–09
KLX15A	623.0–640.0	17.0	–469.3	7.0E–07	3.03E–07
KLX15A	260.0–272.0	12.0	–192.7	5.0E–06	4.96E–08
KLX18A	472.0–489.0	17.0	–452.9	2.7E–07	4.84E–09
KLX19A	509.0–517.0	8.0	–413.9	1.0E–06	1.98E–08
KLX20A	260.0–296.0	36.0	–184.4	2.0E–06	1.16E–08
KLX20A	103.0–144.0	41.0	–68.0	5.0E–05	7.04E–08
KSH01A	532.0–572.0	40.0	–531.5	8.4E–07	7.58E–08
KSH01A	238.0–277.0	39.0	–245.8	7.4E–06	2.57E–08
KSH02	955.0–963.0	8.0	–951.7	6.8E–08	1.61E–09
KSH02	411.0–439.0	28.0	–418.7	9.7E–08	2.93E–09
KLX05	625.0–633.0	8.0	–549.6	1.20E–08	4.17E–09

Table 5-4. Borehole sections for tracer dilution measurements with the dilution probe at Oskarshamn.

Borehole	Section (m)	Section length (m)	Mid-section elevation (m.a.s.l)	T (m^2/s)	Q(m^3/s)
KLX02	250.8–253.8	3.0	–232.9	7.40E–06	4.68E–08
KLX02	338.4–341.4	3.0	–320.1	6.00E–07	6.97E–09
KSH02	176.0–177.0	1.0	–170.6	2.10E–07	1.09E–08
KSH02	422.3–423.3	1.0	–416.5	1.00E–06	3.25E–09
KSH02	576.8–579.8	3.0	–571.7	5.20E–07	1.57E–09
KSH02	858.6–859.6	1.0	–852.0	1.30E–08	5.17E–09
KSH02	957.2–958.2	1.0	–950.4	5.40E–07	7.03E–09
KLX03	123.7–124.3	0.6	–101.3	2.31E–07	2.98E–10
KLX03	195.0–198.0	3.0	–171.4	1.25E–05	8.82E–09
KLX03	266.2–267.2	1.0	–239.3	7.85E–07	3.01E–09
KLX03	409.6–410.6	1.0	–378.3	1.62E–07	5.69E–09
KLX03	662.2–663.2	1.0	–623.7	2.06E–07	1.17E–09
KLX03	740.4–744.4	4.0	–701.2	4.48E–06	7.02E–08
KLX03	769.7–772.7	3.0	–729.2	5.30E–07	6.50E–10
KLX03	969.7–970.7	1.0	–922.8	4.52E–07	4.45E–10
KLX18A	146.0–149.0	3.0	–124.8	4.61E–07	1.48E–09
KLX18A	359.0–362.0	3.0	–334.7	2.34E–07	4.24E–10
KLX18A	473.3–476.3	3.0	–447.3	4.33E–08	6.36E–10
KLX18A	562.0–565.0	3.0	–534.6	5.07E–07	3.29E–09
KLX18A	592.0–595.0	3.0	–564.1	9.52E–07	2.97E–09
KLX11A	167.8–170.8	3.0	–135.3	1.78E–05	4.19E–09
KLX11A	306.0–309.0	3.0	–266.6	1.04E–05	6.36E–09
KLX11A	439.0–442.0	3.0	–392.6	6.21E–08	3.02E–09
KLX11A	516.5–519.5	3.0	–466.0	3.39E–06	8.70E–09
KLX11A	579.0–584.0	5.0	–526.0	5.76E–06	4.80E–08
KLX11A	598.0–599.0	1.0	–542.1	1.35E–07	2.88E–10
KLX21B	124.3–127.3	3.0	–107.5	1.47E–05	2.57E–07
KLX21B	155.0–158.0	3.0	–136.2	6.98E–07	3.42E–09
KLX21B	318.5–319.5	1.0	–287.7	1.66E–07	1.03E–09
KLX21B	472.6–473.7	1.1	–431.2	5.76E–08	1.56E–10
KLX21B	566.5–569.5	3.0	–519.4	5.03E–07	1.94E–09
KLX21B	591.0–594.0	3.0	–542.2	8.19E–07	2.29E–08
KLX21B	624.5–625.5	1.0	–572.4	4.33E–06	2.75E–09
KLX21B	683.7–684.7	1.0	–627.4	1.43E–07	3.75E–10

***Figure 5-1.** Overview of the Forsmark investigation area.*

The dilution measurements performed within the site investigations using the dilution probe are described in the following reports:

- /Gustafsson and Nordqvist 2005/ (KLX02, KSH02)
- /Gustafsson et al. 2005/ (KFM01A,KFM02A,KFM03A,KFM03B)
- /Gustafsson et al. 2006a/ (KLX03)
- /Gustafsson et al 2006b/ (KFM08A)
- /Gustafsson et al. 2006c/ (KFM04A)
- /Thur et al. 2007a/ (KLX18A)
- /Thur et al. 2007b/ (KFM01D)
- /Thur et al. 2007c/ (KLX11A)
- /Thur and Gustafsson 2007/ (KLX21B)

The most recent results (test campaign no. 3) from the monitoring program are presented in /Wass 2008/ for Forsmark and /Thur 2008/ for Oskarshamn.

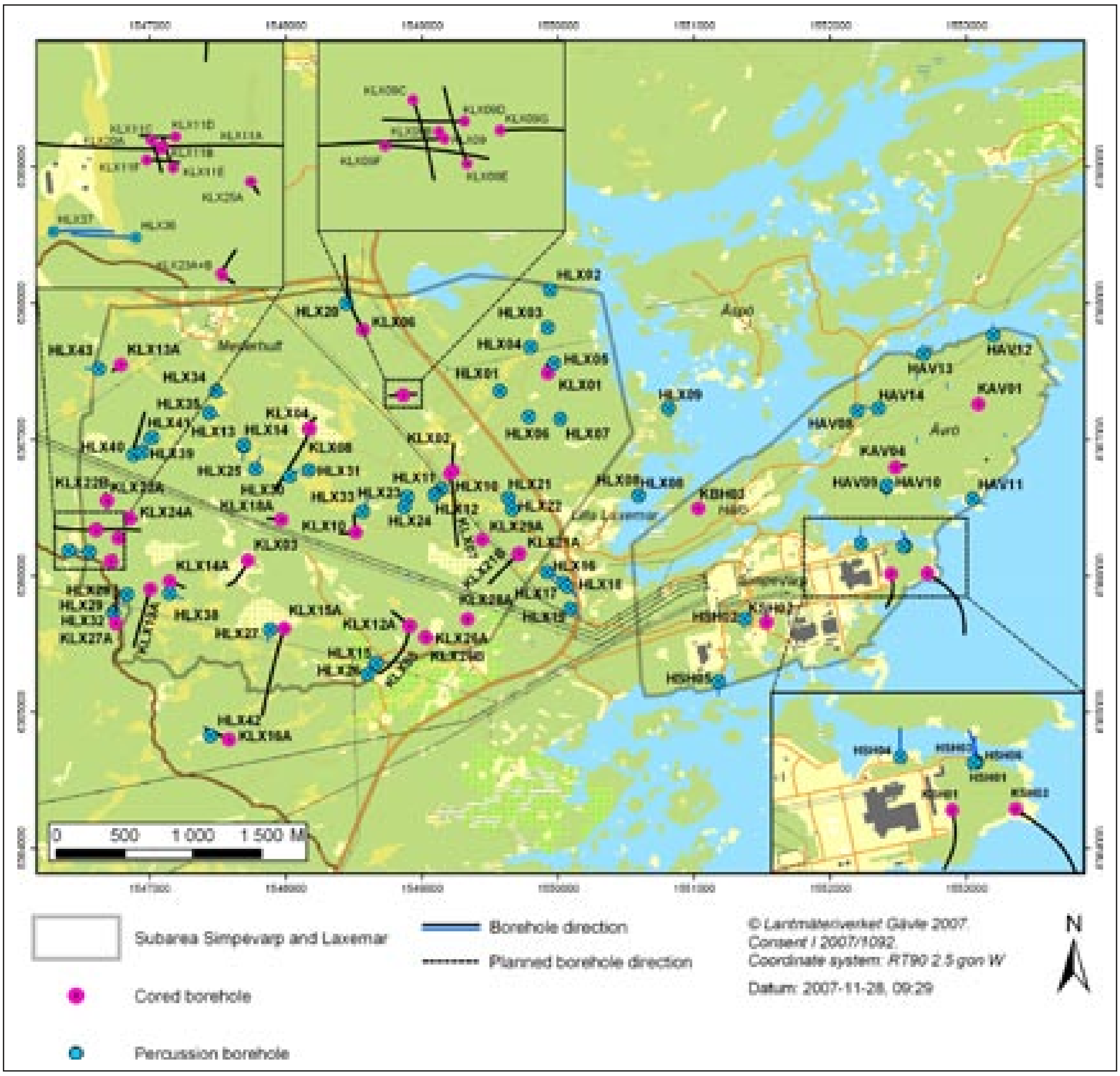


Figure 5-2. Overview of the Oskarshamn investigation area.

As mentioned above, there are some basic differences between the two types of flow measurements regarding the lengths of borehole sections. The measurements with the dilution probe are made in relatively short borehole sections, often with only a one metre long section and at the most in 5 m long sections. In the monitoring sections, sections lengths are generally considerably longer, often tens of metres long and with a largest value of 57 m in one section in Oskarshamn. The distributions of section length for each site are shown in Figure 5-3.

Figure 5-3 shows clearly that the probe measurements predominantly are made in short sections, up the 5 metres long at the most. The monitoring sections are significantly longer and none are shorter than 4 metres. This pattern is similar for both of the sites; the only difference between the sites is that the longest sections are found in boreholes at Oskarshamn.

The corresponding distributions of mid-section elevations are shown in Figure 5-4. Most of the measurements at both sites are made down to depths at about –600 to –700 m.a.s.l. Below this, there are only a few measurements at each site. In this case, there is no obvious difference between the probe measurements and the monitoring program with regard to measurement depth distribution. However, measurements closest to the ground surface are predominantly made in monitoring program sections.

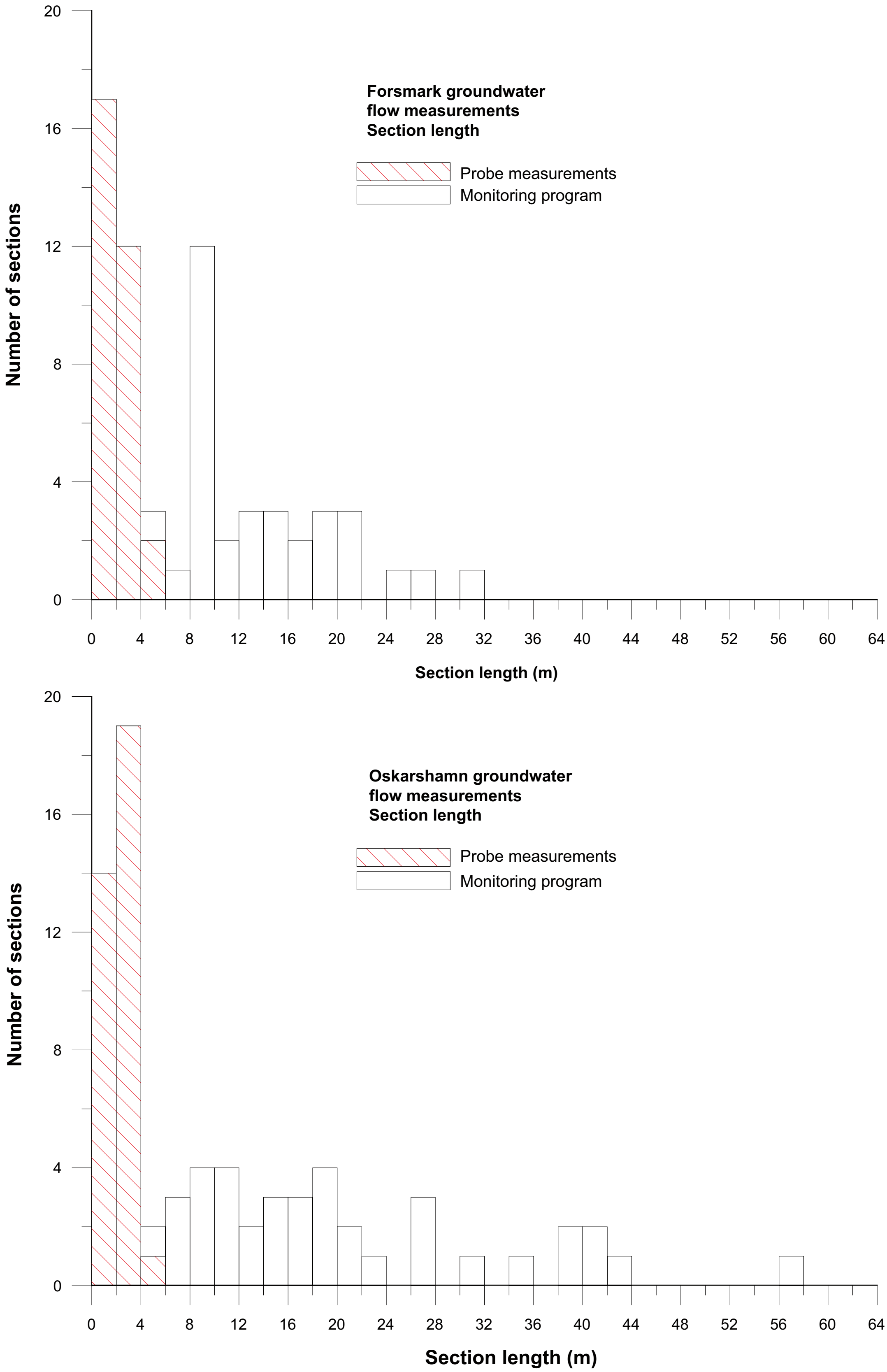


Figure 5-3. *Distribution of section lengths in Forsmark (top) and Oskarshamn (bottom).*

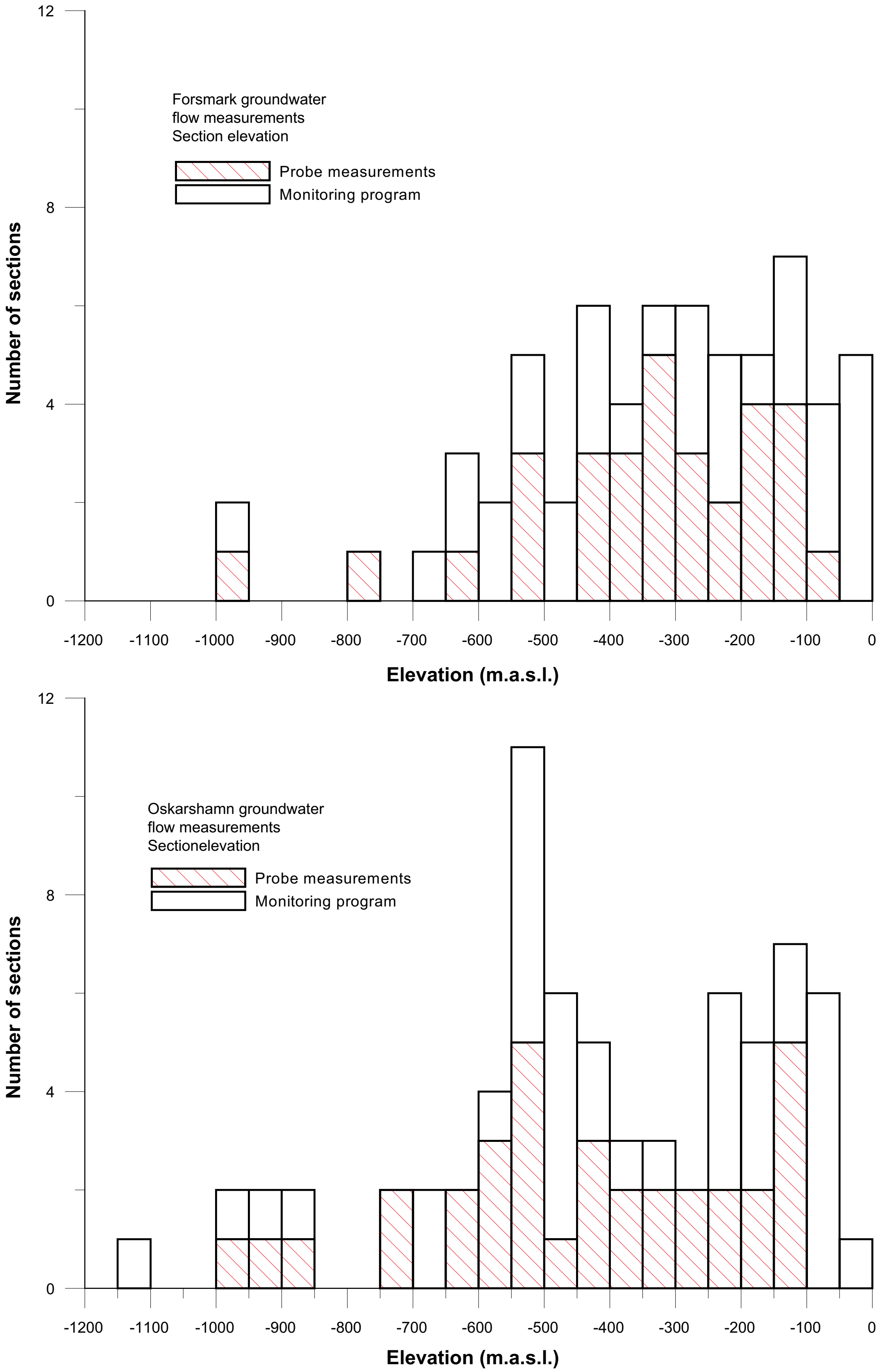


Figure 5-4. *Distribution of mid-section elevation in Forsmark (top) and Oskarshamn (bottom).*

The distributions of transmissivity values, obtained from single-hole hydraulic tests, are shown in Figure 5-5. There are no obvious differences between the two main types of measurement regarding the transmissivity distributions, possibly with the exception that the highest values are found in monitoring sections. The distributions at each site may be considered to be somewhat log-normally distributed although data are sparse. The log-normal fits give similar results for the both sites, although there appears to be a somewhat broader distribution of transmissivity values in Forsmark.

