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Abstract

This report describes the performance, evaluation and interpretation of in situ groundwater flow measurements and a single well injection withdrawal tracer test (SWIW test) at the Oskarshamn site. The objectives of the activity were to determine the natural groundwater flow in selected fractures/fracture zones intersecting the core drilled borehole KLX18A, as well as to determine transport properties of fractures by means of a SWIW test in the borehole.

Groundwater flow measurements were carried out in five local fracture zones at borehole lengths ranging from c. 146 to c. 592 m (144 to 583 m vertical depth). The hydraulic transmissivity ranged within $T = 4.3 \cdot 10^{-8}$ to $9.5 \cdot 10^{-7}$ m^2/s. The results of the dilution measurements in borehole KLX18A show that the groundwater flow varies in fracture zones during natural, i.e. undisturbed, conditions. Nevertheless, the general trend in the borehole is that flow rates and Darcy velocities increase with depth. An exception is the shallow section at c. 146 m, where the flow rate and Darcy velocity is high which is in accordance with results at similar depths in other boreholes in the area. The flow rate ranged from 0.022 to 0.20 ml/min and the Darcy velocity from $8.1 \cdot 10^{-10}$ to $7.2 \cdot 10^{-9}$ m/s ($7.0 \cdot 10^{-5}$ to $6.2 \cdot 10^{-4}$ m/d), values that are similar to results from previously performed dilution measurements under natural gradient conditions at the Oskarshamn site. The highest flow rates and Darcy velocities were measured in sections in the lower part of the borehole outside the deformation zones. Hydraulic gradients, calculated according to the Darcy concept, are within the expected range (0.001–0.05) in four out of five measured sections. The determined groundwater flow rates are fairly proportional to the hydraulic transmissivity although the statistical basis is weak.

Measurements were also attempted in two 5-metre sections at c. 400 m and c. 430 m borehole length. Unfortunately, the measurements could not be finalised due to problems with high content of particles in the borehole water, disturbance to the electronics from the closely located power transmission lines and other technical problems with the dilution probe.

The SWIW test was carried out in the deformation zone DZ9 at a borehole length of c. 473 m (466 m vertical depth) with a hydraulic transmissivity of $T = 4.3 \cdot 10^{-8}$ m^2/s.

A result from the SWIW test is that there is a clear retardation/sorption effect of both cesium and rubidium. The value of the retardation factor R is for cesium about 850 and for rubidium about 2,700. Estimated tracer recovery at the last sampling time yields approximately 87%, 46% and 37% for Uranine, cesium and rubidium, respectively. The model simulations were carried out for four different values of porosity; 0.005, 0.01, 0.02, 0.05 (assuming a 0.1 m thick transport zone), resulting in estimates of longitudinal dispersivity within the range of 0.17–0.87 m.

Sammanfattning

Denna rapport beskriver genomförandet, utvärderingen samt tolkningen av in situ grundvattenflödesmätningar och ett enhålsspårförsök (SWIW test) i Oskarshamn. Syftet med aktiviteten var dels att bestämma det naturliga grundvattenflödet i enskilda sprickor och sprickzoner som skär borrhålet KLX18A, dels att karaktärisera transport-egenskaperna i potentiella flödesvägar genom att utföra och utvärdera ett SWIW test i borrhålet.

Grundvattenflödesmätningar genomfördes i fem lokala sprickzoner på nivåer från ca 146 till ca 592 m borrhålslängd (144 till 583 m vertikalt djup). Den hydrauliska transmissiviteten varierade inom intervallet $T = 4{,}3 \cdot 10^{-8}$ till $9{,}5 \cdot 10^{-7}$ m^2/s. Resultaten från utspädningsmätningarna i borrhålet KLX18A visar att grundvattenflödet varierar under naturliga, dvs. ostörda, hydrauliska förhållanden. Den generella trenden är dock att flödet och Darcyhastigheten ökar med djupet. Undantaget är den ytligaste sektionen vid ca 146 m där flödet och Darcyhastigheten är hög vilket överensstämmer med resultat från motsvarande djup i tidigare undersökta borrhål. Beräknade grundvattenflöden låg inom intervallet 0,022–0,20 ml/min och Darcy hastigheterna varierade mellan $8{,}1 \cdot 10^{-10}$ och $7{,}2 \cdot 10^{-9}$ m/s ($7{,}0 \cdot 10^{-5}$ till $6{,}2 \cdot 10^{-4}$ m/d).

Resultaten överensstämmer med tidigare genomförda mätningar i Oskarshamn. Störst flöde och högsta Darcyhastighet uppmättes i sektionerna i nedre delen av borrhålet, utanför deformationszonerna. Hydrauliska gradienter, beräknade enligt Darcy-konceptet, ligger inom det förväntade området (0,001–0,05) i fyra av fem testade sprickor/zoner. Grundvattenflödet är proportionellt mot den hydrauliska transmissiviteten, dock är det statistiska underlaget litet.

Det var även tänkt att utföra mätningar i två 5-meters sektioner på ca 400 m och ca 430 m borrhålslängd. Dessvärre kunde dessa mätningar inte genomföras på grund av problem med smutsigt borrhålsvatten, närliggande kraftledningar som störde elektroniken, samt andra tekniska problem med sonden.

SWIW testet genomfördes i deformationszon DZ9 på ca 473 m borrhålslängd (466 m vertikalt djup) med $T = 4{,}3 \cdot 10^{-8}$ m^2/s.

SWIW testet visar en klar effekt av fördröjning/sorption av både cesium och rubidium. Retardationsfaktorn R är ca 850 för cesium och ca 2 700 för rubidium. Den beräknade återhämtningen av spårämnena i återpumpningsfasen var cirka 87 %, 46 % och 37 % för Uranin, cesium och rubidium. Modellpassningar till mätdata gjordes för fyra olika värden på porositet; 0.005, 0.01, 0.02 och 0.05 (antagande en 0.1 m bred transportzon), vilket resulterade i beräknad longitudinell dispersivitet från 0.17 till 0.87 m.

Contents

1 Introduction

SKB is currently conducting a site investigation for a deep repository in Oskarshamn, according to general and site specific programmes /SKB 2001ab/. Two, among several methods for site characterisation are in situ groundwater flow measurements and single well injection withdrawal tests (SWIW tests).

This document reports the results gained by a SWIW test and groundwater flow measurements with the borehole dilution probe in borehole KLX18A. The work was conducted by Geosigma AB and carried out between September and November 2006 in borehole KLX18A according to activity plan AP PS 400-06-097. In Table 1-1 controlling documents for performing this activity are listed. Both activity plans and method descriptions/instructions are SKB's internal controlling documents. Data and results were delivered to the SKB site characterization database SICADA.

Borehole KLX18A is located in the centre of the investigation area, near the main power transmission line from the power plant, Figure 1-1. KLX18A is a telescopic borehole where the part below 100 m borehole length is core drilled. KLX18A is inclined –82.04° from the horizontal plane at collaring. The borehole is in total 611 m long and cased down to 101 m. From 101 m down to 611 m the diameter is 76 mm.

Detailed information about borehole KLX18A is listed in Appendix A (excerpt from the SKB database SICADA).

Table 1-1. Controlling documents for performance of the activity.

Activity plan	Number	Version
Grundvattenflödesmätningar och SWIW-test i kärnborrhål KLX18A	AP PS 400-06-097	1.0
Method documents	**Number**	**Version**
Metodbeskrivning för grundvattenflödesmätning	SKB MD 350.001	1.0
Kalibrering av tryckgivare, temperaturgivare och flödesmätare	SKB MD 353.014	2.0
Kalibrering av fluorescensmätning	SKB MD 353.015	2.0
Kalibrering Elektrisk konduktivitet	SKB MD 353.017	2.0
Utspädningsmätning	SKB MD 353.025	2.0
Löpande och avhjälpande underhåll av Utspädningssond	SKB MD 353.065	1.0
Systemöversikt – SWIW-test utrustning	SKB MD 353.069	1.0
Löpande och avhjälpande underhåll av SWIW-test utrustning	SKB MD 353.070	1.0
Kalibrering av flödesmätare i SWIW-test utrustning	SKB MD 353.090	1.0
Instruktion för rengöring av borrhålsutrustning och viss markbaserad utrustning	SKB MD 600.004	1.0
Instruktion för längdkalibrering vid undersökningar i kärnborrhål	SKB MD 620.010	1.0

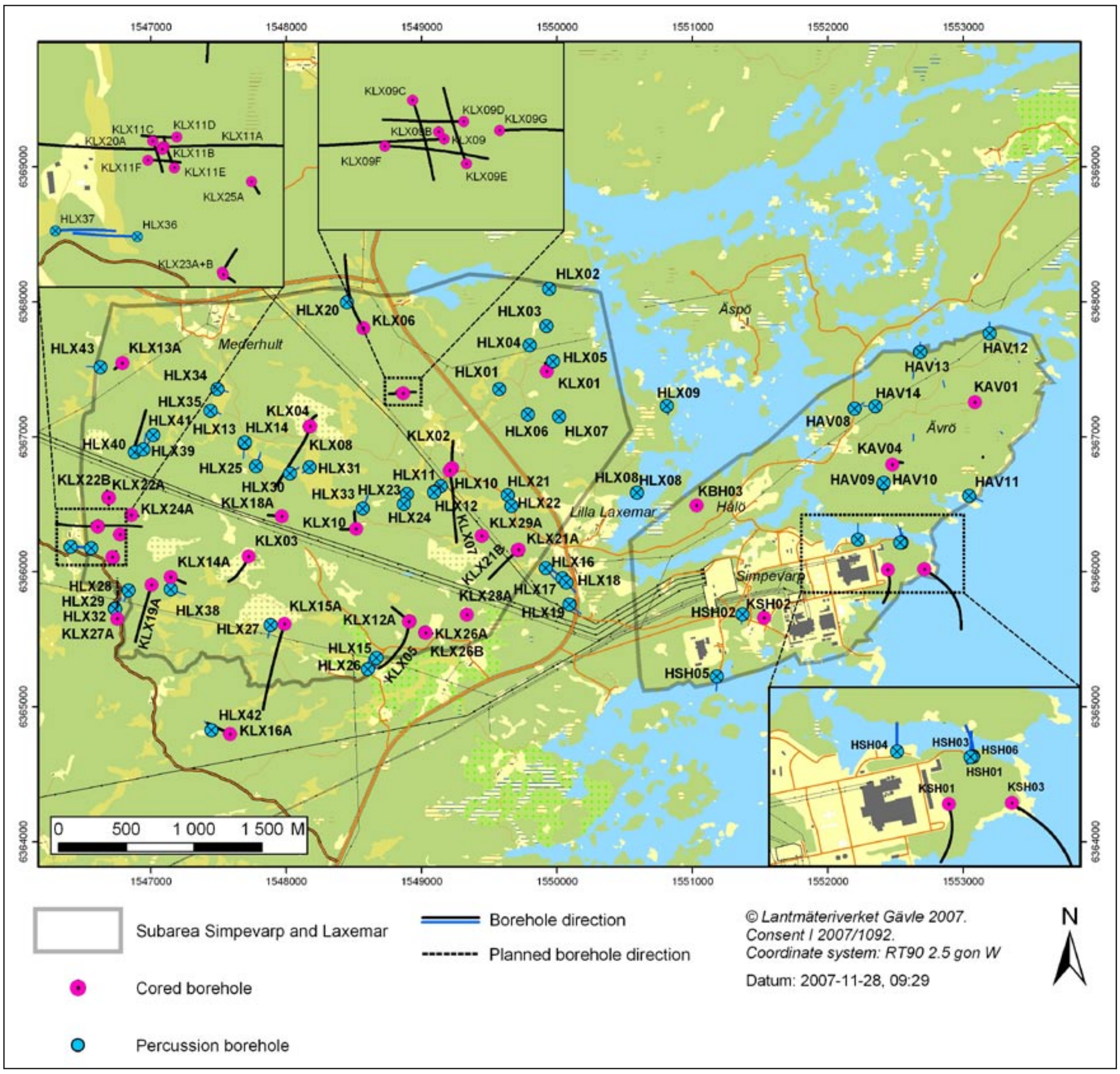

***Figure 1-1.** Overview of the Oskarshamn site investigation area, showing core boreholes (purple) and percussion boreholes (blue). KLX18A at coordinates 6366413 north and 1547966 east.*

2 Objectives and scope

One objective of the activity was to determine groundwater flow under natural gradient in the Oskarshamn area.

The objective of the SWIW test was to determine transport properties of groundwater flow paths in fractures/fracture zones in a depth range of 300–700 m and a hydraulic transmissivity of $1\cdot10^{-8}$ to $1\cdot10^{-6}$ m^2/s in the test section.

The groundwater flow measurements were performed in fractures and fracture zones at a borehole length range of 146–592 m (144–583 m vertical depth) using the SKB borehole dilution probe. The hydraulic transmissivity in the test sections ranged between $4.3\cdot10^{-8}$ to $9.5\cdot10^{-7}$ m^2/s. Groundwater flow measurements were carried out in totally five test sections. In one of these sections a SWIW test was also conducted using both sorbing and non-sorbing tracers, simultaneously.

3 Equipment

3.1 Borehole dilution probe

The borehole dilution probe is a mobile system for groundwater flow measurements, Figure 3-1. Measurements can be made in boreholes with 56 mm or 76–77 mm diameter and the test section length can be arranged for 1, 2, 3, 4 or 5 m with an optimised special packer/dummy system 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 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.

3.1.1 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, 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, $v = 4\cdot10^{-9}$ 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.

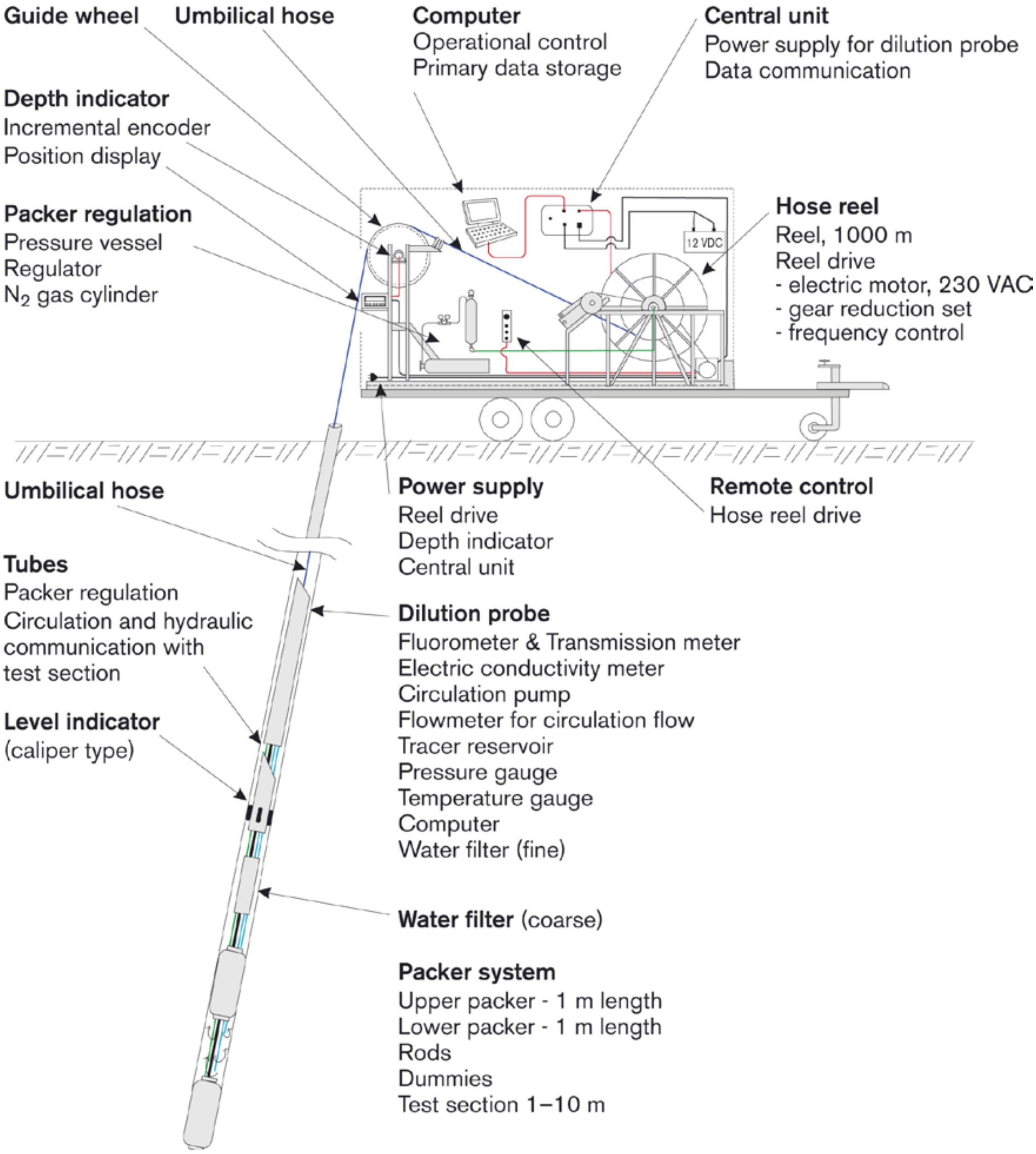

Figure 3-1. *The SKB borehole dilution probe.*

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 below in Section 4.4.1. The value of α will, at least, vary within $\alpha = 2 \pm 1.5$ in fractured rock /Gustafsson 2002/. Hence, the groundwater flow in the rock formation is calculated with an accuracy of about ± 75%, depending on the flow-field distortion.

3.2 SWIW test equipment

The SWIW (Single Well Injection Withdrawal) test equipment constitutes a complement to the borehole dilution probe making it possible to carry out a SWIW test in the same test section as the dilution measurement, Figure 3-2. Measurements can be made in boreholes with 56 mm or 76–77 mm diameter 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 boreholes. The equipment is primarily designed for measurements in the depth interval 300–700 m borehole length. However, measurements can be carried out at shallower depths as well as at depths larger than 700 m. The possibility to carry out a SWIW test much depends on the hydraulic transmissivity in the investigated test section and frictional loss in the tubing at tracer withdrawal pumping. Besides the dilution probe, the main parts of the SWIW test equipment are:

- Polyamide tubing constituting the hydraulic connection between SWIW test equipment at ground surface and the dilution probe in the borehole.
- Air tight vessel for storage of groundwater under anoxic conditions, i.e. N_2-athmosphere.
- Control system for injection of tracer solution and groundwater (chaser fluid).
- Injection pumps for tracer solution and groundwater.