Although the transmissivity in sections for groundwater flow measurements is not the primary focus for this investigation, it may be interesting to characterise the transmissivity values somewhat further. Scatter plots for the $\log_{10}$ of the transmissivity vs. section length are showed in Figure 5-6. Figure 5-6 shows no clear correlation between the transmissivity and test section length.

In Figure 5-7, transmissivity is plotted against mid-section elevation, which is of interest because of the expected depth-dependence for transmissivity. In this case, there is some correlation with elevation although there also is considerable variability in transmissivity values. For both sites, there is a weak tendency to find fewer values with high transmissivity with increasing depth. For Forsmark, one can also observe that all of the surface-near sections show relatively high transmissivity.

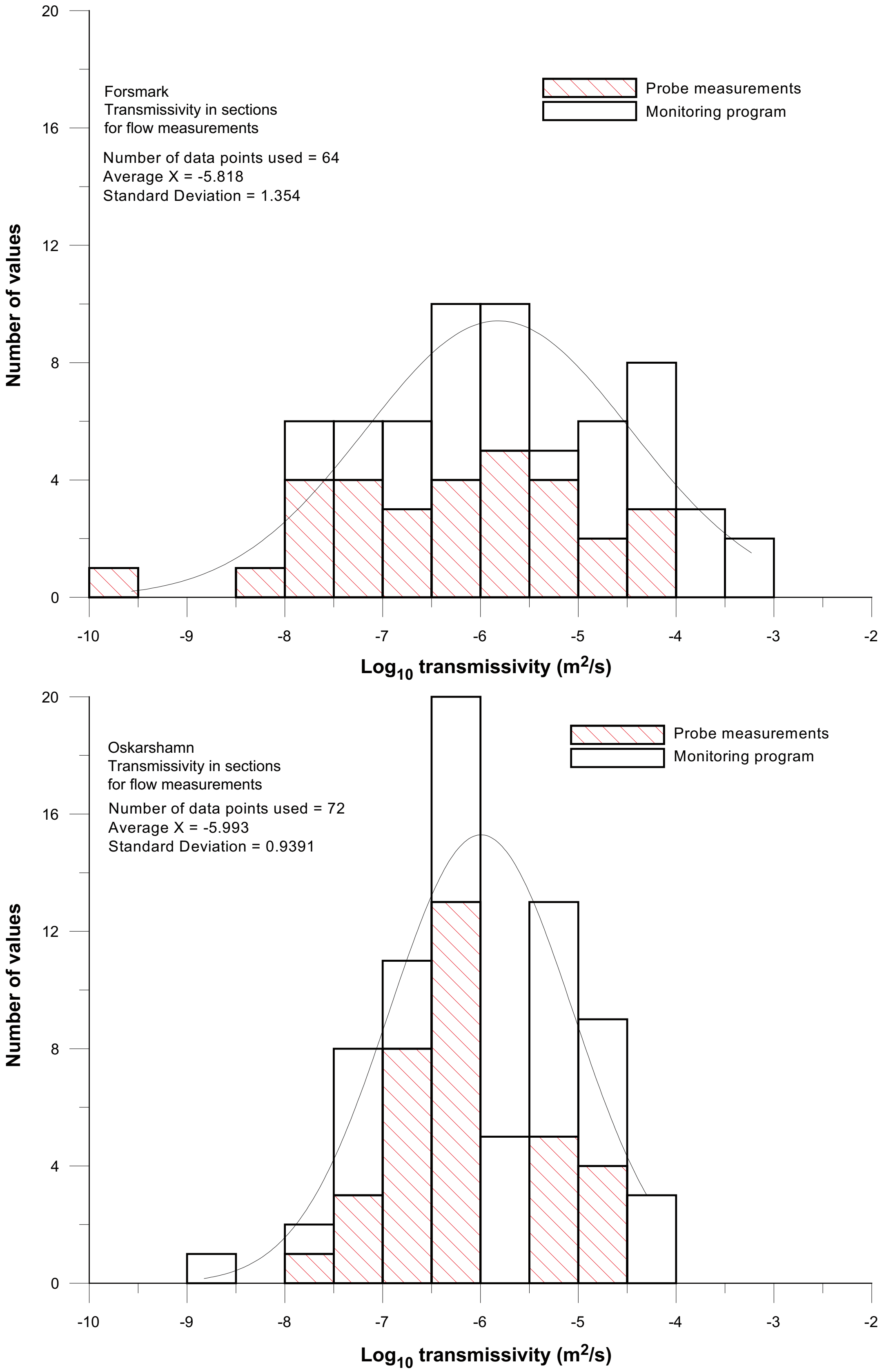


***Figure 5-5.** Distribution of transmissivity in Forsmark (top) and Oskarshamn (bottom) in section used for tracer dilution measurements.*

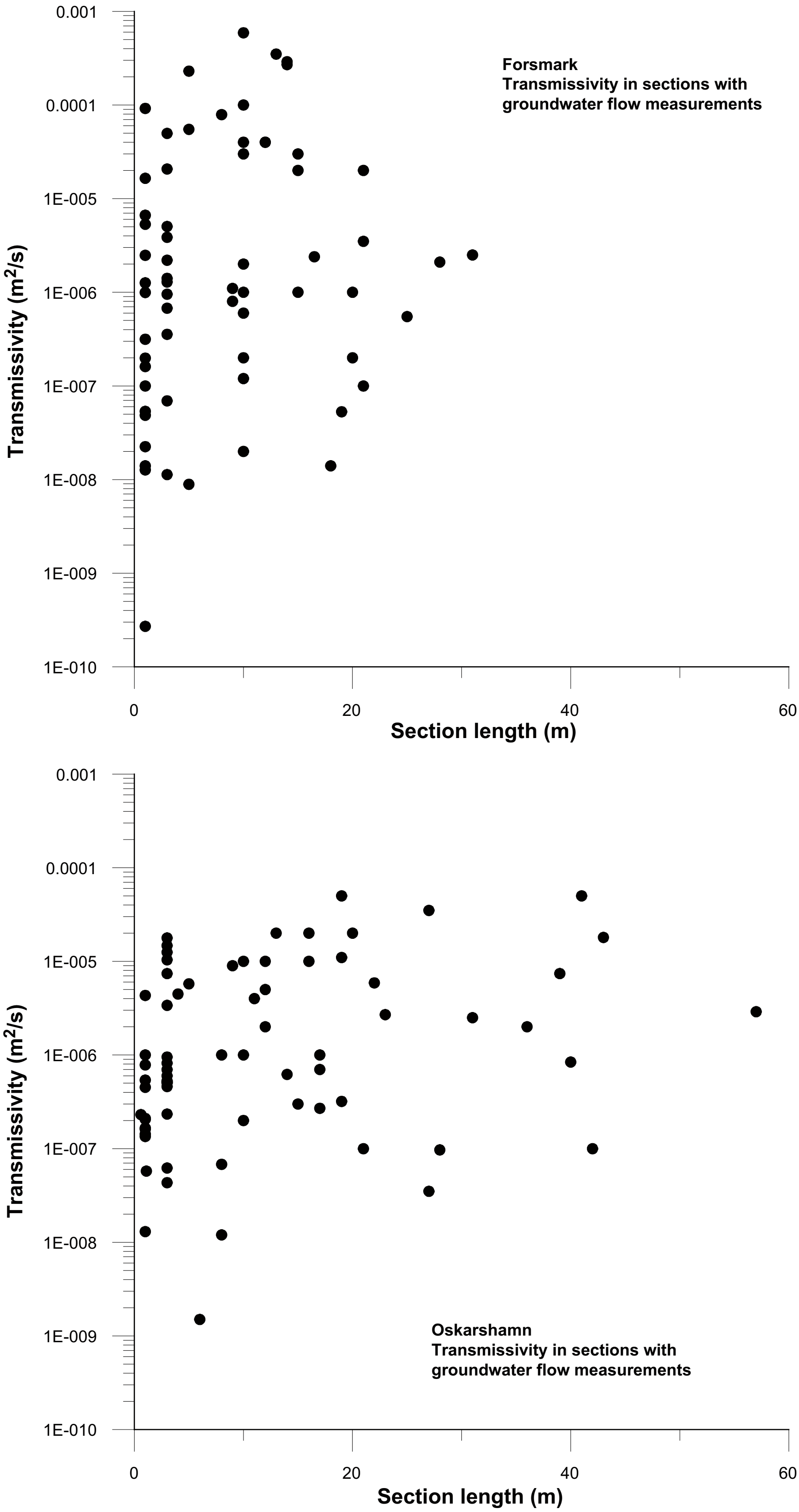


__Figure 5-6.__ Transmissivity vs. section length for Forsmark (top) and Oskarshamn (bottom).

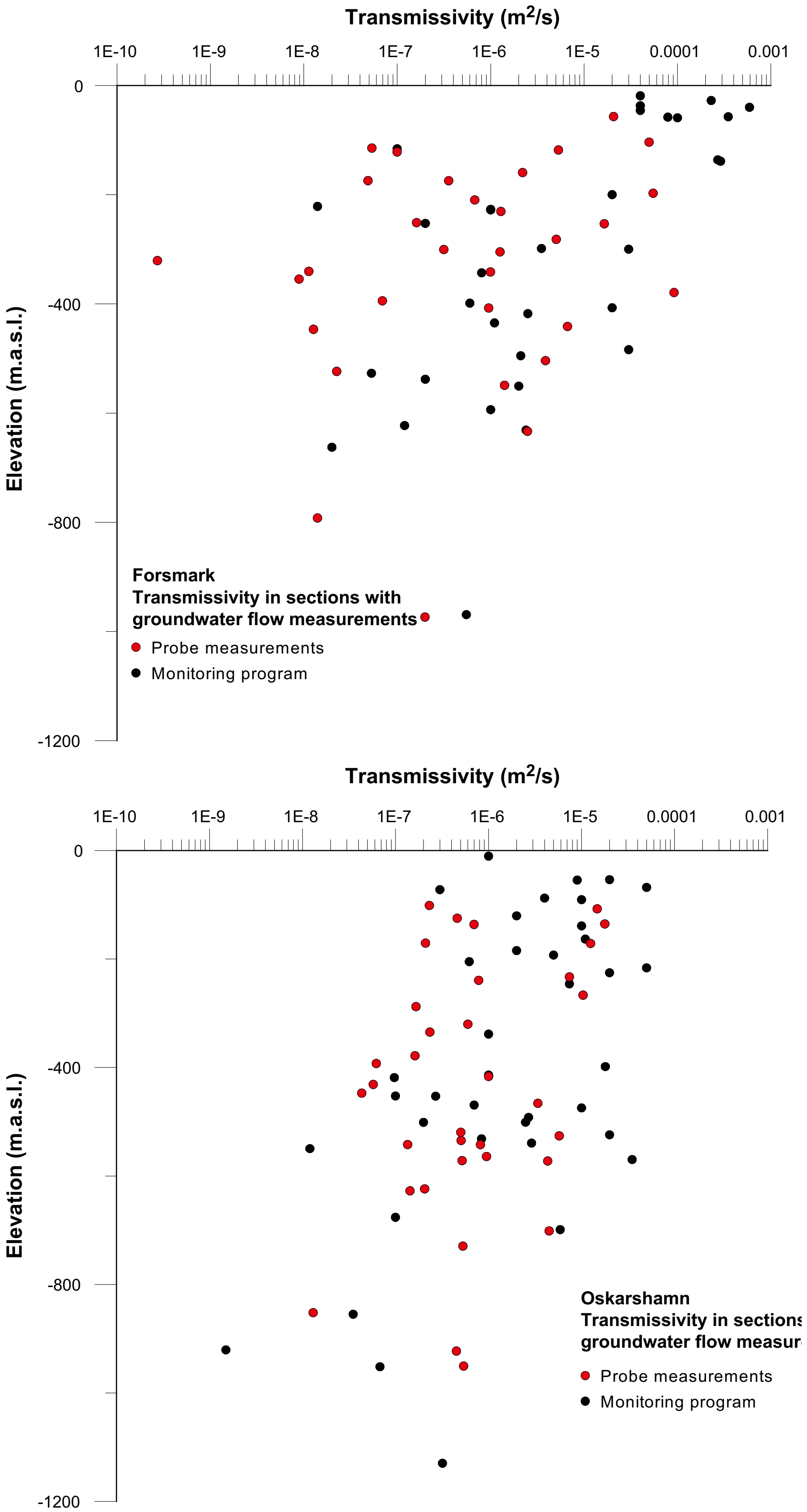


Figure 5-7. *Transmissivity vs. section mid-point elevation for Forsmark (top) and Oskarshamn (bottom).*

6 Analysis of groundwater flow under natural conditions in Forsmark and Oskarshamn

6.1 General approach

The basic approach to the analysis presented in this chapter is to examine overall properties and relationships in the experimental data. With the combined data from dilution probe and monitoring program dilution measurements, there is a fairly large number of measurements available for each site and it might be possible to identify general trends and patterns in the data.

The analysis herein does not involve detailed examination of individual boreholes or zones. However, in some of the plots presented below, data have been sorted according to current classification into deformation zones and fracture domains, as available in the SICADA database and /Follin et al. 2007/. The term deformation zone (DZ) refers to an essentially two-dimensional structure with a concentration of brittle and/or ductile deformation /Follin et al. 2007/. The deformation zones are denoted ZFMxxx and ZSMxxx for Forsmark and Oskarshamn, respectively.

The rock volume outside the deformation zones are classified into fracture domains, which refer to rock volumes in which rock units show similar composition, grain size, degree of bedrock heterogeneity and degree and style of ductile deformation. The fracture domains in Forsmark are denoted FFmxxx, while the fracture domains in Oskarshamn are denoted FSM_xxx. The concept of deformation zones and fracture domains forms a basis for geological and hydrogeological modelling of the sites.

The most important supporting data in this report consist of transmissivity values for the tested borehole sections, as the transmissivity is used for estimating the hydraulic gradient across the section. The transmissivity values presented herein are the values that were available at the time for evaluating and reporting the hydraulic gradients from the borehole dilution measurements. These transmissivity values are in many cases preliminary and may have been modified in later analyses. Further, hydraulic testing for estimation of transmissivity has generally not been carried out in the exact same section intervals as have been used for the dilution measurements. Estimates of the transmissivity for the dilution sections have in those cases instead been obtained by summation of transmissivities from smaller intervals or flow anomalies contained within the section for the dilution measurement.

Depending on availability, the transmissivity values that, so far, have been used to evaluate the dilution measurements are based on either flow logging (PFL, HTHB) or transient hydraulic injection tests (PSS). The flow logging methods are carried out in open boreholes. Transmissivity values from PFL are typically estimated after several day of pumping, while the HTHB (used in percussion-drilled boreholes) typically uses a pumping period of a few hours. The PSS measurements are even shorter, typically around 20 minutes of water injection. Another significant difference is that during PFL and HTHB measurements, the entire borehole represent a hydraulic line sink, while the PSS measurements are in packed-off sections and more resembles a hydraulic point source.

The importance of relevant transmissivity estimates for estimation of hydraulic gradients is further discussed in section 7.2.

6.2 Forsmark dilution measurements

6.2.1 Groundwater flow

The distribution of the measured groundwater flow rates ($\log_{10}$) in Forsmark is shown in Figure 6-1. The measured flows conform fairly well to a log-normal distribution, with a fitted average value of about –8.2, corresponding to a flow value of about 6×10^{-9} m^3/s. The standard deviation of the log values is about 1.

There is a very clear difference between measurements with the dilution probe and the measurements in the monitoring program. Higher flow values are found in the monitoring sections, while low values then to be found among the dilution probe measurements. This difference might indicate that measured flow rates are, at least partly, dependent on the section length. A scatter point of log flow rates vs. section length is shown in Figure 6-2. This figure indicates some correlation between flow rates and section length although the variability appears to be about 2-3 orders of magnitude for any given flow rate. The apparent dependence on section length may probably be contributed to a combination of factors. In Forsmark, many of the longer monitoring sections are located in relatively shallow rock with higher transmissivity (see Figure 5-7).