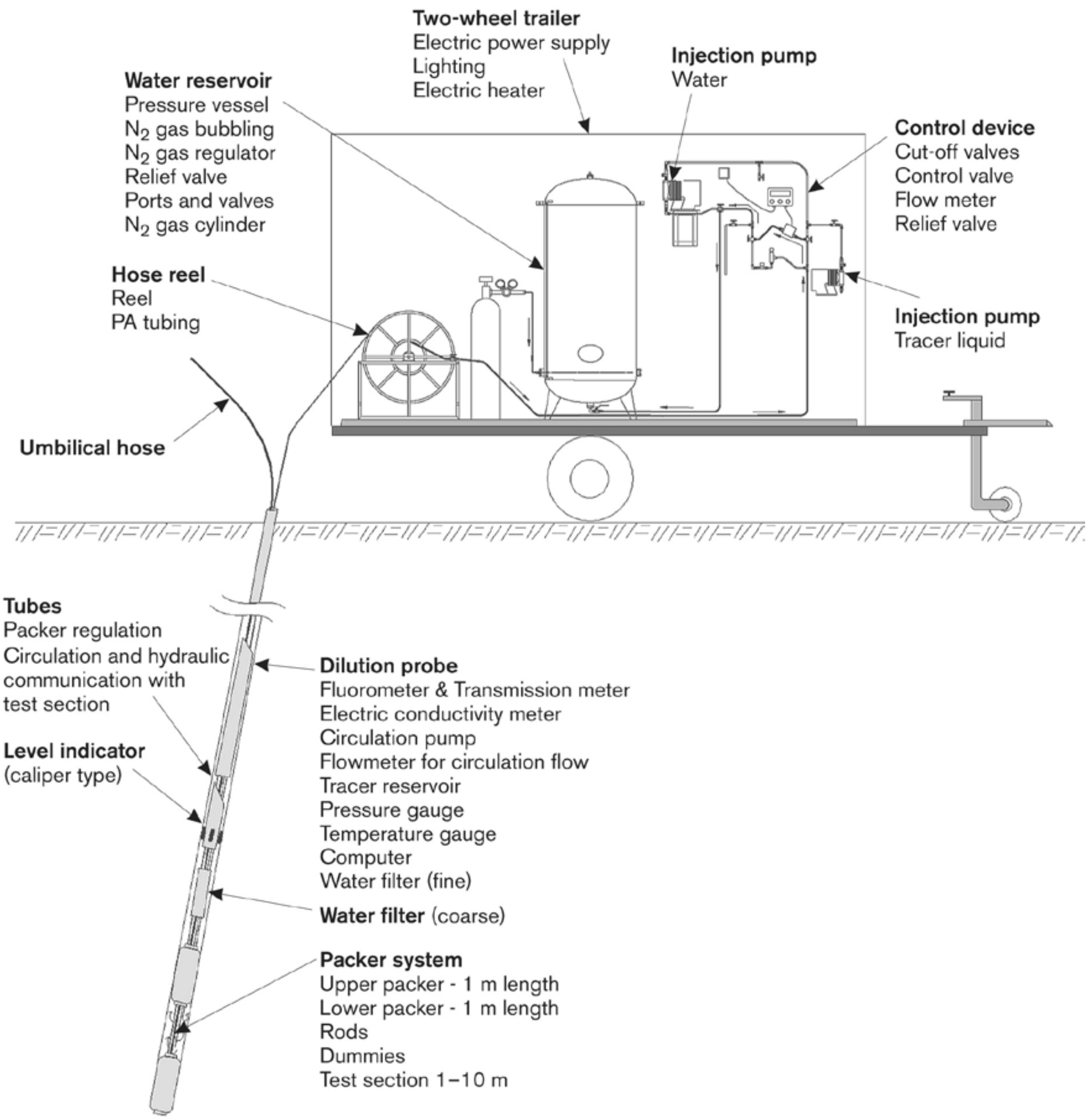

Figure 3-2. *SWIW test equipment, connected to the borehole dilution probe.*

3.2.1 Measurement range and accuracy

The result of a SWIW test depends on the accuracy in the determination of the tracer concentration in injection solutions and withdrawn water. The result also depends on the accuracy in the volume of injection solution and volumes of injected and withdrawn water. For non-sorbing dye tracers (e.g. Uranine) the tracer concentration in collected water samples can be analysed with a resolution of 10 µg/l in the range 0.0–4.0 mg/l. The accuracy is within ± 5%. The volume injected tracer solution can be determined within ± 0.1% and the volume of injected and withdrawn water determined within 5%.

The evaluation of a SWIW test and determination of transport parameters is done with model simulations, fitting the model to the measured data (concentration as a function of time). The accuracy in determined transport parameters depends on selection of model concept and how well the model fit the measured data.

4 Execution

The measurements were performed according to AP PS 400-06-097 (SKB internal controlling document) in compliance with the methodology descriptions for the borehole dilution probe equipment – SKB MD 350.001, Metodbeskrivning för grundvattenflödesmätning –, and the measurement system description for SWIW test – SKB MD 353.069, MSB; Systemöversikt – SWIW-test utrustning – (SKB Internal controlling documents), Table 1-1.

4.1 Preparations

The preparations included calibration of the fluorometer and the electric conductivity meter before arriving at the site. Briefly, this was performed by adding certain amounts of the tracer to a known test volume while registering the measured A/D-levels. From this, calibration constants were calculated and saved for future use by using the measurement application. The other sensors had been calibrated previously and were hence only control calibrated.

Extensive functionality checks were accomplished prior to transport to the site and limited function checks were performed at the site. The equipment was cleaned to comply with SKB cleaning level 1 before lowering it into the borehole. All preparations were performed according to SKB Internal controlling documents, cf. Table 1-1.

4.2 Procedure

4.2.1 Groundwater flow measurement

In total five groundwater flow measurements were carried out, Table 4-1.

Each measurement was performed according to the following procedure. The equipment was lowered to the correct borehole length where background values of tracer concentration and supporting parameters, pressure and temperature, were measured and logged. Then, after inflating the packers and the pressure had stabilized, tracer was injected in the test section. The tracer concentration and supporting parameters were measured and logged continuously until the tracer had been diluted to such a degree that the groundwater flow rate could be calculated.

Table 4-1. Performed dilution (flow) measurements.

Borehole	Test section (m)+	Number of flowing fractures*	T (m^2/s)	Tracer	Test period (yymmdd–yymmdd)
KLX18A	146.0–149.0 (144.2–147.2)	4	4.61E–07*	Uranine	061002–061004
KLX18A	359.0–362.0 (354.0–357.0)	2	2.34E–07*	NaCl	061005–061009
KLX18A	473.3–476.3 (466.5–469.4)	3–4	4.33E–08*	Uranine	061018–061029
KLX18A	562.0–565.0 (553.7–556.6)	2–3	5.07E–07*	Uranine	061102–061105
KLX18A	592.0–595.0 (583.1–586.1)	3–4	9.52E–07*	Uranine	061105–061106

* /SICADA/.

+ Test section vertical depth (metre above sea level) is given within brackets.

4.2.2 SWIW test

One SWIW test was performed, Table 4-2. A BIPS image of the test section is shown in Appendix C. To conduct a SWIW test requires that the SWIW equipment is connected to the borehole dilution probe, Figures 3-1 and 3-2.

The SWIW test was carried out according to the following procedure. The equipment was lowered to the correct borehole length where background values of Uranine and supporting parameters, pressure and temperature, were measured and logged. Then, after inflating the packers and the pressure had stabilized, the circulation pump in the dilution probe was used to pump groundwater from the test section to the air tight vessel at ground surface. Water samples were also taken for analysis of background concentration of Uranine, rubidium and cesium. When pressure had recovered after the pumping in the test section, the injection phases started with pre-injection of the native groundwater to reach steady state flow conditions. Thereafter groundwater spiked with the tracers Uranine, rubidium and cesium was injected. Finally, injection of native groundwater to push the tracers out into the fracture/fracture zone was performed. The withdrawal phase started by pumping water to the ground surface. An automatic sampler at ground surface was used to take water samples for analysis of Uranine, rubidium and cesium in the withdrawn water.

4.3 Data handling

During groundwater flow measurement with the dilution probe, data are automatically transferred from the measurement application to a SQL database. Data relevant for analysis and interpretation are then automatically transferred from SQL to Excel via an MSSQL (ODBC) data link, set up by the operator. After each measurement the Excel data file is copied to a CD.

The water samples from the SWIW test were analysed for Uranine tracer content at the Geosigma Laboratory in Uppsala. Cesium and rubidium contents were analysed at the Analytica laboratory in Luleå.

4.4 Analyses and interpretation

4.4.1 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 into a bore-hole test section. The tracer is subsequently diluted by the ambient groundwater, flowing through the borehole test section. The dilution of the tracer is proportional to the water flow through the borehole section, Figure 4-1.

Table 4-2. Performed SWIW test.

Borehole	Test section (m)+	Number of flowing fractures*	T (m^2/s)*	Tracers	Test period (yymmdd–yymmdd)
KLX18A	473.3–476.3 (466.5–469.4)	3–4	4.33E–08	Uranine/cesium/ rubidium	061029–061123

* /SICADA/.

+ Test section vertical depth (metre above sea level) is given within brackets.

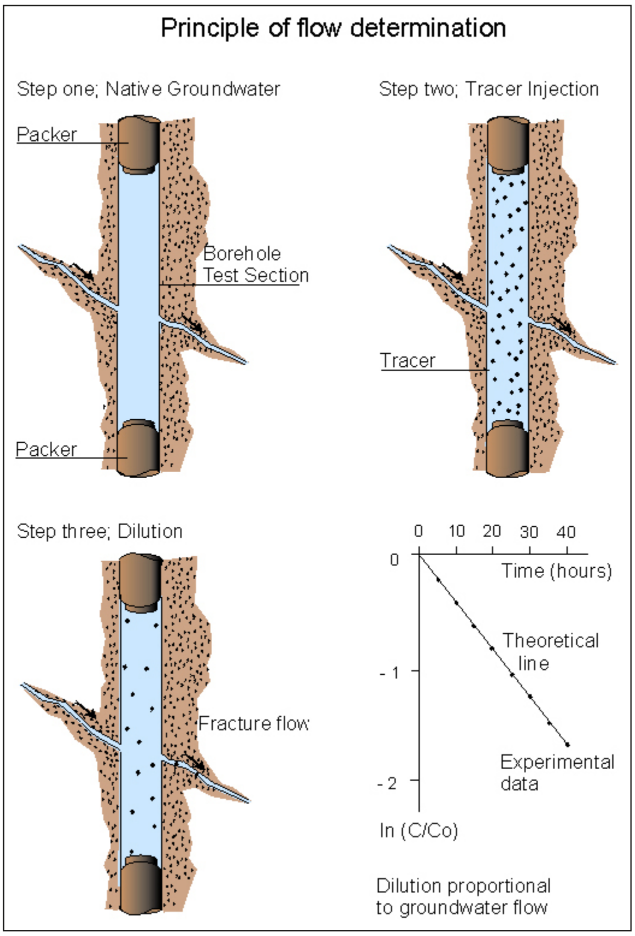

Figure 4-1. *General principles of dilution and flow determination.*

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

$$\ln(C/C_0) = -\frac{Q_w}{V} \cdot t \qquad \text{(Equation 4-1)}$$

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). Since V is known, the flow rate may then be determined from the slope of the line in a plot of ln (C/C_0), or ln C, versus t.

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

$$A = 2 \cdot r \cdot L \cdot \alpha \qquad \text{(Equation 4-2)}$$

where A is the cross-sectional area (m^2) perpendicular to groundwater flow, r is borehole radius (m), L is the length (m) of the borehole test section and α is the correction factor. Figure 4-2 schematically shows the cross-sectional area, A, and how flow lines converge and diverge in the vicinity of the borehole test section.

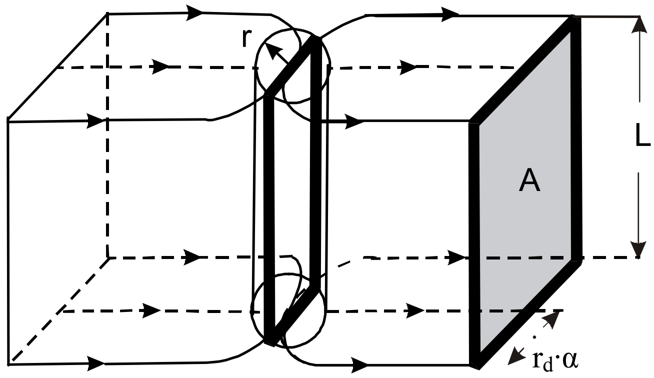

Figure 4-2. *Diversion and conversion of flow lines in the vicinity of a borehole test section.*

Assuming laminar flow in a plane parallel fissure or a homogeneous porous medium, the correction factor α is calculated according to Equation (4-3), 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 axis-symmetrical and circular form.

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

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 twice the borehole radius will converge through the borehole test section, as illustrated in Figures 4-2 and 4-3.

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 4-3, 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). 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 2002/ and /Rhén et al. 1991/.

In order to obtain the Darcy velocity in the undisturbed rock the calculated groundwater flow, Q_w is divided by A, Equation 4-4.

$$v = Q_w / A \qquad \text{(Equation 4-4)}$$

The hydraulic gradient is then calculated as

$$I = v/K \qquad \text{(Equation 4-5)}$$

where K is the hydraulic conductivity.

4.4.2 The dilution method – evaluation and analysis

The first step of evaluation included studying a graph of the measured concentration versus time data. For further evaluation background concentration, i.e. any tracer concentration in the groundwater before tracer injection, was subtracted from the measured concentrations.

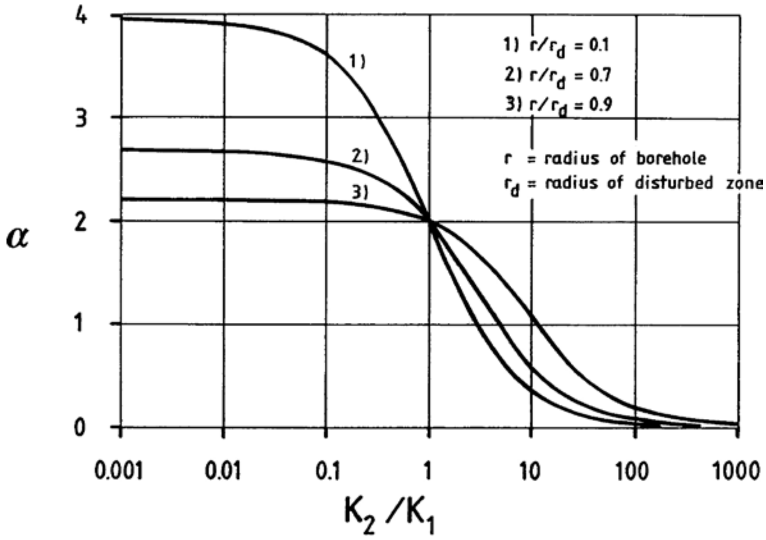

Figure 4-3. *The correction factor, α, as a function of K_2/K_1 at different radial extent (r/r_d) of the disturbed zone (skin zone) around the borehole.*

Thereafter ln (C/C_0) was plotted versus time. In most cases that relationship was linear and the proportionality constant was then calculated by performing a linear regression. In the cases where the relationship between ln (C/C_0) and time was non-linear, a sub-interval was chosen in which the relationship was linear.

The value of ln (C/C_0)/t obtained from the linear regression was then used to calculate Q_w according to Equation (4-1).

The hydraulic gradient, I, was calculated by combining Equations (4-2), (4-4) and (4-5), and choosing $\alpha = 2$. The hydraulic conductivity, K, in Equation (4-5) was obtained from previously performed Posiva Flow Log measurements (PFL) /SICADA/.

4.4.3 SWIW test – basic outline

A Single Well Injection Withdrawal (SWIW) test may consist of all or some of the following phases:

1. filling-up pressure vessel with groundwater from the selected fracture,
2. injection of water to establish steady state hydraulic conditions (pre-injection),
3. injection of one or more tracers,
4. injection of groundwater (chaser fluid) after tracer injection is stopped,
5. waiting phase,
6. withdrawal (recovery) phase.

The tracer breakthrough data used for evaluation are obtained from the withdrawal phase. The injection of chaser fluid, i.e. groundwater from the pressure vessel, has the effect of pushing the tracer out as a "ring" in the formation surrounding the tested section. This is generally a benefit, because when the tracer is pumped back, both ascending and descending parts are obtained in the recovery breakthrough curve. During the waiting phase there is no injection or withdrawal of fluid. The purpose of this phase is to increase the time available for time-dependent transport-processes so that these may be more easily evaluated from the resulting breakthrough curve. A schematic example of a resulting breakthrough curve during a SWIW test is shown in Figure 4-4.

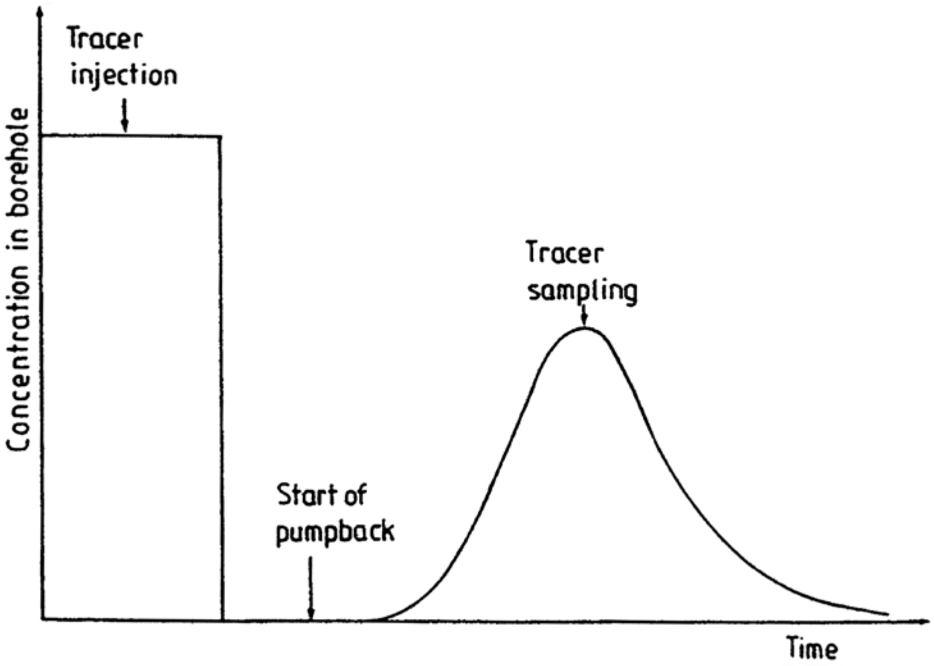

Figure 4-4. *Schematic tracer concentration sequence during a SWIW test /Andersson 1995/.*

The design of a successful SWIW test requires prior determination of injection and withdrawal flow rates, duration of tracer injection, duration of the various injections, waiting and pumping phases, selection of tracers, tracer injection concentrations, etc.

4.4.4 SWIW test – evaluation and analysis

The model evaluation of the experimental results was carried out assuming homogenous conditions. Model simulations were made using the model code SUTRA /Voss 1984/ and the experiments were simulated without a background hydraulic gradient. It was assumed that flow and transport occur within a planar fracture zone of some thickness. The volume available for flow was represented by assigning a porosity value to the assumed zone. Modelled transport processes include advection, dispersion and linear equilibrium sorption.

The sequence of the different injection phases was modelled as accurately as possible based on supporting data for flows and tracer injection concentration. Generally, experimental flows and times may vary from one phase to another, and the flow may also vary within phases. The specific experimental sequences for the borehole sections are listed in Table 5-2.

In the simulation model, tracer injection was simulated as a function accounting for mixing in the borehole section and sorption (for cesium and rubidium) on the borehole walls. The function assumes a completely mixed borehole section and linear equilibrium surface sorption:

$$C = (C_0 - C_{in})e^{-(\frac{Q}{V_{bh}+K_a A_{bh}})t} + C_{in} \qquad \text{(Equation 4-6)}$$

where C is concentration in water leaving the borehole section and entering the formation (kg/m^3), V_{bh} is the borehole volume including circulation tubes (m^3), A_{bh} is area of borehole walls (m^2), Q is flow rate (m^3/s), C_{in} is concentration in the water entering the borehole section (kg/m^3), C_0 is initial concentration in the borehole section (kg/m^3), K_a is surface sorption coefficient (m) and t is elapsed time (s).

Based on in situ experiments /Andersson et al. 2002/ and laboratory measurements on samples of crystalline rock /Byegård and Tullborg 2005/ the sorption coefficient K_a was assigned a value of 10^{-2} m in all simulations. An example of the tracer injection input function is given in Figure 4-5, showing a 50 minutes long tracer injection phase followed by a chaser phase.