Measured flow rates vs. mid-section elevation is shown in Figure 6-3. The data points are in this plot classified into deformation zones and fracture domains, as described above. Due to its hydrogeological importance in the Forsmark area, deformation zone A2 is labelled separately.

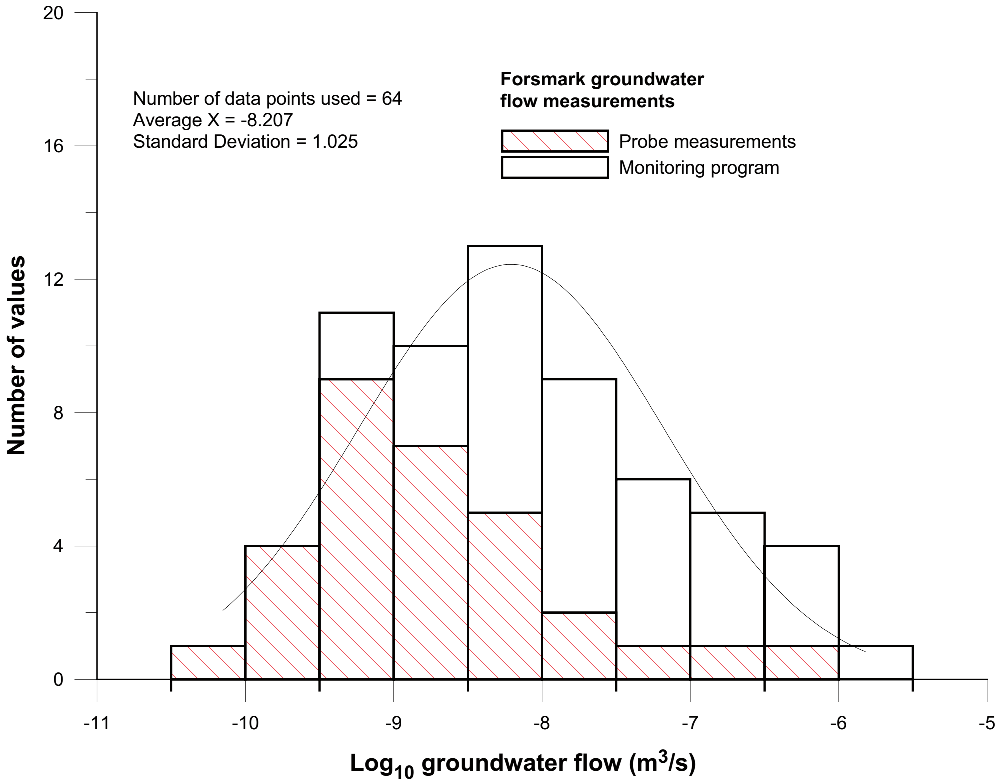


Figure 6-1. Histogram of groundwater flow in Forsmark measured with the tracer dilution method. The data are fitted to a normal distribution.

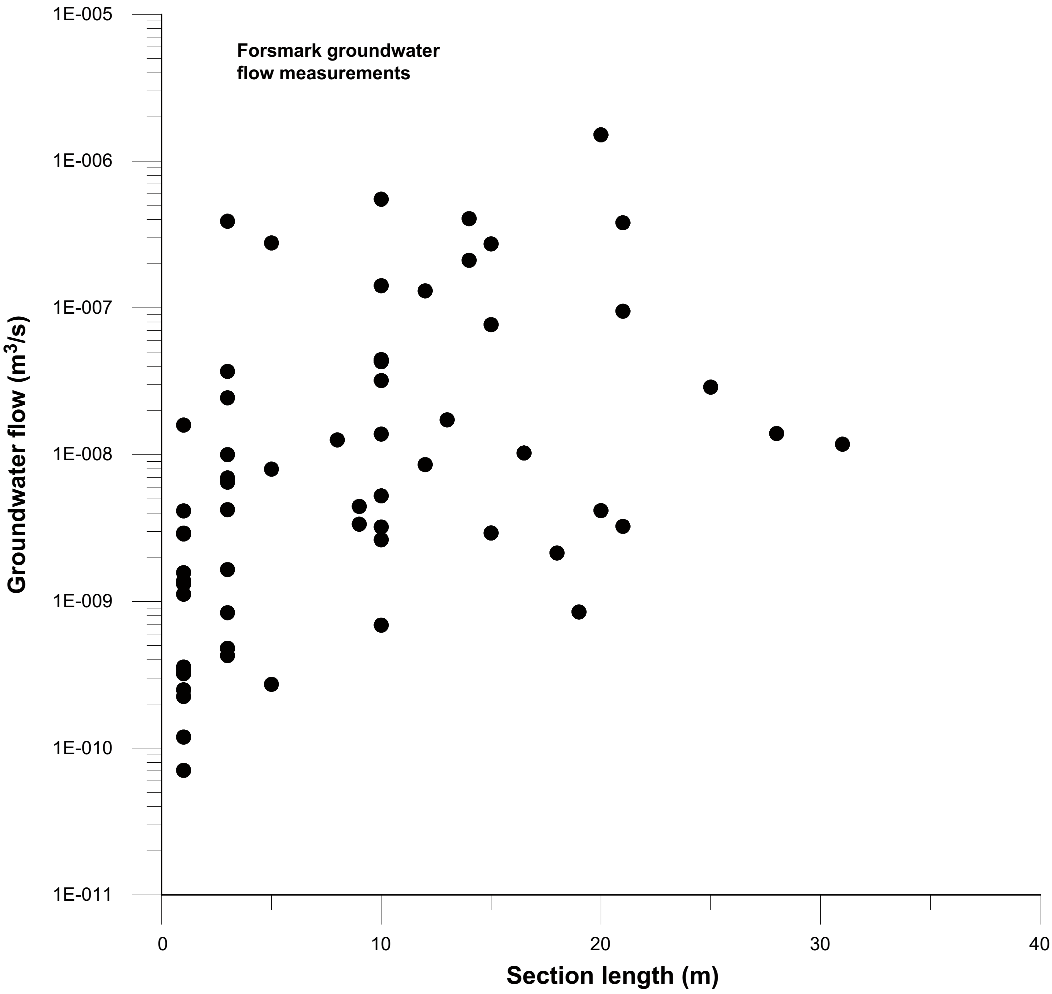


Figure 6-2. *Groundwater flow rate vs. section length for dilution measurements in Forsmark.*

Figure 6-3 shows clearly that high groundwater flow rates are predominantly found in deformation zones, and vice versa although there are some low flow rates also in deformation zones. All but one of the measured sections in zone A2 has flow rates roughly between 10^{-8} and 10^{-6} m^3/s. The A2 section with a low flow rate might not be representative as it is very close to fracture domain FFM03.

Figure 6-3 does, however, not show any clear indication of depth-dependence for the measured groundwater flow rates.

Another potential correlation of interest is between flow rate and transmissivity. Although the measured flow rate also depends on the local hydraulic gradient, one might expect a general dependence on the transmissivity of the tested section. Figure 6-4 shows a log-log plot of flow rate vs. transmissivity for all of the measured sections.

In this case there is a clear correlation between flow rates and transmissivity and a fitted line (based on all points) is shown in Figure 6-4. The spread around the line is roughly 2 orders of magnitude.

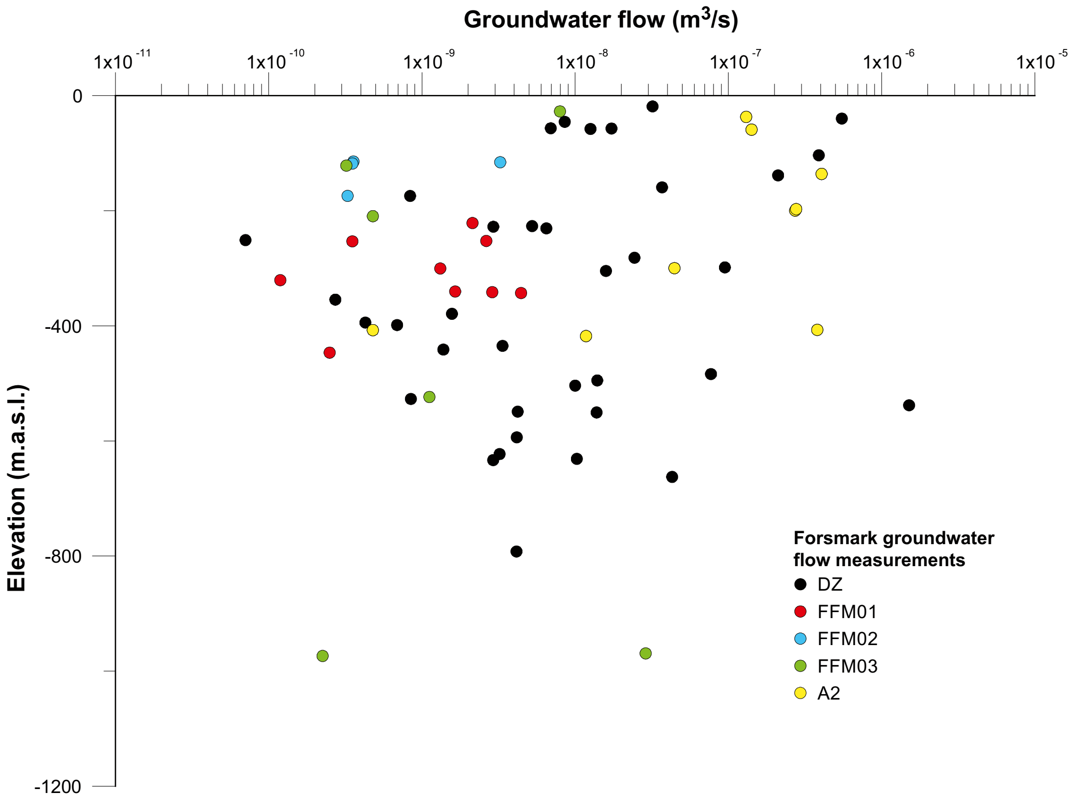


Figure 6-3. Groundwater flow vs. mid-section elevation for dilution measurements in Forsmark. Plotted points are classified into deformation zones and fracture domains.

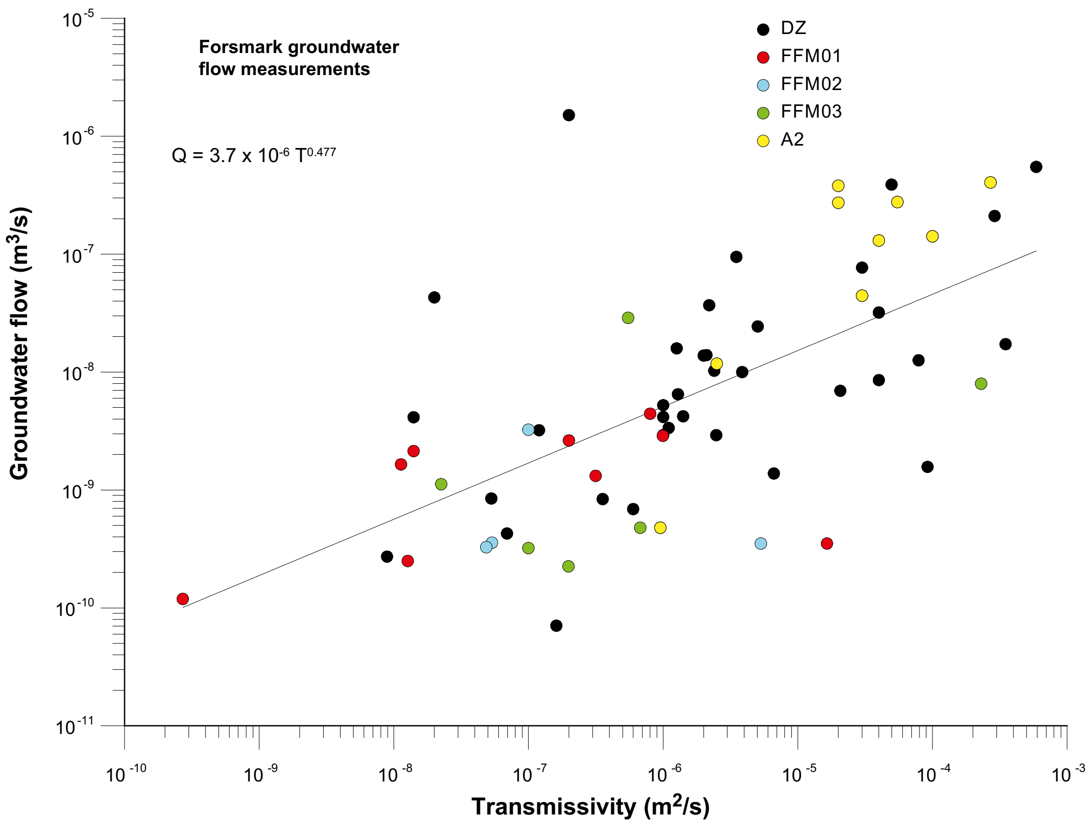


Figure 6-4. Groundwater flow vs. transmissivity for dilution measurements in Forsmark. Plotted points are classified into deformation zones and fracture domains.

6.2.2 Darcy velocity

The Darcy velocity, or specific discharge, is calculated by taking the measured groundwater flow through the borehole section and multiply by the section length and an assumed flow width based on flow convergence around the borehole. Thus, this number represents flow across a thought area defined along the entire section length. However, the flow is not homogenously distributed along the borehole section, but concentrated to the flowing fractures and therefore the Darcy velocity is not directly applicable to the flowing features.

The Darcy velocity distribution for Forsmark is shown in Figure 6-5.

6.2.3 Hydraulic gradients

Hydraulic gradients obtained in the field are of considerable interest for transport modelling at the sites. As discussed above, the gradients are not measured directly but calculated from measured groundwater flows through the section and from transmissivities obtained from single hole hydraulic tests (see Equation 3-5). The calculated gradient should be considered a local one. If the measured flows and estimated transmissivities are representative for the naturally flowing fracture(s), then the calculated gradient should be a relatively good estimate of the local gradient around the measured section.

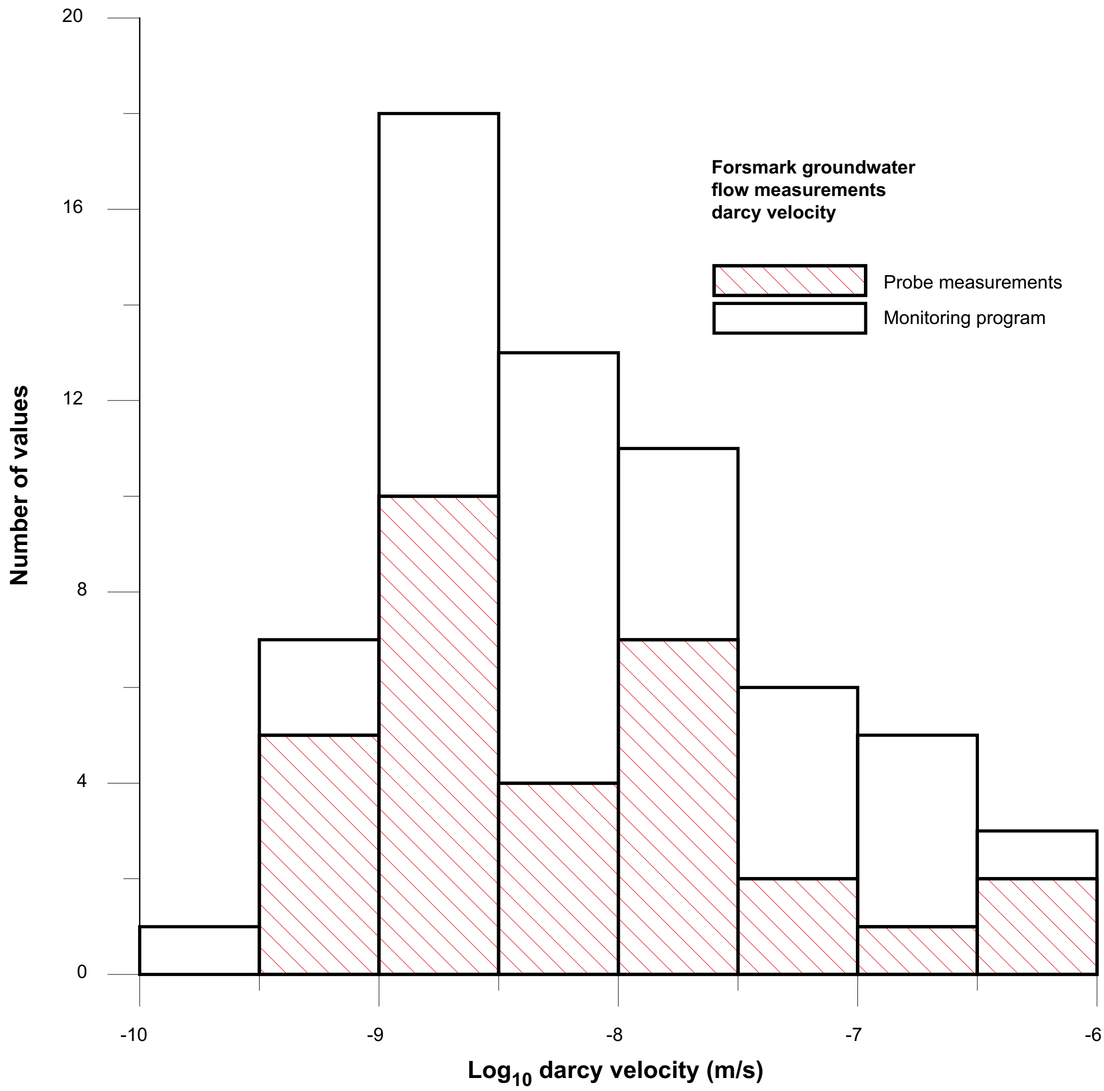


Figure 6-5. *Histogram of calculated Darcy velocities for Forsmark.*

The distribution of calculated gradients in Forsmark is shown in Figure 6-6. This shows that most of the gradients are in the interval 0.01 to 0.1. Some of the gradients are very low, primarily a result of high transmissivity estimates. A few of the gradients have unrealistically high values. At least one of these very high values may be considered uncertain due to pump malfunction during the dilution test.