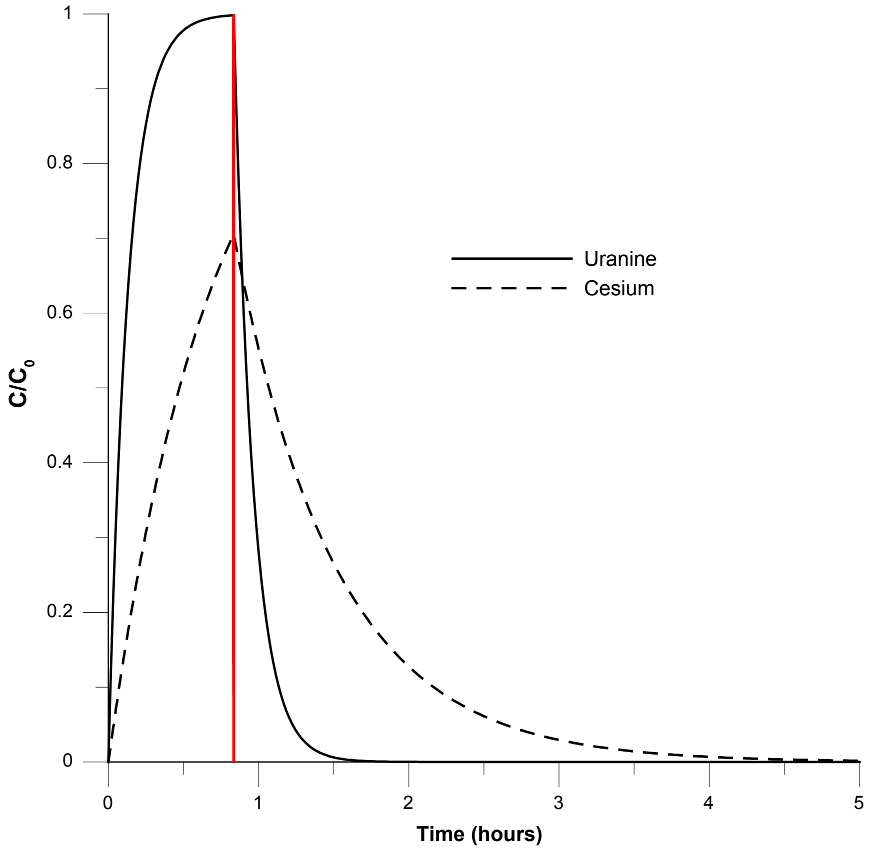

Figure 4-5. *Example of simulated tracer injection functions for a tracer injection phase (ending at 50 minutes shown by the vertical red line) immediately followed by a chaser phase.*

Non-linear regression was used to fit the simulation model to experimental data. The estimation strategy was generally to estimate the dispersivity (a_L) and a retardation factor (R), while setting the porosity (i.e. the available volume for flow) to a fixed value. Simultaneous fitting of both tracer breakthrough curves (Uranine and cesium in the example), and calculation of fitting statistics, was carried out using the approach described in /Nordqvist and Gustafsson 2004/. Tracer breakthrough curves for Uranine and rubidium are related and calculated in the same way.

4.5 Nonconformities

The activity was performed according to the activity plan and the method description with the exception that sections 400.0–405.0 m and 430.7–435.7 m was not measured as a consequence of delays in the measurement programme. These delays were caused by the following:

- The borehole water was found to have a high particle content and chemical composition that caused clogging of the optical measurement device. This delayed the measurements as cleaning of the optical device had to be done several times to obtain reliable data.
- Problems occurred with hoisting the borehole probe past the transition cone between the upper, percussion drilled and the lower core drilled, part of the borehole. Thus, hoisting for cleaning and shifting of measurement technique/tracer, aiming to achieve reliable groundwater flow measurements, took some time and delayed the measurements.
- At 359–362 m borehole length the tracer NaCl was used. However, the nearness to the power transmission line caused disturbance and scattered data, therefore NaCl was decided not to be used in the rest of the sections.

- The circulation pump needed to circulate the water for several hours in some sections before the particles in the water were rinsed out and tracer injections could start.
- One of the reference marks at 473 m could not be detected the second time a measurement was to be started in section 473.3–476.3.0 m. Reference marks from the first lowering was used instead.
- Interruptions in the data transfer were another recurrent problem. This was caused by potential drops in the electric power supply due to broken electrical (canbus) circuit or unexplainable interruptions in communication with the probe. The recovery pumping in the SWIW test was interrupted in the beginning of pumping when the canbus circuit broke.
- Damages on the multi cable as well as on the signal cable were discovered and repaired. The resistance in the optical device was changed to one with lower amplification to obtain a more stable signal.

5 Results

Original data from the reported activity are stored in the primary database Sicada, where they are traceable by the Activity Plan number (AP PS 400-06-097). Only data in SKB's databases are accepted for further interpretation and modelling. The data presented in this report are regarded as copies of the original data. Data in the databases may be revised, if needed. Such revisions will not necessarily result in a revision of the P-report, although the normal procedure is that major data revisions entail a revision of the P-report. Minor data revisions are normally presented as supplements, available at www.skb.se.

5.1 Dilution measurements

Figure 5-1 exemplifies a typical dilution curve in a fracture zone straddled by the test section at 592.0–595.0 m borehole length (583.1– 586.1 m vertical depth) in borehole KLX18A. In the first phase the background value is recorded for about half an hour. In phase two, Uranine tracer is injected, and after mixing a start concentration (C_0) of about 0.93 mg/l is achieved. In phase three the dilution is measured for about 30 hours. Thereafter the packers are deflated and the remaining tracer flows out of the test section. Figure 5-2 shows the measured pressure during the dilution measurement. Since the pressure gauge is positioned about seven metres from top of test section there is a bias from the pressure in the test section which is not corrected for, as only changes and trends relative to the start value are of great importance for the dilution measurement. Figure 5-3 is a plot of the ln (C/C_0) versus time data and linear regression best fit to data showing a good fit with correlation R^2 = 0.9931. The standard deviation, STDAV, shows the mean divergence of the values from the best fit line and is calculated from

$$\text{STDAV} = \sqrt{\frac{n\sum x^2 - \left(\sum x\right)^2}{n(n-1)}}$$

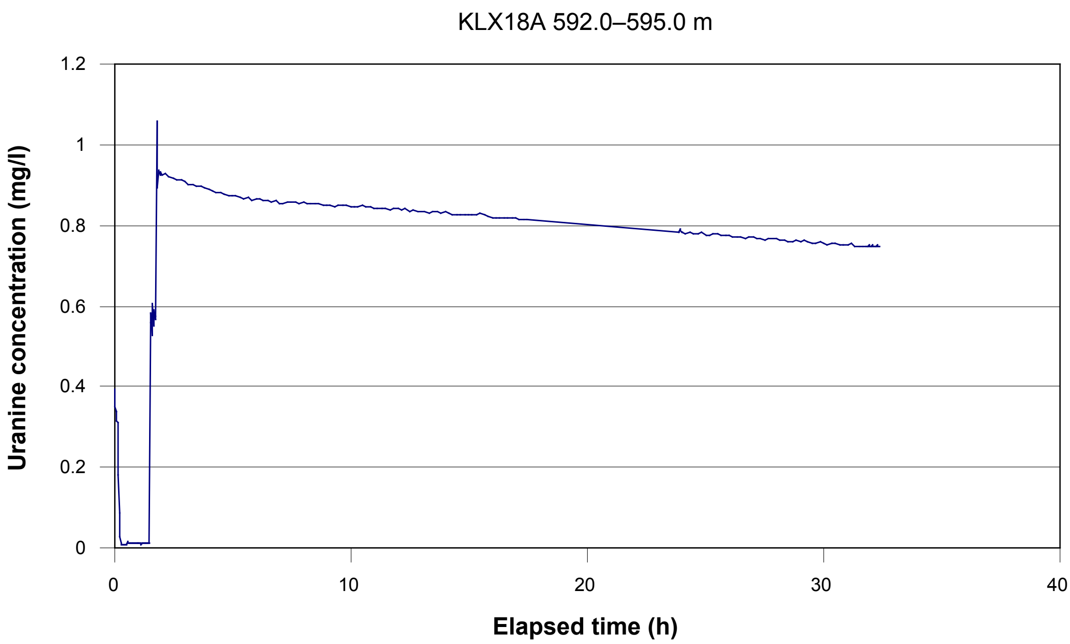

Figure 5-1. *Dilution measurement in borehole KLX18A, section 592.0–595.0 m. Uranine concentration versus time.*

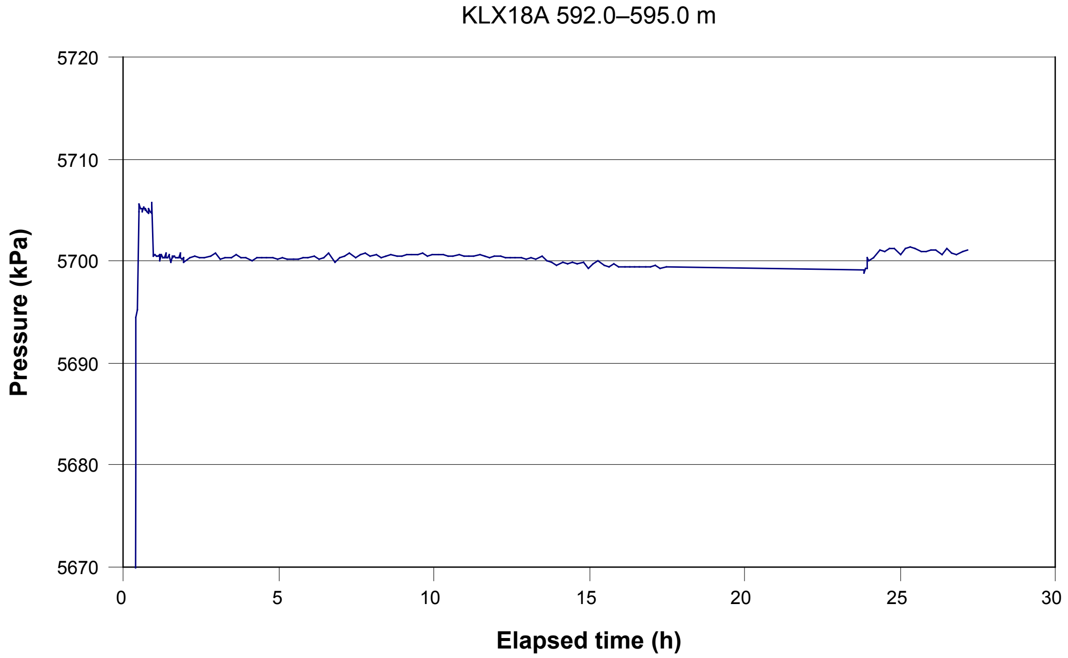

Figure 5-2. *Measured pressure during dilution measurement in borehole KLX18A, section 592.0–595.0 m.*

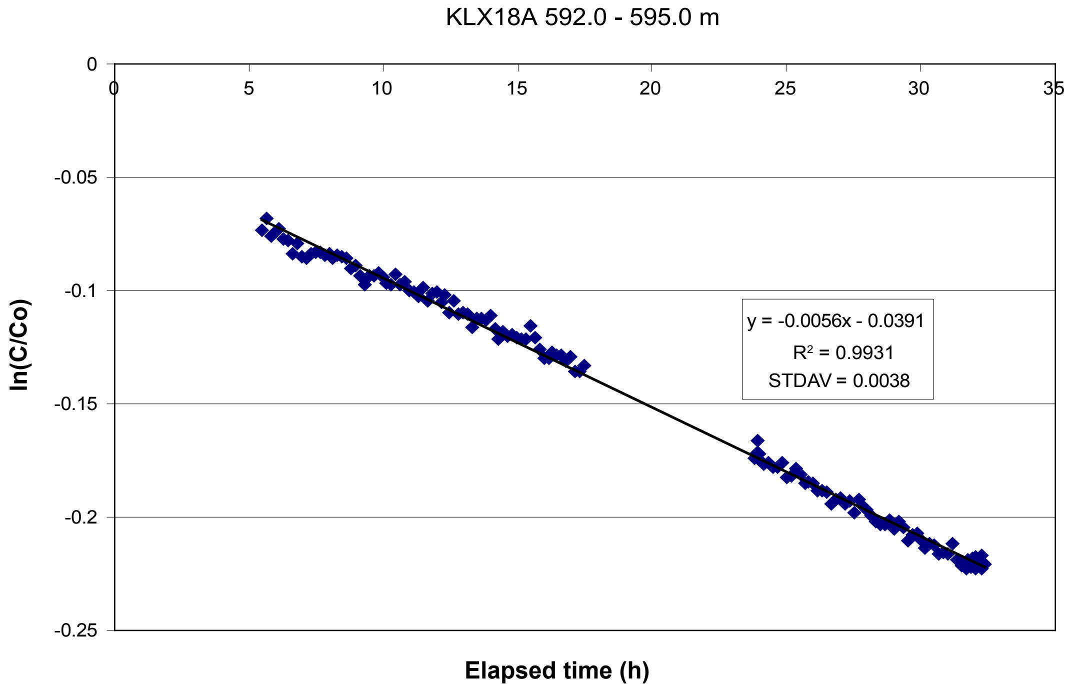

Figure 5-3. *Linear regression best fit to data from dilution measurement in borehole KLX18A, section 592.0–595.0 m.*

Calculated groundwater flow rate, Darcy velocity and hydraulic gradient are presented in Table 5-1 together with the results from all other dilution measurements carried out in borehole KLX18A.

The dilution measurements were carried out either with the dye tracer Uranine or the saline tracer NaCl. Uranine tracer was the first choice because it normally has a low background concentration and the tracer can be injected and measured in concentrations far above the background value, which gives a large dynamic range and accurate flow determinations. However, in some test sections precipitations and groundwater composition made it impossible to perform in situ measurements of Uranine with the fluorescence technique, which is an optical method. NaCl tracer, measured by means of electric conductivity, was then used instead. The drawback with NaCl measurements is the high background concentration at larger depth. Changes in the background concentration may have an influence on the measured tracer concentration in the test section, and thus also on the determined groundwater flow rate.

Details of all dilution measurements, with diagrams of dilution versus time and the supporting parameters pressure, temperature and circulation flow rate are presented in Appendix B1–B5.

5.1.1 KLX18A, section 146.0–149.0 m

This dilution measurement was carried out with the dye tracer Uranine in a test section with four flowing fractures. The complete test procedure can be followed in Figure 5-4. Background concentration (0.036 mg/l) is measured for about 26 hour while the water is circulated to rinse the dirty borehole water. Thereafter the Uranine tracer is injected in four steps, and after mixing it finally reaches a start concentration of 0.69 mg/l above background. Dilution is measured for about 43 hours with several interruptions in the data transfer. The packers are then deflated. Hydraulic pressure is stable (Appendix B1). The final evaluation was made on the 80 to 117 hours part of the dilution curve. The regression line fits well to the slope of the dilution with a correlation coefficient of R^2 = 0.9540 for the best fit line (Figure 5-5). The groundwater flow rate, calculated from the best fit line, is 0.089 ml/min. Calculated hydraulic gradient is 0.021 and Darcy velocity $3.3 \cdot 10^{-9}$ m/s.

5.1.2 KLX18A, section 359.0–362.0 m

This dilution measurement was carried out with the dye tracer NaCl in a test section with two flowing fractures. The background measurement, tracer injection and dilution can be followed in Figure 5-6. Background concentration is 0.32 g/l. The NaCl tracer is injected in three steps and after mixing it reaches a start concentration of 5.54 g/l above background. Dilution is measured for about 90 hours, thereafter the packers are deflated and the remaining tracer flows out of the test section. Hydraulic pressure is stable but shows small diurnal pressure variations

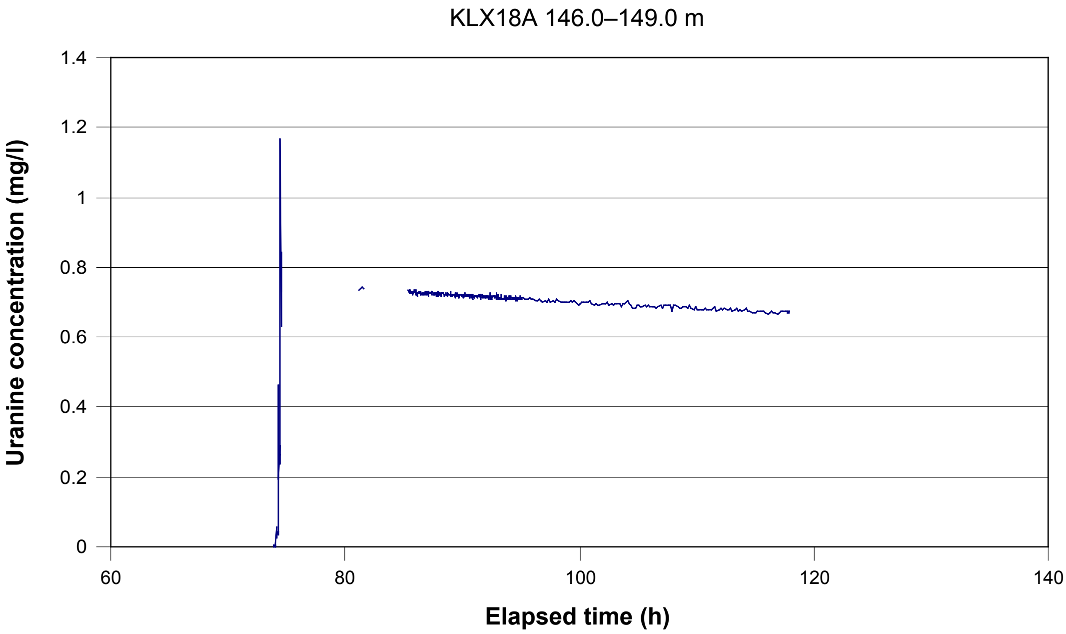

Figure 5-4. *Dilution measurement in borehole KLX18A, section 146.0–149.0 m. Uranine concentration versus time.*

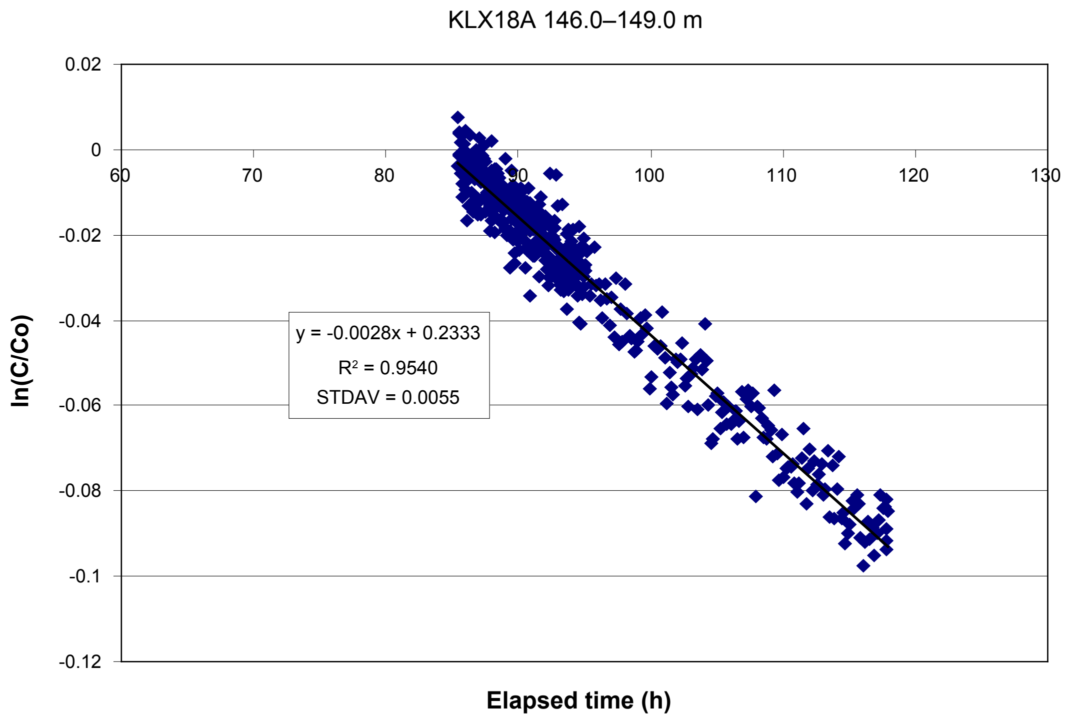

Figure 5-5. *Linear regression best fit to data from dilution measurement in borehole KLX18A , section 146.0–149.0 m.*