There does not appear to be any particular bias due to measurement method (dilution probe or monitoring program). The distribution of the gradients appear to be approximately log-normally distributed. Hydraulic gradients will be discussed further later in the report.

Hydraulic gradients are plotted against mid-section elevation in Figure 6-7. Although there is considerable variability, there is apparently some depth-dependence for the hydraulic gradients. Primarily, the low gradients tend to be found in the more surface-near borehole sections, most of them associated with deformation zones. Apart from the shallow measurement points, there does not appear to be any significant depth-dependence.

Hydraulic gradients are plotted (log-log) against transmissivity in Figure 6-8. This of interest because it is to some extent reasonable to expect higher gradients in areas of lower transmissivity. Indeed, Figure 6-8 shows a fairly clear relationship between gradients and transmissivity and in the figure a straight line is fitted. The spread around the fitted line appears to be about two orders of magnitude. One may also note that most of the points with low gradients and high transmissivities are from deformation zones.

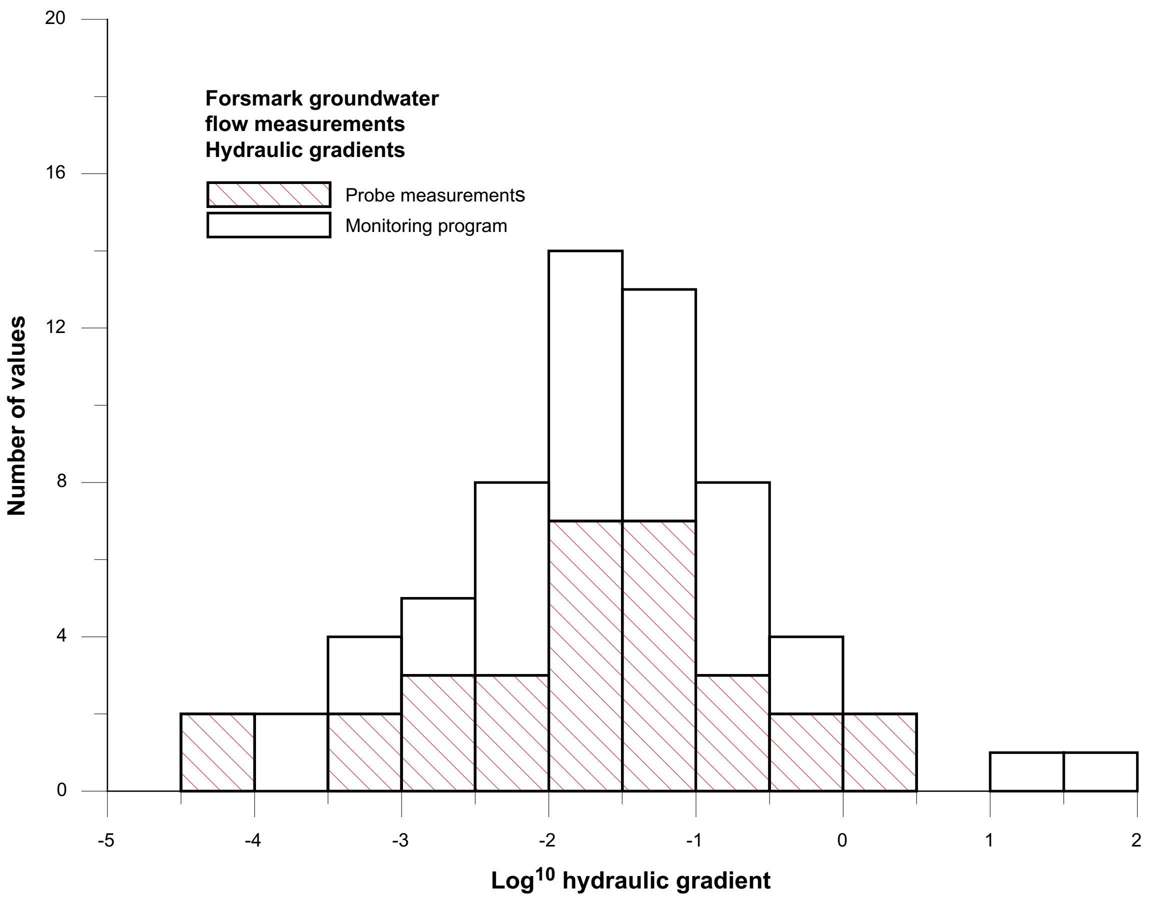


Figure 6-6. *Histogram of hydraulic gradients based on groundwater flows estimated with the dilution method and transmissivity values estimated from single-hole hydraulic tests.*

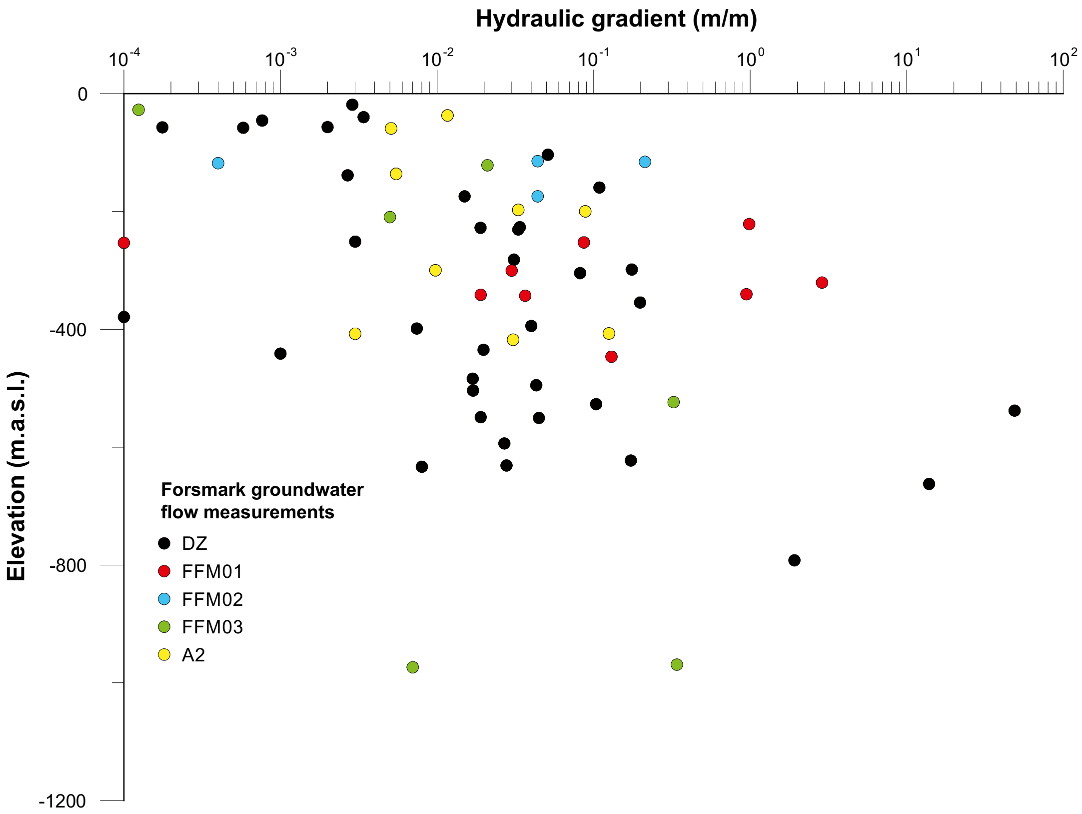


Figure 6-7. *Hydraulic gradient vs. mid-section elevation for dilution measurements in Forsmark. Plotted points are classified into deformation zones and fracture domains.*

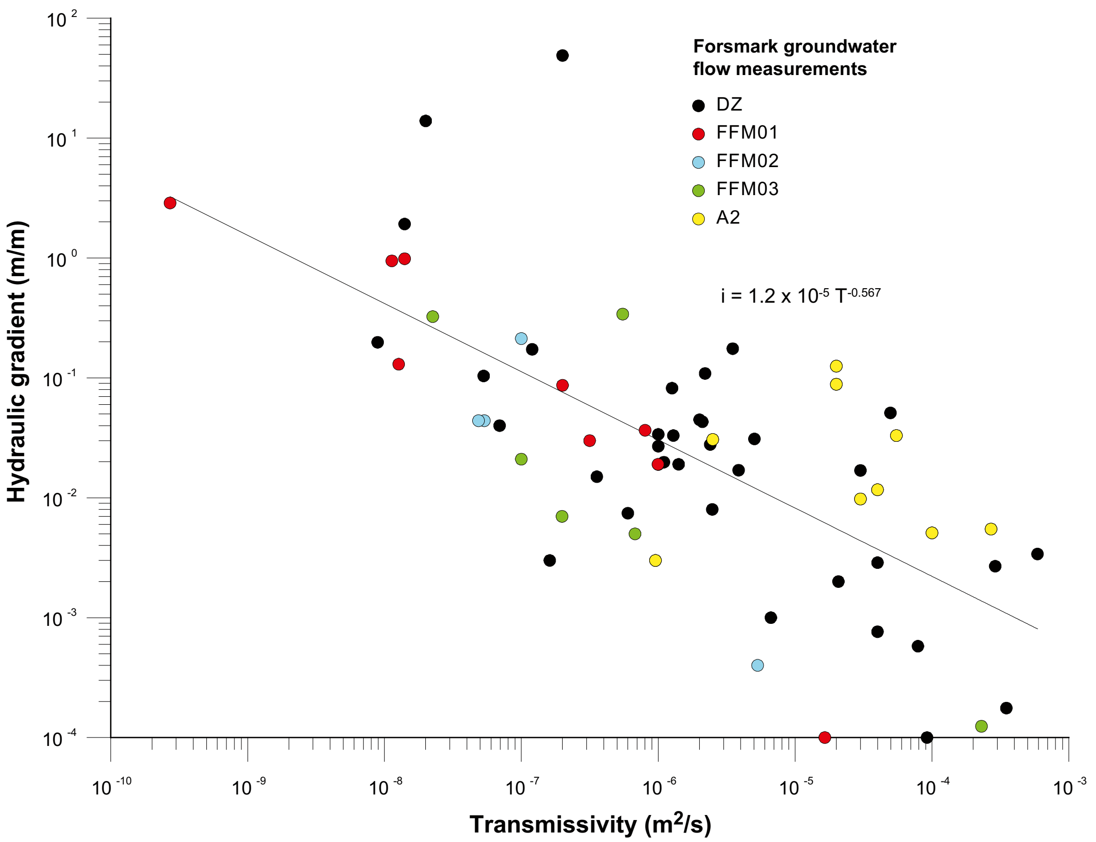


Figure 6-8. *Hydraulic gradient vs. transmissivity for dilution measurements in Forsmark. Plotted points are classified into deformation zones and fracture domains.*

The number of interpreted flowing fractures varies from a single fracture to tens of fractures among the tested borehole sections. In order to see whether this has any effects on the calculated gradients, the gradient is plotted against the number of flowing fractures in Figure 6-9. Although there are only a few sections with many flowing fractures, there appears to be a possibility that the variability in hydraulic gradient decreases with increasing number of flowing fractures. This could be reasonable if a larger number of flowing fractures have a smoothing effect so that the calculated gradient across the borehole sections tends to be closer to some overall larger-scale gradient.

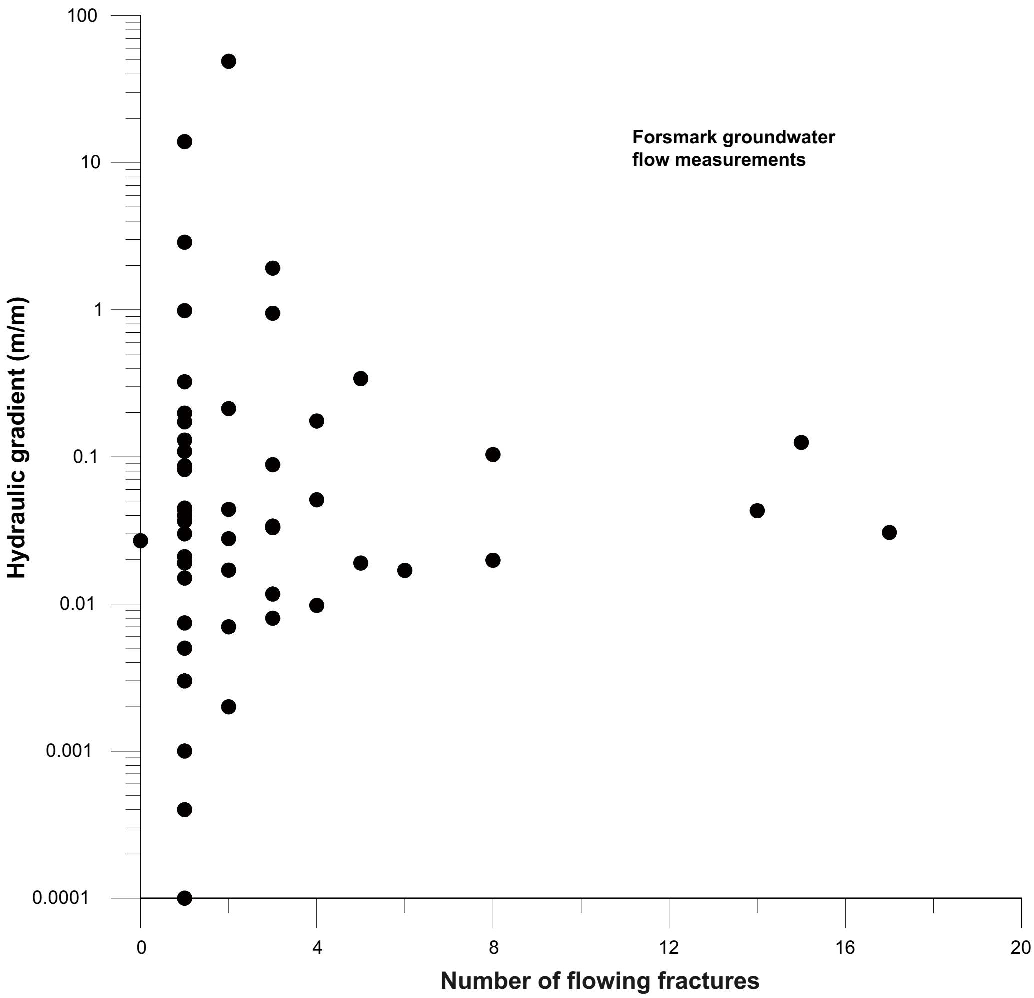


Figure 6-9. Hydraulic gradient vs. number of flowing fractures, excluding sections in percussion-drilled boreholes.

6.3 Oskarshamn dilution measurements

6.3.1 Groundwater flow

The distribution of the groundwater flow measurements ($\log_{10}$) in Oskarshamn is shown in Figure 6-10. The measured flows conform fairly well to a log-normal distribution, with a fitted average value of about –8.0, corresponding to a flow value of about 1×10^{-8} m^3/s. The standard deviation of the log values is about 0.9. The fitted statistics do not indicate any significant difference compared with the Forsmark flow measurements.

There is a clear difference between measurements with the dilution probe and the measurements in the monitoring program. Higher flow values are found in the monitoring sections, while low values tend to be found among the dilution probe measurements. This difference might indicate that measured flow rates are, at least partly, dependent on the section length. A scatter point of log flow rates vs. section length is shown in Figure 6-11. This figure indicates some correlation between flow rates and section length although the variability appears to be about 2-3 orders of magnitude for a given flow rate. Although there are not so many long sections, the figure gives the appearance of some type of increasing "lower bound" with increasing section length, and possibly also less variability with increasing section length.