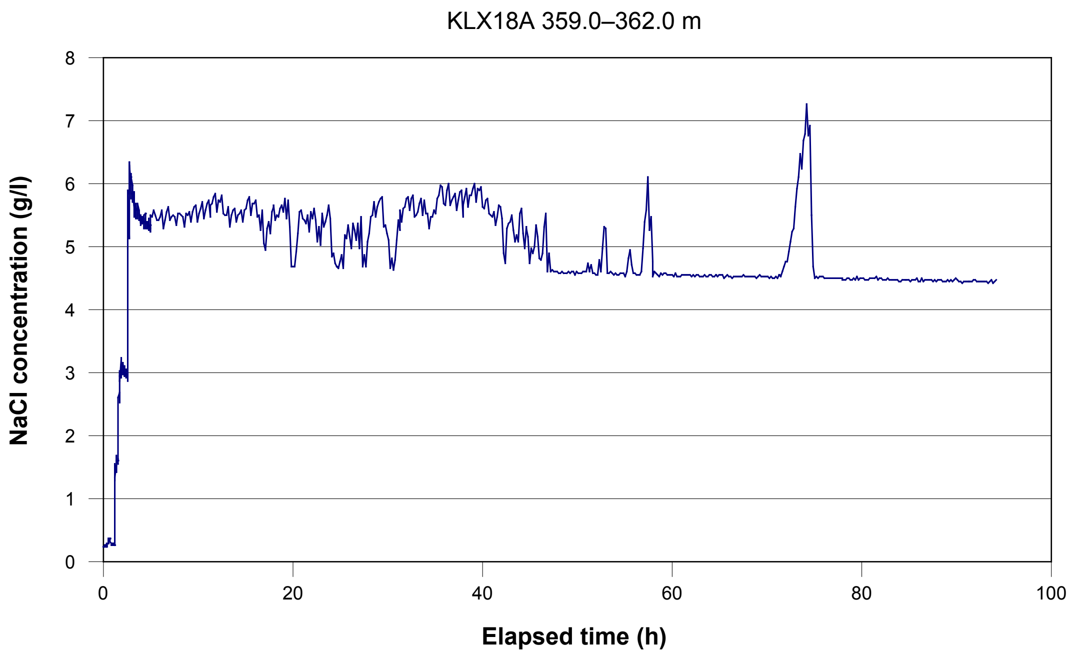

Figure 5-6. *Dilution measurement in borehole KLX18A, section 359.0–362.0 m. NaCl concentration versus time.*

due to earth tidal effects (Appendix B2). Groundwater flow is determined from the 47–94 hours part of the dilution measurement. The correlation coefficient of the best fit line is $R^2 = 0.9028$ (Figure 5-7), and the groundwater flow rate, calculated from the best fit line, is 0.022 ml/min. Calculated hydraulic gradient is 0.010 and Darcy velocity $8.1 \cdot 10^{-10}$ m/s.

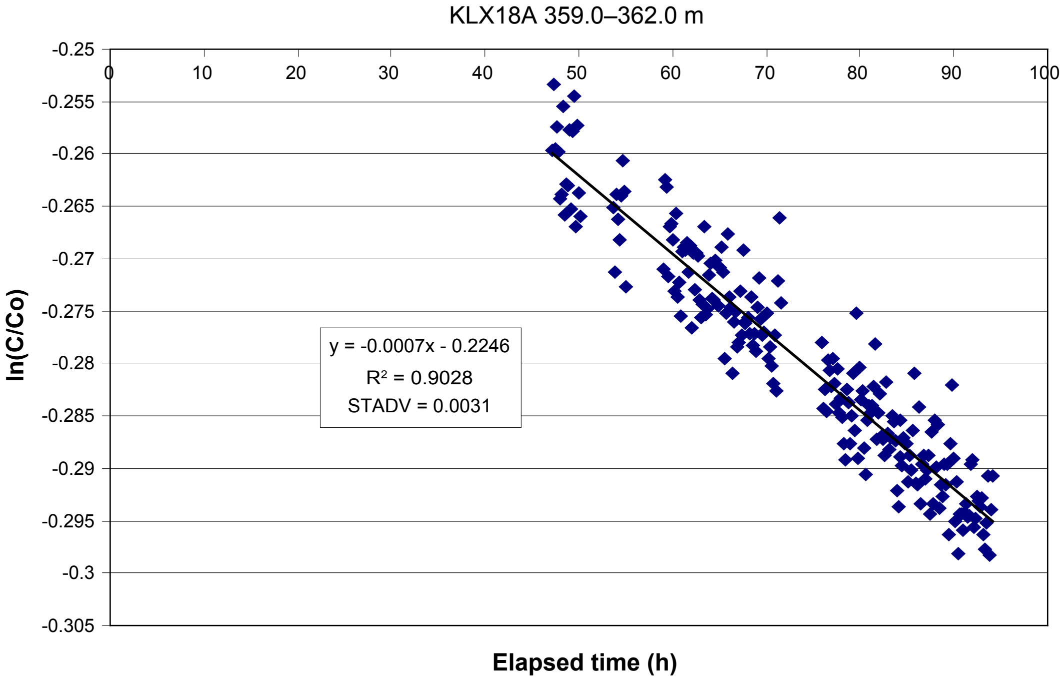

Figure 5-7. *Linear regression best fit to data from dilution measurement in borehole KLX18A , section 359.0–362.0 m.*

5.1.3 KLX18A, section 473.3–476.3 m

This dilution measurement was carried out in a test section with three to four flowing fractures. The background measurement, tracer injection and dilution can be followed in Figure 5-8. Background concentration (0.004 mg/l) is measured for about 30 minutes with the packers inflated. The Uranine tracer is injected in three steps and after mixing it reaches a start concentration of 1.02 mg/l above background. Dilution is measured for about 260 hours. Thereafter the packers are deflated and the remaining tracer flows out of the test section. The borehole water was found to have high particle content and a chemical composition which appears to have caused a clogging of the optical device, this might explain the odd shape of the dilution curve. Hydraulic pressure shows small diurnal pressure variations due to earth tidal effects (Appendix B3). At the end an increase in pressure is shown, therefore the final evaluation was made from 10 to 237 hours of elapsed time when the pressure is stable. The regression line does not fit very well to the slope of the dilution curve, although the correlation coefficient for the best fit line is good, $R^2 = 0.9396$ (Figure 5-9). The groundwater flow rate, calculated from the best fit line, is 0.041 ml/min. Calculated hydraulic gradient is 0.10 and Darcy velocity $1.5 \cdot 10^{-9}$ m/s. The hydraulic gradient is large and may be caused by local effects, where the measured fracture constitutes a hydraulic conductor between other fractures with different hydraulic heads, or wrong estimates of the correction factor, α, and/or the hydraulic conductivity of the fracture. Clogging of the optical device due to the particle content and chemical composition in the water may give some contribution to the estimated large hydraulic gradient. The hydraulic transmissivity of the section is near the lower limit of measurement range for the dilution probe which may decrease accuracy in determined groundwater flow rate.

5.1.4 KLX18A, section 562.0–565.0 m

This dilution measurement was carried out with the dye tracer Uranine in a test section with two to three flowing fractures. The background measurement, tracer injection and dilution can be followed in Figure 5-10. Background concentration (0.004 mg/l) is measured for about one hour. Thereafter the Uranine tracer is injected in three steps and after mixing it finally reaches a start concentration of 0.99 mg/l above background. Dilution is measured for about 60 hours.

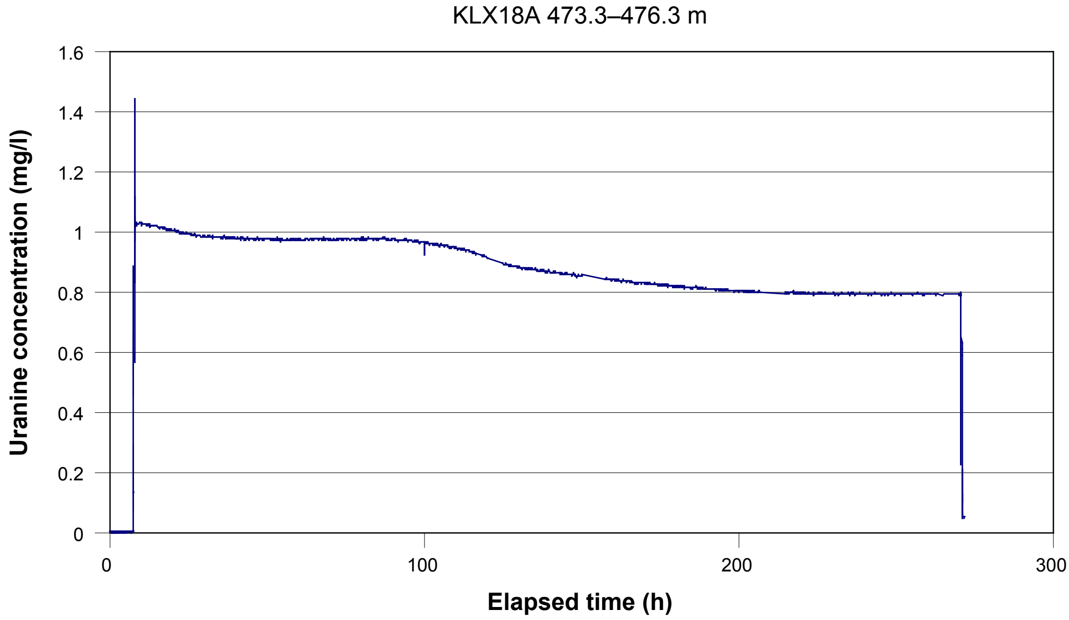

Figure 5-8. Dilution measurement in borehole KLX18A, section 473.3–476.3 m. Uranine concentration versus time.