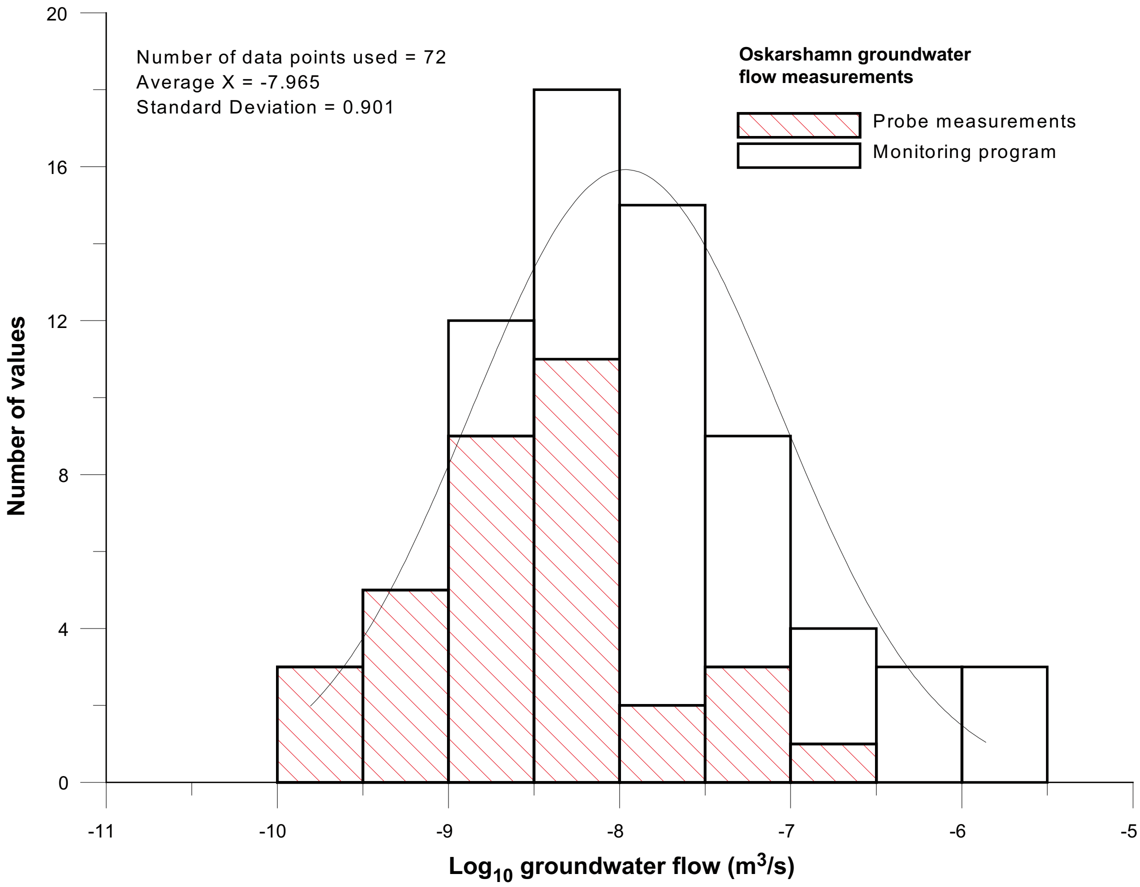


Figure 6-10. Histogram of the logarithm of groundwater flow in Oskarshamn measured with the tracer dilution method. The data are fitted to a normal distribution.

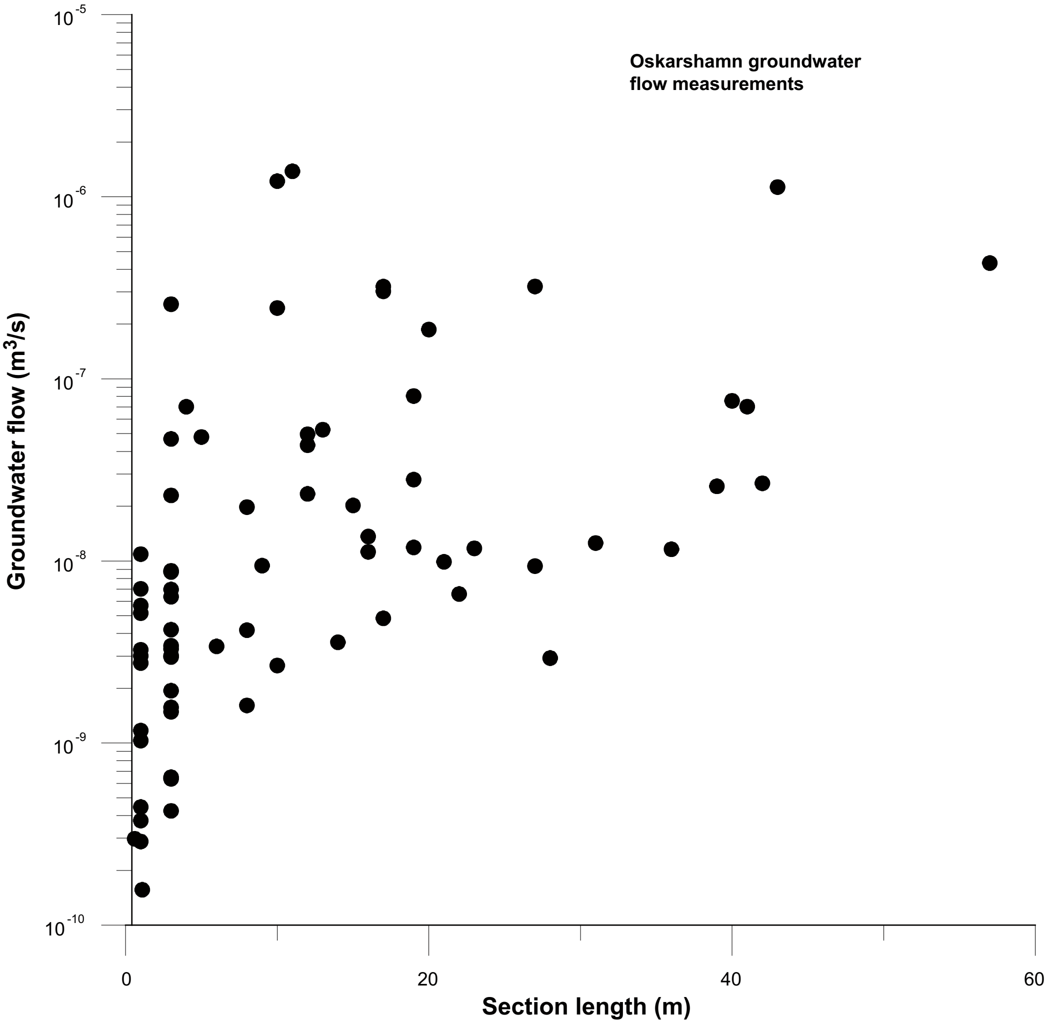


__Figure 6-11.__ Groundwater flow vs. section length for dilution measurements in Oskarshamn.

Measured flow rates vs. mid-section elevation is shown in Figure 6-12. The data points are in this plot classified into deformation zones and fracture domains, as described in section 6.1.

In contrast to the Forsmark flow measurements, Figure 6-12 does not show any obvious differences between measurement in deformation zones and in fracture domains. A weak depth-dependence may be noted, seen as a tendency to find fewer high flow rates with increasing depth.

Another potential correlation of interest is between flow rate and transmissivity. Although the measured flow rate also depends on the local hydraulic gradient, one might expect a general dependence on the transmissivity of the tested section. Figure 6-13 shows a log-log plot of flow rate vs. transmissivity for all of the measured sections.

In this case there is a clear correlation between flow rates and transmissivity and a fitted line (based on all points) is shown in Figure 6-13. The spread around the fitted line is roughly about two orders of magnitude.

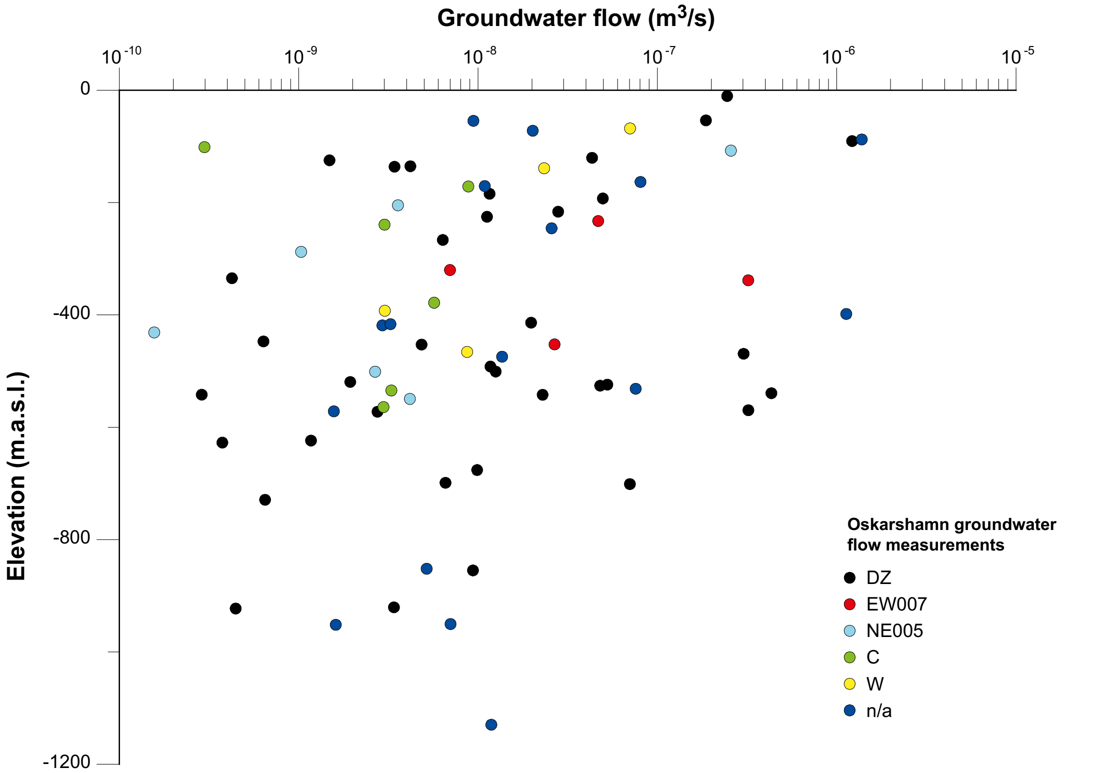


Figure 6-12. *Groundwater flow vs. mid-section elevation for dilution measurements in Oskarshamn. Plotted points are classified into deformation zones and fracture domains. For some of the data points, noclassification is yet available.*

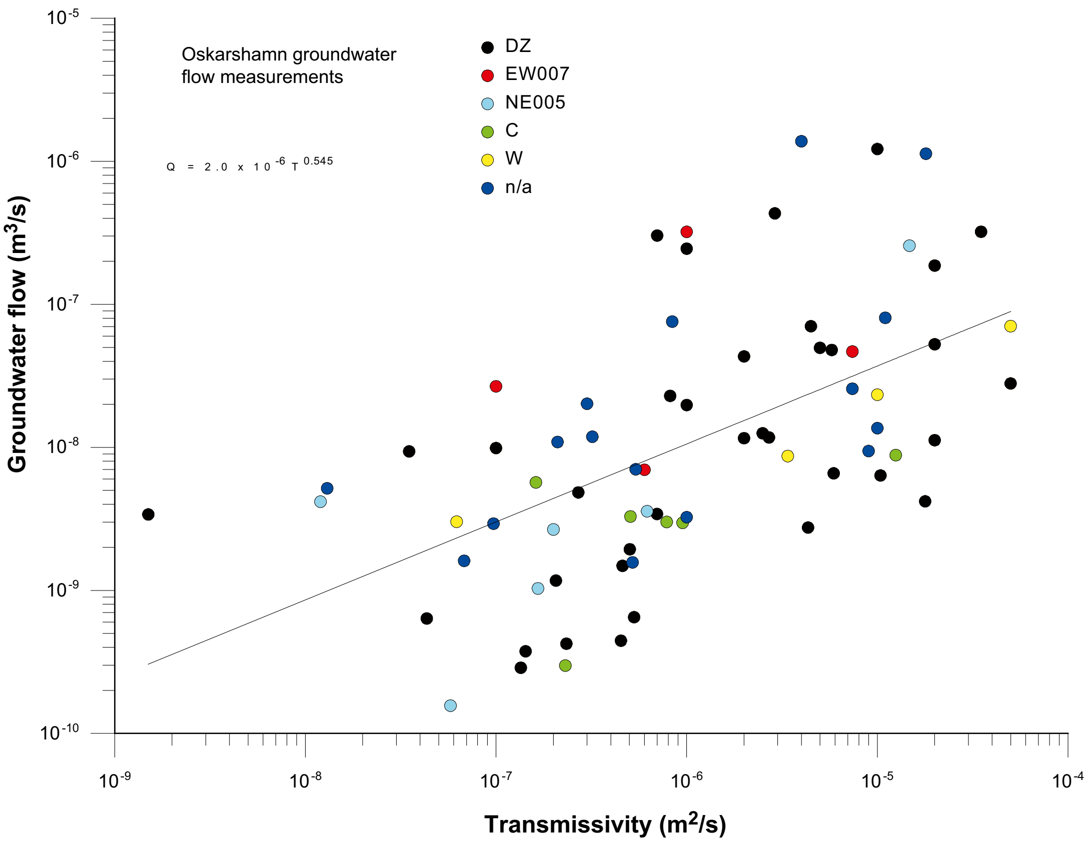


Figure 6-13. *Groundwater flow vs. transmissivity for dilution measurements in Oskarshamn. Plotted points are classified into deformation zones and fracture domains. For some of the data points, no classification is yet available.*

6.3.2 Darcy velocity

The Darcy velocity, or specific discharge, is calculated by taking the measured groundwater flow through the borehole section and multiply by the section length and an assumed flow width based on flow convergence around the borehole. Thus, this number represents flow across a thought area defined along the entire section length. However, the flow is not homogenously distributed along the borehole section, but concentrated to the flowing fractures and therefore the Darcy velocity is not directly applicable to the flowing features.

The Darcy velocity distribution for Oskarshamn is shown in Figure 6-14.

6.3.3 Hydraulic gradient

Hydraulic gradients obtained in the field are of considerable interest for transport modelling at the sites. As discussed above, the gradients are not measured directly but calculated from measured groundwater flows through the section and from transmissivities obtained from single hole hydraulic tests (see Equation 3-5). The calculated gradient should be considered a local one. If the measured flows and estimated transmissivities are representative for the naturally flowing fracture(s), then the calculated gradient should be a relatively good estimate of the local gradient around the measured section.

The distribution of calculated gradients in Oskarshamn is shown in Figure 6-15. This shows a fairly wide spread in the interval of about 0.003 to 3. Several of the calculated gradients are large (on the order of 1 and larger) which may be considered un-realistic.

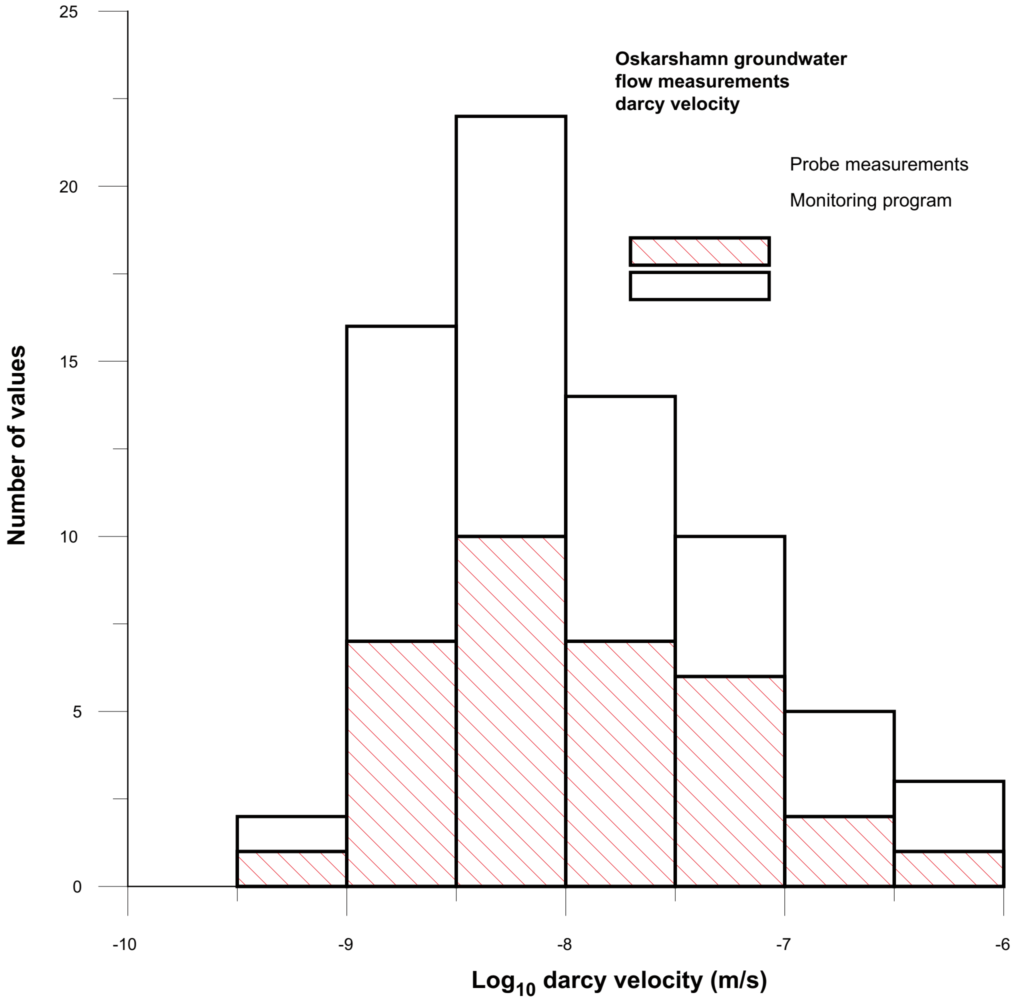


Figure 6-14. *Histogram of calculated Darcy velocities for Oskarshamn.*

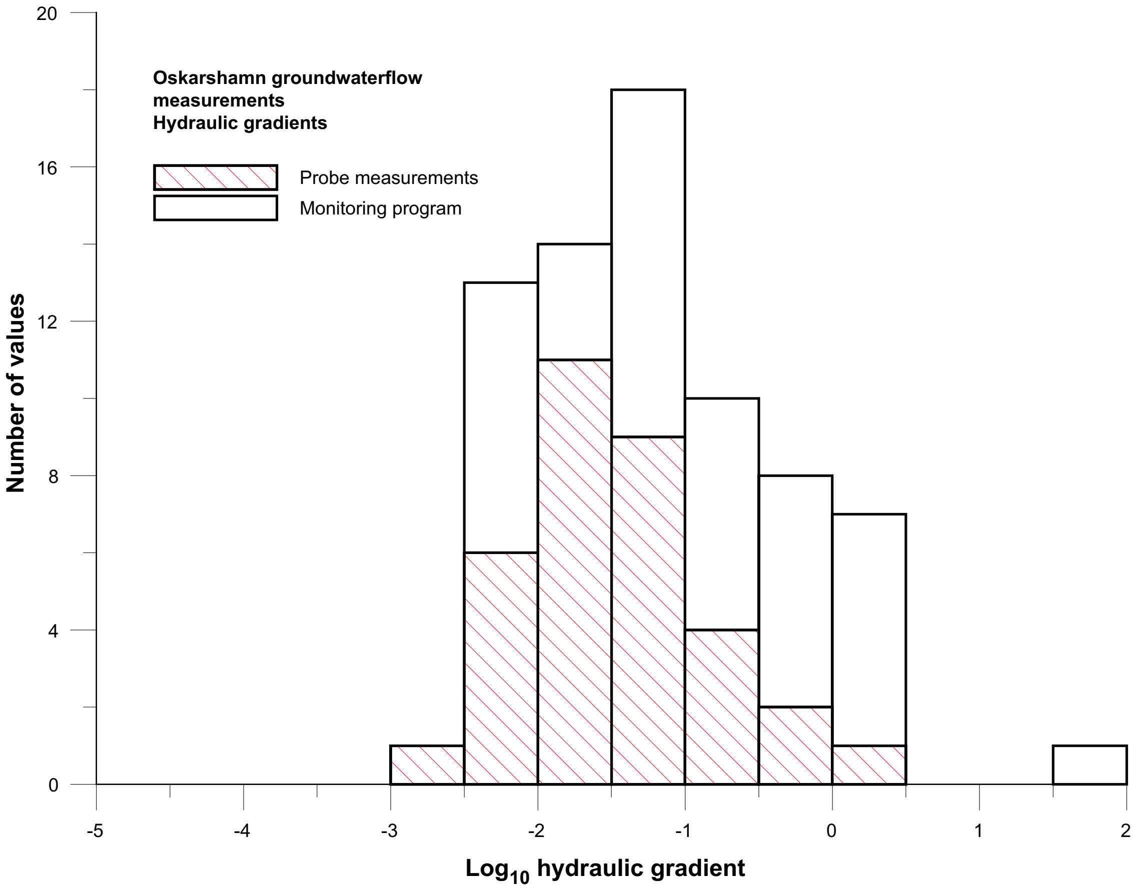


Figure 6-15. *Histogram of hydraulic gradients based on groundwater flows estimated with the dilution method and transmissivity values estimated from single-hole hydraulic tests.*

There may be a small bias due to measurement method (dilution probe or monitoring program) with lower values for the dilution probe and vice versa. The distribution of the gradients appears to be approximately log-normally distributed. Hydraulic gradients are discussed further later in this report.

Hydraulic gradients are plotted against mid-section elevation in Figure 6-16. As indicated above, there is considerable variability in the hydraulic gradients. There does not seem to be any significant correlation between gradient and elevation and the variability appears to be about the same irrespective of elevation. Further, there is no visible difference between measurements in deformation zones and fracture domains, respectively.

Hydraulic gradients are plotted (log-log) against transmissivity in Figure 6-17. This is of interest because it is to some extent reasonable to expect higher gradients in areas of lower transmissivity. Indeed, Figure 6-17 shows a fairly clear, but less so than for Forsmark, relationship between gradients and transmissivity and in the figure a straight line is fitted. The spread around the fitted line appears to be about 2-3 orders of magnitude. One may also note that there is no visible distinction between measurements in deformation zones and fracture domains, respectively.

For the Forsmark data, the variability in calculated gradients appeared to decrease with increasing number of flowing fractures in the borehole section (Figure 6-9). The corresponding plot for Oskarshamn is shown in Figure 6-18. Although the largest variability appears to be for sections with few flowing fractures, the overall impression is not as clear as for the Forsmark data.

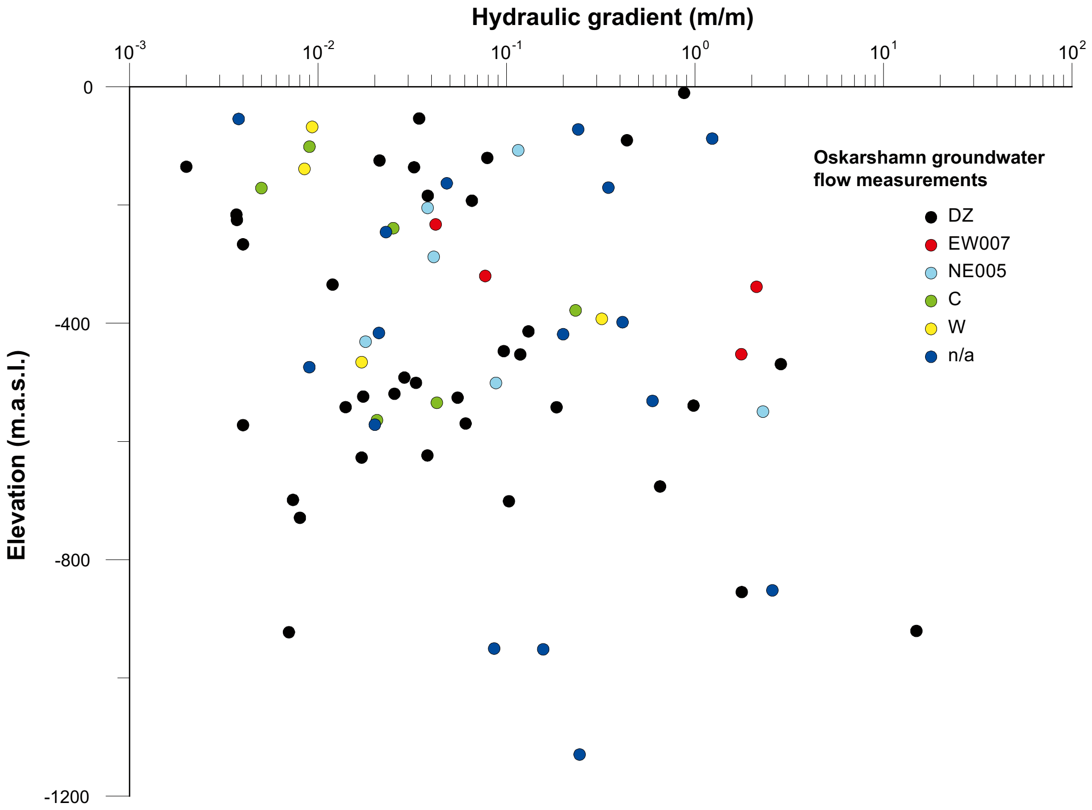


Figure 6-16. Hydraulic gradient vs. mid-section elevation for dilution measurements in Oskarshamn. Plotted points are classified into deformation zones and fracture domains. For some of the data points, no classification is yet available.

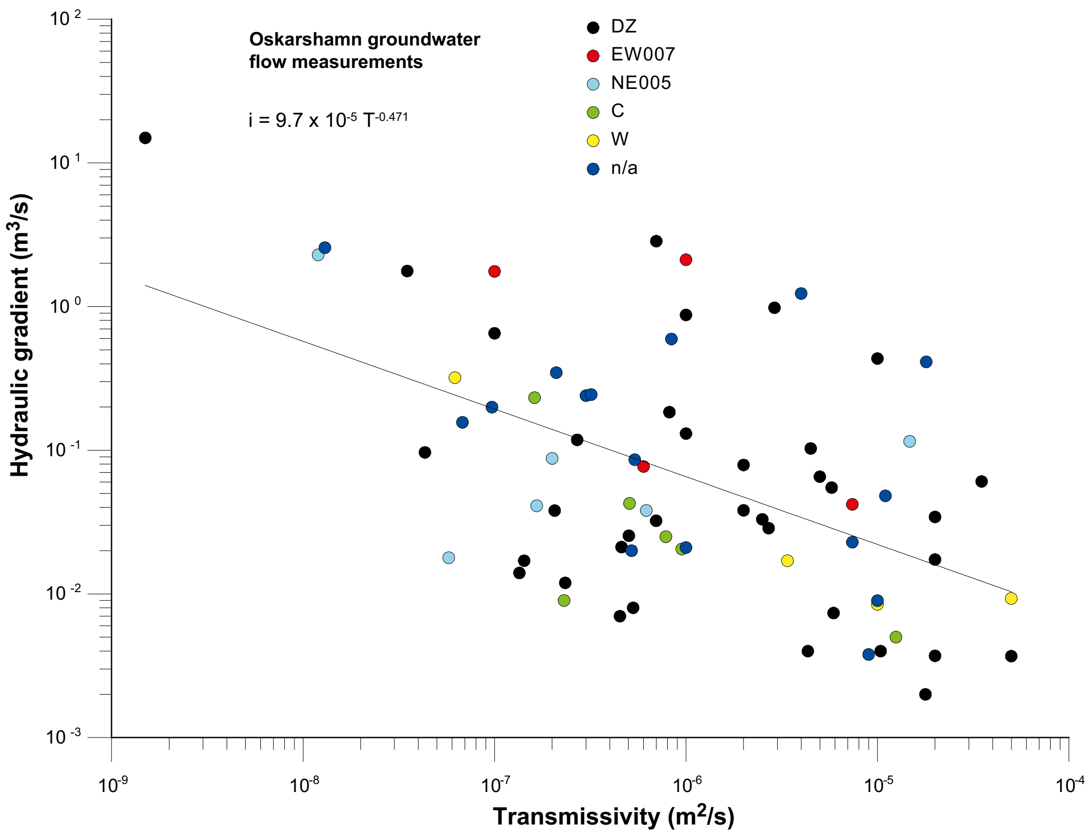


Figure 6-17. Hydraulic gradient vs. transmissivity for dilution measurements in Oskarshamn. Plotted points are classified into deformation zones and fracture domains. For some of the data points, no classification is yet available.

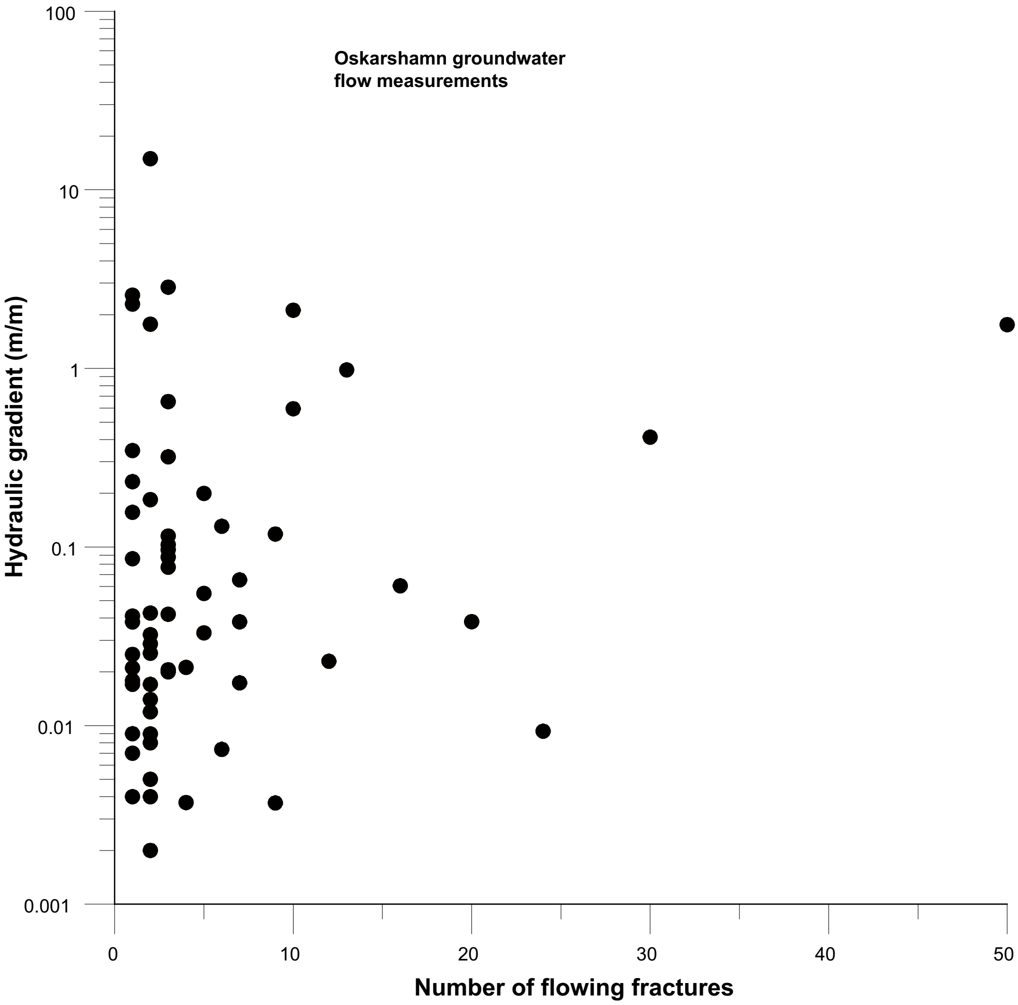


Figure 6-18. Hydraulic gradient vs. number of flowing fractures, excluding sections in percussion-drilled boreholes.

6.4 Temporal variation of groundwater flow rates

The monitoring programs in Forsmark and Oskarshamn have been underway since winter 2005/2006 and for several of the borehole sections short time series of dilution measurements are available. In the preceding analysis, only the most recent value was used for such sections. A closer look at time variations, based on currently available data /Wass 2008, Thur 2008/, gives further indications of the natural variability of the flow systems.

The time series available with at least three or more data points are plotted in Figure 6-19 for Forsmark and Figure 6-20 for Oskarshamn. The figures are divided into large and small flows for better visibility.

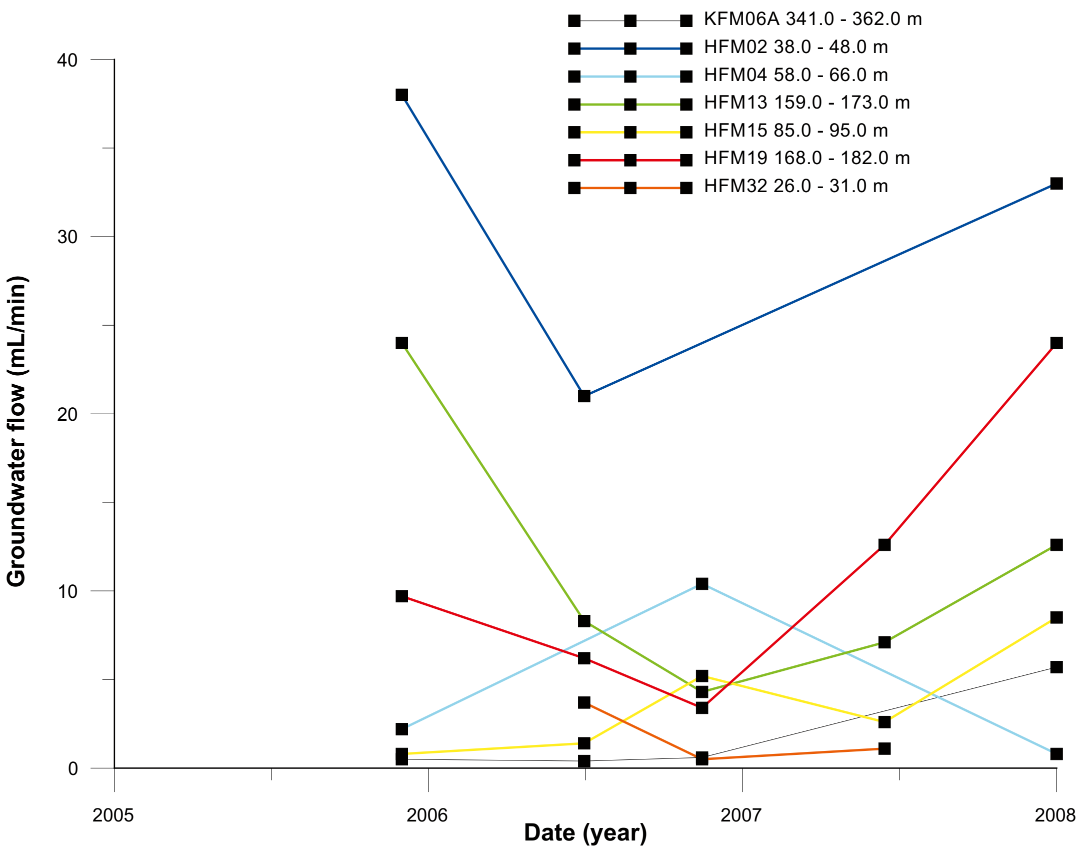
The time series show that the flow rates in some sections vary considerably while other sections show fairly stable flow rates. Generally, there appears to be smaller variations in Oskarshamn than in Forsmark.

In the sections with large variations, flow rates sometimes vary with several factors and up to one order of magnitude, as in KFM05A (254.0–272.0 m) where flow rates decrease from about 1.5 to 0.1 mL/min and in HFM04 (58.0–66.0 m) where it decreases from about 10.4 to 0.8 mL/min from winter 2006/2007 to winter 2007/2008.

There may be several explanations for such flow rate variations. It is well documented that groundwater levels in packed-off borehole sections sometimes responds quickly to rain or snowmelt /Nyberg and Wass 2007/. Such groundwater level changes might also imply that the local hydraulic gradient across the borehole section changes. Another mechanism for natural variability in groundwater flow rate may be variations in the groundwater table, which may affect the large-scale connectivity of water-conducting features /Cook 2003/.

Other common reasons for changes in groundwater levels include nearby drilling of boreholes and various activities in existing boreholes or tunnels, such as injection or pumping of water. It has also been observed that deflation of packers may significantly affect groundwater levels in other borehole sections.

There are no consistent trend patterns for either site, possibly except for a tendency for a moderately decreasing trend in Oskarshamn. In Forsmark, several sections indicates an increasing trend from winter 2006/2007, but there are also some sections with a considerable decrease during the same period. However, the sections with increasing trends are primarily from relatively shallow percussion-drilled boreholes. Prior to this measurement campaign, major pumping in borehole HFM14 had occurred during a hydraulic interference test for about 6 months, and pumping had also occurred in borehole HFM33. It is possible that transient recovery effects after the pumping have caused the increased flow rates in some of the shallower borehole sections. It may here also be mentioned that there are no significant visible effects from the Äspö HRL on groundwater levels in the Laxemar boreholes in the monitoring program /Nyberg and Wass 2007/.



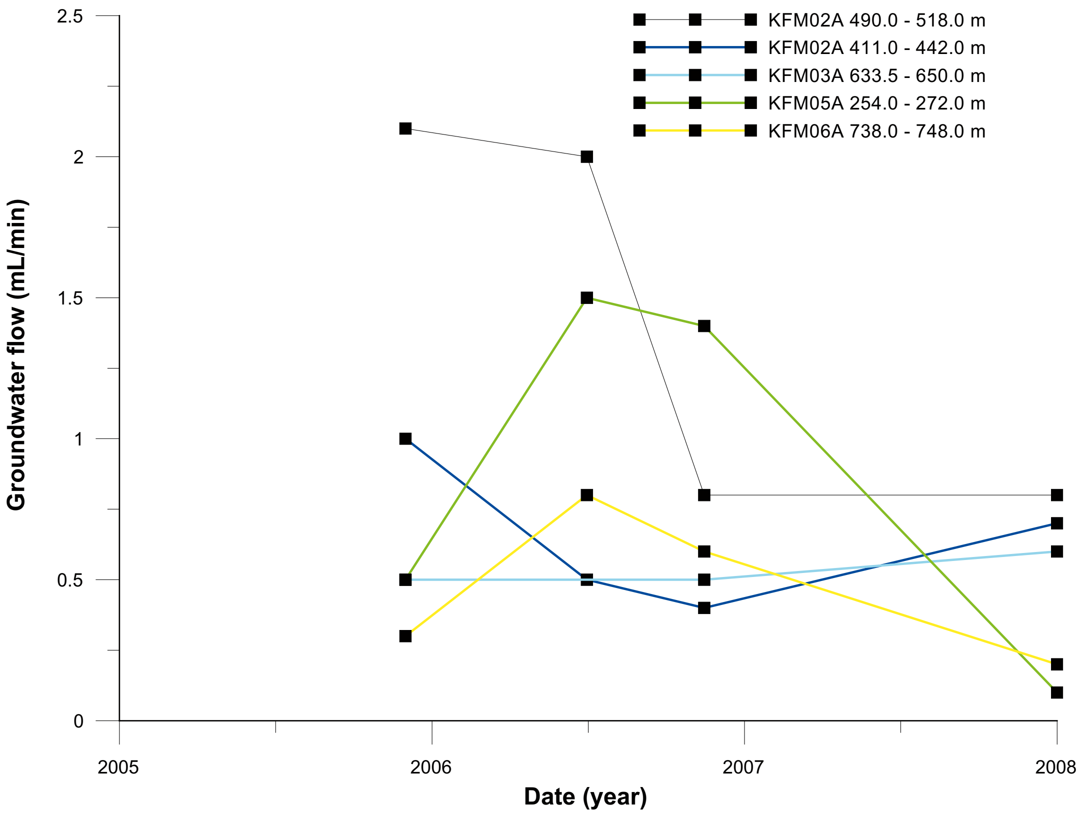
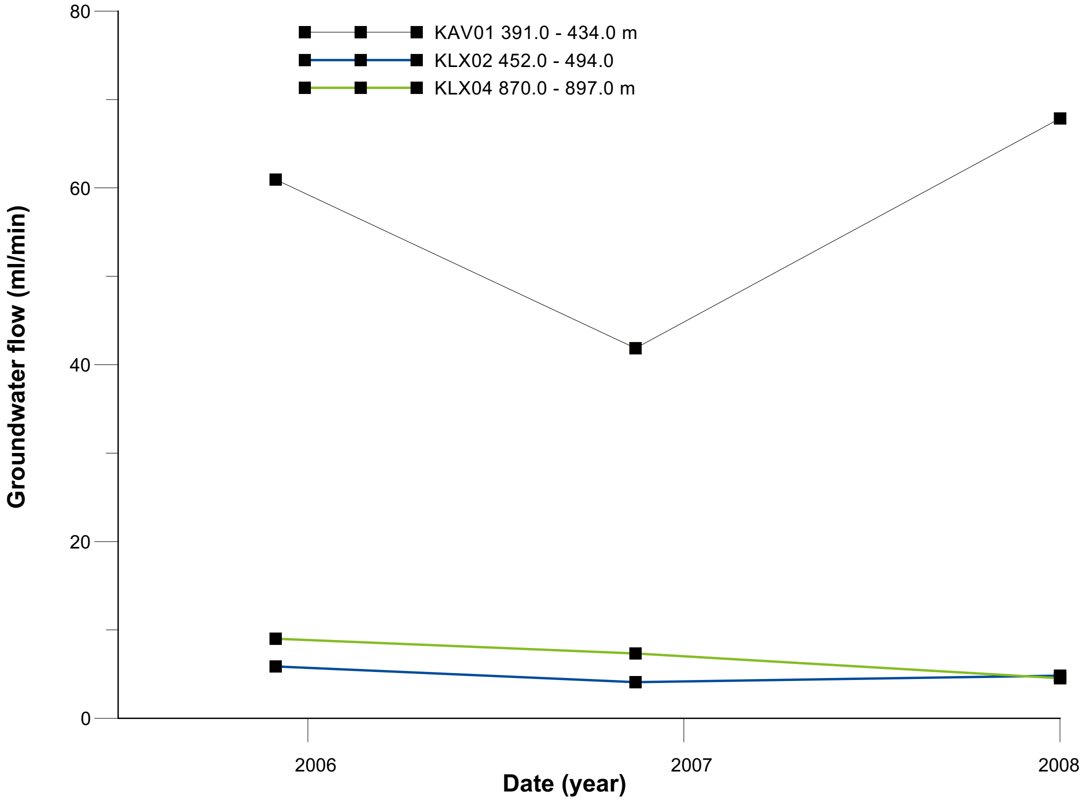


***Figure 6-19.** Selected time series of flow measurements from the monitoring program in Forsmark, divided into larger (top) and smaller (bottom) flows.*



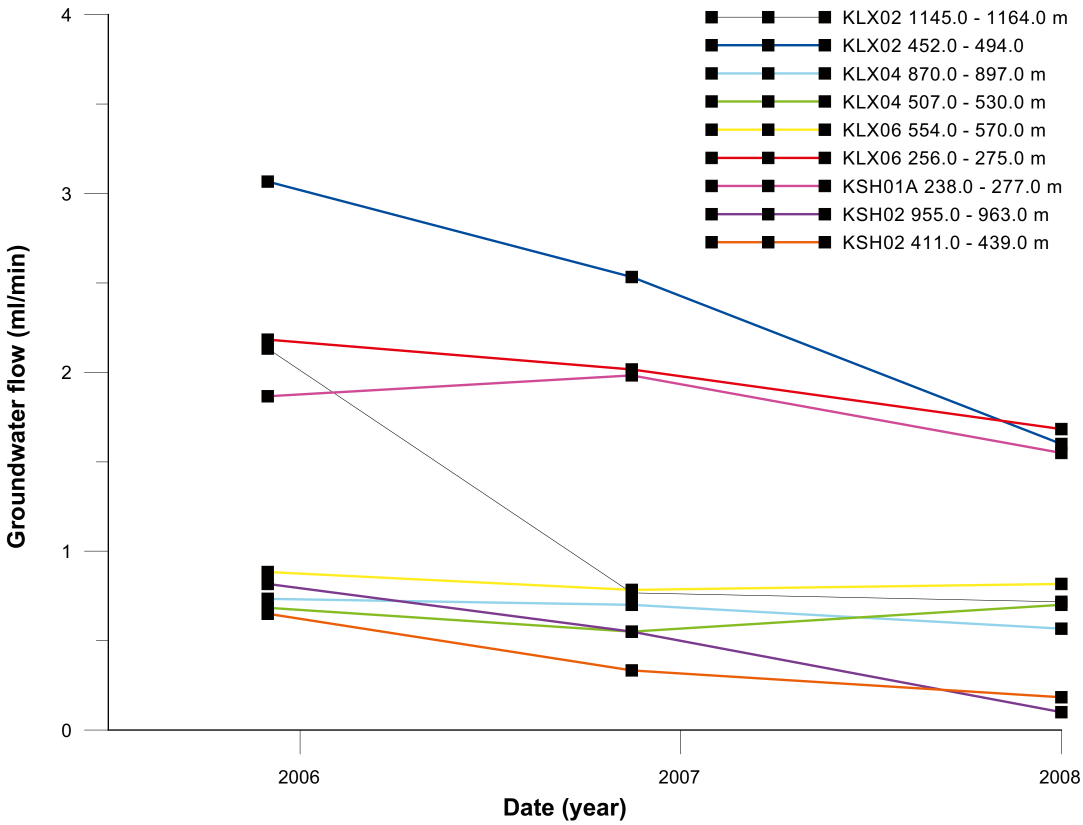


Figure 6-20. *Selected time series of flow measurements from the monitoring program in Oskarshamn, divided into larger (top) and smaller (bottom) flows.*

7 Discussion

7.1 Groundwater flow rates

Groundwater flow rates, estimated from borehole dilution measurements, from the site investigations in Forsmark and Oskarshamn have been compiled and analysed. The analysis presented here is oriented towards examining general features of available data and potential trends and relationships between various variables. A total of 64 (33 monitoring sections, 31 dilution probe) borehole sections in Forsmark and a total of 72 borehole section (38 monitoring, 34 dilution probe) in Oskarshamn have been subjected to tracer dilution measurements within the site investigations. The monitoring sections are permanent installations in which dilution measurements are repeated periodically over time.

The borehole sections are selected based on prior borehole investigations. The intention is that selected sections should contain naturally flowing open fractures with relatively high transmissivity. *Thus, the data presented herein are intended to represent rock features with a potential for significant groundwater flow under natural conditions. Dilution measurements in sections expected to have no or very little significant flow have not been performed.*

The two types of measurement (dilution probe and monitoring program, respectively) differ in some respects. The permanently installed borehole sections in the monitoring program typically have longer sections than the sections for dilution probe measurements. This in turn also appears to be, at least partly, related to somewhat higher flow rates in the monitoring sections. Another difference is that the dilution probe measurements are made relatively shortly after the borehole packers are inflated while the measurements in the monitoring program are made with permanently installed packers. This could mean that steady-state conditions around the borehole might not be fully developed prior to the start of dilution probe measurements. Despite these differences, it is judged that data from both measurement types may be combined when examining various properties of the available data.

The transmissivity of the sections selected for dilution measurements vary approximately between 10^{-8} and 10^{-3} m^2/s with a median at about 10^{-6} m^2s. It should be pointed out that the transmissivity values are obtained from different test methods, see further discussion in the subsequent section.

The flow rates vary approximately between 10^{-10} and 10^{-6} m^3/s with a median of about 10^{-8} m^3/s. There is a general tendency for higher flow rates in the monitoring sections, which generally are longer and contain more flowing fractures. The flow rates appear to be approximately log-normally distributed. There are no obvious differences between the two sites with respect to distribution of groundwater flow rates. In fact, basic statistical measures indicate very similar flow characteristics; the median and standard deviations of logarithm ($\log_{10}$) of the flow rates are –8.2 and 1.0 for Forsmark and –8.0 and 0.90 for Oskarshamn, respectively.

There is no visible correlation between groundwater flow rates and depth (elevation), with the possible exception of surface-near sections in Forsmark, which have relatively high flow rates. This is also related to the general feature of the Forsmark data that higher flow rates are found in deformation zones than in fracture domains. In Oskarshamn, however, there appears to be no visible difference between deformation zones and fracture domains with respect to groundwater flow rates.

Correlation between groundwater flow and transmissivity is fairly clearly indicated at both of the sites. This is reasonable because, on the whole, higher transmissivity also means higher potential to carry groundwater flow under natural conditions. However, a high transmissivity value does not necessarily indicate a high natural groundwater flow. Poor flow connectivity and/or variable density effects may result in a low natural flow even in the presence of a locally high transmissivity value.

The first few measurements available from the permanently installed monitoring sections show that temporal variation in groundwater flow rates can be considerable, in a few cases up to an order of magnitude. Such variations may be attributed to factors such as long- or short-term variations in rain/snowmelt, tidal variations or variations of the groundwater table. Other hydraulic disturbances may originate from nearby pumping in other boreholes. The temporal data gives a good illustration that the groundwater flow rate at a given point is not a static measure, but can vary considerably with time.

Although the estimated flow rates through the borehole sections may be regarded as fairly certain, unless there are problem with packers or other experimental equipment, there is larger uncertainty about how the flow rate through the section relates to the natural flow rate in the formation without the disturbing presence of a borehole. It is commonly assumed when evaluating dilution tests that the borehole creates a stream line convergence due to the high hydraulic conductivity of the borehole (see section 3.1). For the calculations presented in the various site investigation reports of Darcy velocities and hydraulic gradients, a convergence factor of 2 is assumed. This is a reasonable value if the flowing fractures are approximately perpendicular to the borehole and if there is no skin zone (zone of altered hydraulic conductivity) around the borehole.

If the flowing fracture(s) is not perpendicular to the borehole, then the effective width of the borehole relative the natural groundwater flow direction may be at least as wide as the borehole diameter due to spatial geometry effects as discussed in section 3.1. Thus, in this respect, the assumption of a value of 2 for the convergence factor should be considered a minimum value.

The presence of an altered zone, often referred to as the skin zone, affects the hydraulic properties adjacent to the borehole. In un-consolidated porous media, the correction factor may be estimated fairly accurately with knowledge of well screen and gravel pack properties /Gaspar 1987/, but in consolidated fractured rock this issue is much more complex. The skin around the borehole may be either positive (decreased hydraulic conductivity) or negative (increased hydraulic conductivity). Positive skin affecting natural flow through the borehole section may be caused by, for example, clogging of flowing fractures as a result of drilling. Negative skin may be caused by well development or increased hydraulic conductivity around the borehole due to re-distribution of pressure in the rock. Positive skin may give a convergence factor of less than 2 while negative skin would give factors larger than 2. Effects of relatively complex skin on tracer dilution interpretation were investigated by /Bidaux and Tsang 1991/ who concluded that complex negative skin may produce convergence factors exceeding 10.

For the borehole sections within the site investigations, it is reasonable to expect skin, if present, to be negative, i.e. increased hydraulic conductivity. There is generally no evidence that flowing features should have become clogged or otherwise developed decreased conductivity. Thus, the occurrence of skin would tend to make the flow convergence correction factor larger than the commonly assumed value of 2. This is further discussed for hydraulic gradients below.

It is possible that the borehole itself might connect flowing fractures otherwise not connected, especially in longer sections with larger number of flowing fractures. Such short-circuiting may tend to artificially increase the flow, compared with natural conditions without the presence of a borehole. In Figure 7-1, groundwater flow rates and transmissivity values from both of the sites are plotted against the number of flowing fractures. Although it is clear that borehole sections with a large number of fractures all have relatively high groundwater flow rates, the same pattern also holds for the transmissivity. Thus, the pre-dominance of higher flow rates with increasing fractures may not necessarily be caused by short-circuiting effect but simply be a reflection of increased transmissivity.

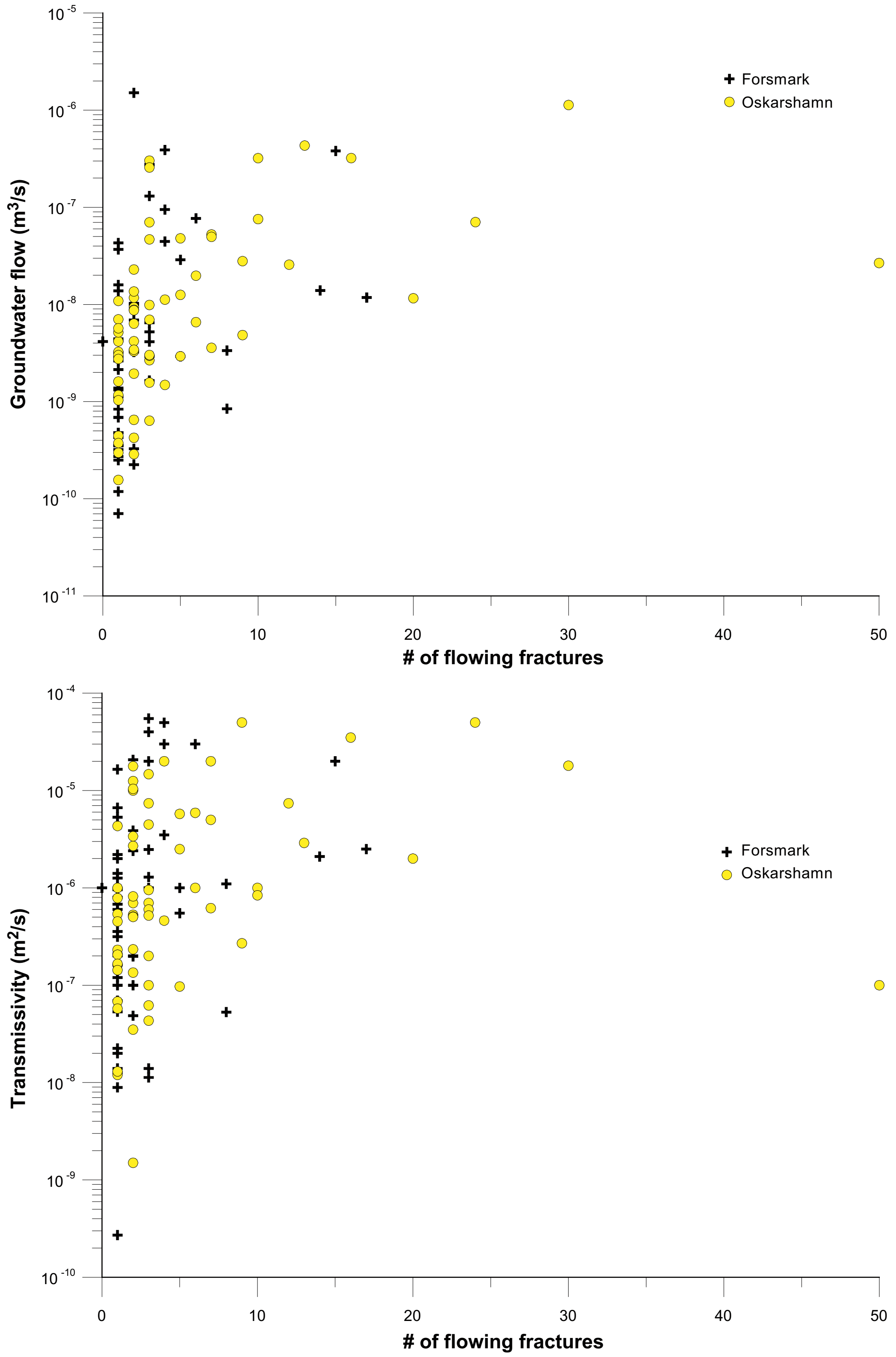


Figure 7-1. *Groundwater flow rate (top) and transmissivity (bottom) vs. number of flowing fractures.*

7.2 Hydraulic gradients

The hydraulic gradients calculated from the dilution measurements is conceptually a local gradient that prevails across the tested borehole section. This also assumes that variable-density effects are not significant for the flow through the borehole. If variable-density effects are important, the potential concept of groundwater flow is not valid and likewise the concept of a potential gradient.

The calculated gradient through the borehole section might differ from the large-scale gradient because of the spatial variability of the hydraulic conductivity in the connected flowing parts of the rock. The hydraulic gradient data for Forsmark and Oskarshamn presented in the preceding chapter show a large variability but also a fairly clear correlation with the transmissivity. Intuitively, such a relationship appears reasonable. For example, if one considers flow in a one-dimensional path with varying transmissivity, it is obvious that parts with lower transmissivity will have higher gradients, and vice versa. Scoping simulations in more complex flow geometries with 2- and 3-D channel networks /Crawford 2008/ showed a similar inverse relation between gradient and transmissivity.

The large variability and the occurrence of seemingly very high hydraulic gradient values prompt some further discussion of the uncertainty of calculated hydraulic gradients from groundwater flow measurements. In some cases, sections tested with the dilution probe are also contained in the monitoring program, although the latter sections are longer. A pair-wise comparison of such sections shows that the calculated gradients might differ considerably. For example, in KFM03A, the calculated gradient in section 643.5–644.5 (dilution probe) m is 0.008 and 0.028 in section 633.5–650.0 m (monitoring program). Another example is in KLX03, where in section 740.4–744.4 m (dilution probe) the gradient is calculated to be 0.103 and in section 729.0–751.0 m (monitoring program) 0.007.

An accurate estimate of the local hydraulic gradient under natural conditions requires accurate estimates of three variables: 1) the groundwater flow through the section, 2) the transmissivity of the flowing path 3) the correction factor accounting for the convergence of flow lines around the borehole.

In a simple case of a short (e.g. 1 metre) borehole section containing a single flowing fracture perpendicular to the borehole and no skin zone, the convergence correction factor may be assumed to be approximately 2. However, as discussed in the preceding section, other fracture orientations and possible skin zone properties may introduce considerable uncertainty in the flow convergence factor. As an overall assumption, it seems reasonable to regard the commonly used value of 2 for the convergence factor as a minimum value. Thus, this would in turn contribute to an over-estimation of the hydraulic gradient. It is very difficult to estimate the magnitude of this potential uncertainty, but a plausible rough estimate may be that the “real” convergence factor could be 1– 5 times the assumed value of 2.

A perhaps more significant source of uncertainty when estimating the hydraulic gradient in such a case would be the transmissivity. The transmissivity is obtained from the interpretation of single-hole hydraulic tests. The hydraulic tests are carried out using either difference flow logging (PFL, HTHB) or injection tests between packers (PSS). The transmissivity data used for calculating the hydraulic gradient are sometimes from interpretation of injection tests and sometimes from flow logging, depending on availability and judged representativeness for the tested borehole section.

The methods differ with respect to performance as well as to interpretation /Hjerne et al. 2008/, see section 6.1. During flow logging with PFL, an essentially steady-state flow field is established by pumping for several days and the transmissivity is obtained using steady-state interpretation methods assuming radial flow. For the injection tests, typical injection times are about 20 minutes, making the radius of influence considerably smaller than for the flow logging measurements. Interpretation of the injection tests considers skin effects, flow regime evaluation and interpretation of boundary effects. Thus, one may expect transmissivity estimates for these two methods to differ. The agreement between the two methods has been examined in several reports /e.g. Källgården et al. 2004, Gokall-Norman et al. 2005, Andersson et al. 2002/. Although there in most cases is fairly good agreement, an order of magnitude or so difference between the two methods is not uncommon.

A recent in-depth analysis of the differences between results from flow logging and injection tests, respectively, was presented by /Hjerne et al. 2008/, where one conclusion was that differences in interpreted transmissivity values between the two types of tests was correlated to the type of interpreted flow regime. In particular, for tests with apparent no-flow boundaries (as interpreted from injection tests) the transmissivities from injection tests were often much higher than for the flow logging tests, which would reflect the conceptual differences between the two types of test.

Irrespective of the test type used for estimating transmissivity from single-hole tests, an artificial flow field (usually assumed to be radial) is created around the borehole section. The transmissivity value from such a test may not be representative of the flow path that carries water through the borehole section during a dilution test under ambient groundwater flow conditions.

Flow regime interpretations during the transient injection tests show that radial flow is indicated in most cases /Hjerne et al. 2008/. Thus, the determined transmissivity values from flow logging (radial flow always assumed) and transient injection tests are pre-dominantly based on the assumption of radial flow. In a heterogeneous fracture, however, flow is not evenly distributed around the pumping/injection section. It is possible that only a fraction of the full radius around the borehole contributes significantly to the injection/pumping flow. Even if radial flow (i.e. flow dimension of two) is indicated by the shapes of type curves or some other flow dimension analysis, it does not provide any information about the degree to which the flow fills the available space /Doe and Geier 1990/. One implication of this is that the representative transmissivity for a naturally flowing flow path might tend to be underestimated, because the standard interpretation methods assumes that the injection/pumping flow during a hydraulic tests is evenly distributed around the borehole. Consequently, if the transmissivity for a naturally flowing path tends to be underestimated, the calculated hydraulic gradients would tend to be over-estimated (Equation 3-5).

Figure 7-2 shows the hydraulic gradient vs. transmissivity for all of the points at both of the sites. The plotted data is sorted with respect to which method is used for the interpretation of the transmissivity (PFL/HTHB/PSS). Although there is considerable variability there is a clear pattern that the lower end of the calculated gradients from T-values of about 10^{-8} m^2/s and up consist only of values calculated using T-values interpreted from PFL flow logging measurements. Since an overall impression of available data from the site investigations is that calculated hydraulic gradients often have unrealistically high values, one indication from Figure 7-2 is that transmissivity from the relatively long-term PFL flow logging measurements (if available and within a range of reasonable accuracy) might be preferable for use together with dilution data to calculate hydraulic gradients.

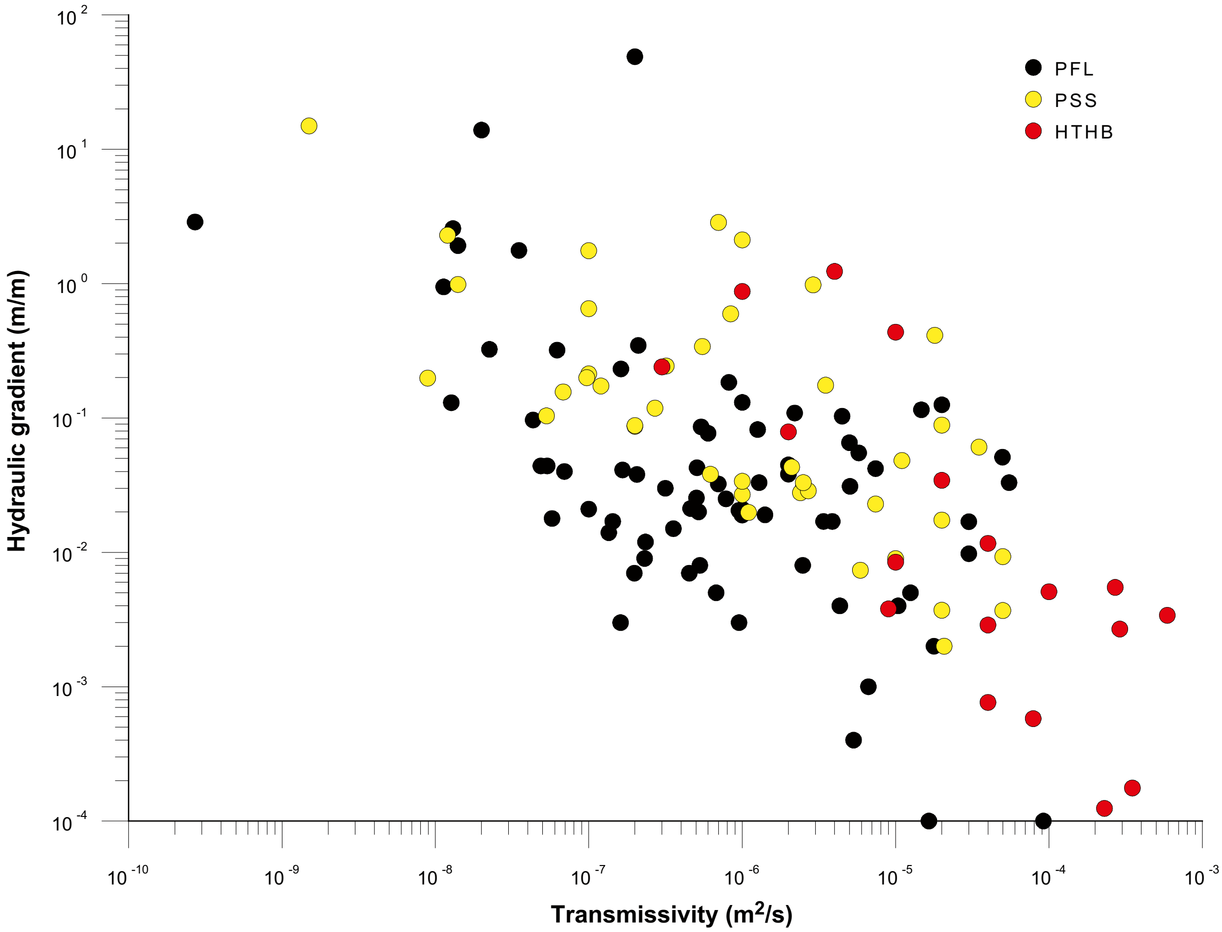


Figure 7-2. *Comparison of hydraulic gradients vs. transmissivity depending on whether the transmissivity is interpreted from relatively long-term tests (PFL) or from tests of shorter duration (PSS or HTHB).*

8 Conclusions

This report comprises a summary and overall analysis of tracer dilution data collected within the SKB site investigations at Forsmark and Oskarshamn. In addition, a brief overview of older measurements and previous method development is presented.

The primary results of the dilution measurements are estimated groundwater flow rates through the borehole section. This estimation is very straight-forward and, in the absence of equipment malfunctioning, should provide a very accurate estimate of the flow through the section. The main uncertainties arise when interpretations are made for how the primary flow data relates to the natural flow and hydraulic gradients in a borehole-free rock environment.

Although the flow rate through the borehole is fairly accurate, there is uncertainty in determining how large of a volume in the un-disturbed rock that contributes to the borehole flow. Despite this uncertainty, it should be reasonable to regard the distribution of borehole section flow rates as roughly representative also for some distribution of "real" (i.e. without the presence of the borehole) groundwater flow rates.

The groundwater flow rates analysed here are on the whole approximately log-normally distributed with a median of about 10^{-8} m^3/s. It may be repeated here that there is a general bias in data due to prior selection of suitable borehole sections. Flow rates show no systematic depth-dependence, high or low flow rates may occur at any depth. The only exception to this is that there appears to be a tendency for high flow rat es in shallow borehole sections at Forsmark.

The estimated flow rates show some correlation to the hydraulic transmissivity, although the variability is high. This result is reasonable because higher transmissivity values also means higher potential to carry groundwater flow.

Another main variable that is analysed is the hydraulic gradient, derived from borehole flow rates, a transmissivity estimate and assumptions about the flow convergence around the borehole. Available data shows very large variation from extremely low gradients to in several cases seemingly unrealistically high gradients. Most of the calculated gradients are within the interval of 0.01–0.1 m/m.

As for the flow rates, the hydraulic gradients do not show any significant systematic variation with depth, except for some shallow borehole sections in Forsmark which indicate very low gradients. There is a clear correlation between hydraulic gradients and transmissivity, with decreasing gradient with increasing transmissivity. This is expected because, for a given flow path with a given flow, low-transmissive parts require a higher gradient drop than high-transmissive parts.

There is an overall impression that the magnitudes of the calculated hydraulic gradient values tend to be too high relative to reasonable topographically-based estimates of the regional hydraulic gradient. An examination of possible sources of error for the gradient estimation indicates that it is likely that gradients tend to be over-estimated. One reason for this is that the flow convergence correction factor probably often is larger than the commonly assumed value of 2, due to fracture orientation and artificially increased hydraulic conductivity (negative skin) around the borehole. Of particular importance is the transmissivity values used for estimation of hydraulic gradients and this may be one of the largest sources of error. The transmissivity values used are obtained from different methods (PFL, PSS or HTHB). Further, independent of method, transmissivity values are obtained during a different flow regime (radial flow) than what prevails during the tracer experiments. Reported data are often based on preliminary transmissivity estimates from then available measurements. One may argue that the relatively long-term PFL measurements provide more representative transmissivity estimates for the connected flowing path, and some support for this may also be found in available data (Figure 7-2). In order to improve the hydraulic gradient estimates, the used transmissivity data should be updated using final transmissivity estimates, and preferably from PFL measurements if available.

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