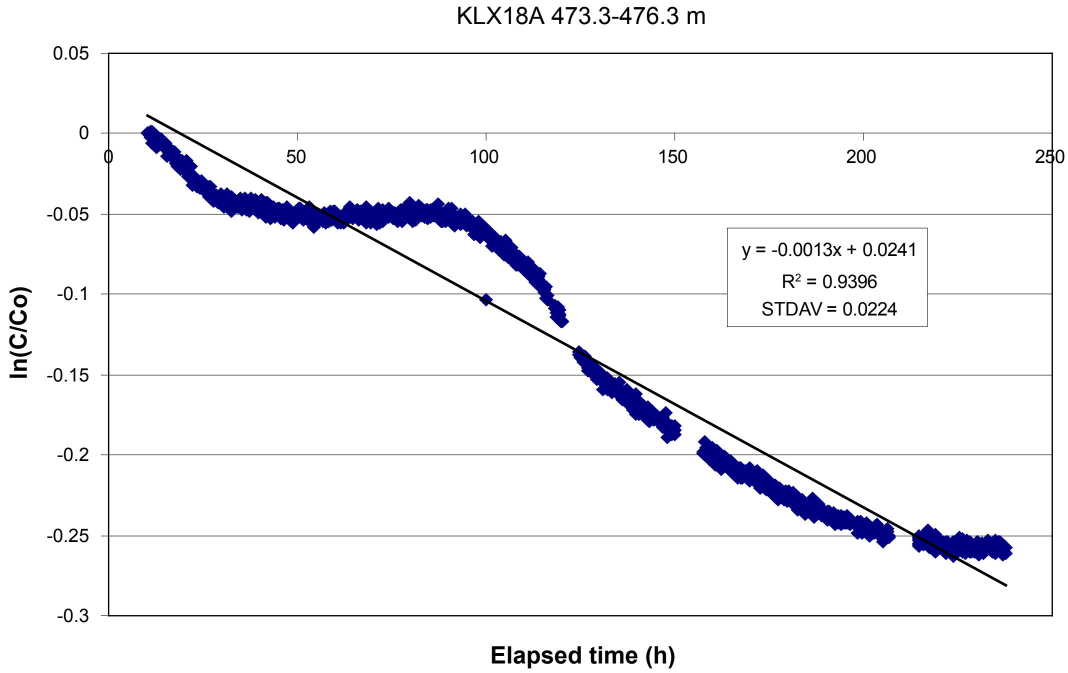

Figure 5-9. Linear regression best fit to data from dilution measurement in borehole KLX18A, section 473.3–476.3 m.

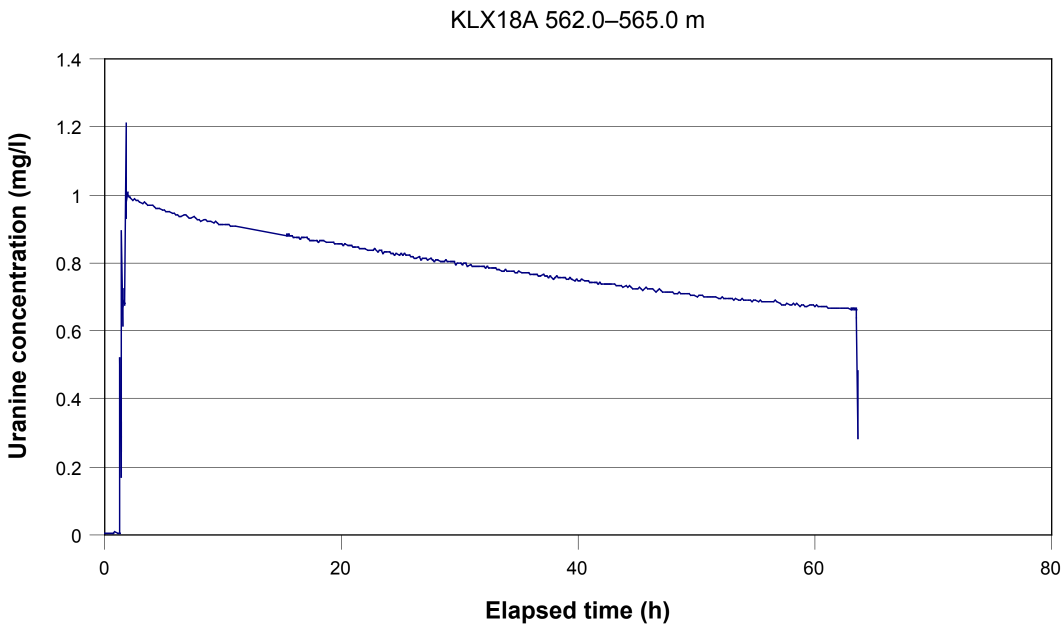

Figure 5-10. *Dilution measurement in borehole KLX18A, section 562.0–565.0 m. Uranine concentration versus time.*

Thereafter the packers are deflated and the remaining tracer flows out of the test section. Hydraulic pressure is stable but shows small diurnal pressure variations due to earth tidal effects (Appendix B4). Groundwater flow is determined from the 6–63 hours part of the dilution measurement. The correlation coefficient of the best fit line is $R^2 = 0.9947$ (Figure 5-11), and the groundwater flow rate, calculated from the best fit line, is 0.20 ml/min. Calculated hydraulic gradient is 0.043 and Darcy velocity $7.2 \cdot 10^{-9}$ m/s.

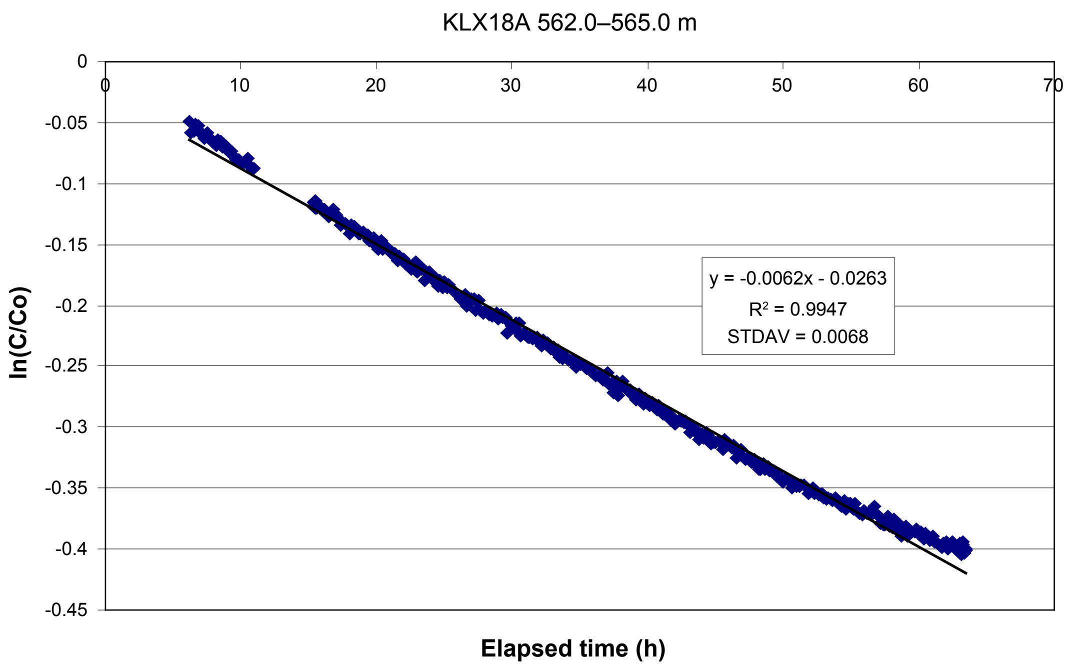

Figure 5-11. *Linear regression best fit to data from dilution measurement in borehole KLX18A, section 562.0–565.0 m.*

5.1.5 KLX18A, section 592.0–595.0 m

This dilution measurement was carried out with the dye tracer Uranine in a test section with three to four flowing fractures. The background measurement, tracer injection and dilution can be followed in Figure 5-12. Background concentration (0.010 mg/l) is measured for about 30 minutes. Thereafter the Uranine tracer is injected in two steps and after mixing it finally reaches a start concentration of 0.92 mg/l above background. Dilution is measured for about 30 hours. Thereafter the packers are deflated and the remaining tracer flows out of the test section. Hydraulic pressure is stable (Appendix B5). Groundwater flow is determined from the 5–27 hours part of the dilution measurement. The correlation coefficient of the best fit line is $R^2 = 0.9931$ (Figure 5-13), and the groundwater flow rate, calculated from the best fit line, is 0.18 ml/min. Calculated hydraulic gradient is 0.021 and Darcy velocity $6.5 \cdot 10^{-9}$ m/s.

5.1.6 Summary of dilution results

Calculated groundwater flow rates, Darcy velocities and hydraulic gradients from all dilution measurements carried out in borehole KLX18A are presented in Table 5-1.

The results show small variations in groundwater flow during natural, i.e. undisturbed, conditions, with flow rates from 0.022 to 0.20 ml/min and Darcy velocities from $8.1 \cdot 10^{-10}$ to $7.2 \cdot 10^{-9}$ m/s. In this study the flow rates and Darcy velocities increase with depth. An exception is the shallow section at c. 146 m, where the flow rate and Darcy velocity is high which is in accordance with results at similar depths in other boreholes in the area. The highest flow rates, Darcy velocities and hydraulic gradients were measured in the sections in the lower part of the borehole outside the deformation zones at c. 562–565 and 592–595 m borehole length (553.7–556.7 and 583.1–586.1 m vertical depth), see Figures 5-14, 5-15 and 5-16. The lowest flow rate, Darcy velocity and hydraulic gradient is measured in the section intersecting deformation zone DZ4 at 359.0–362.0 m borehole length (354.0–357.0 m vertical depth). Correlation between flow rate and transmissivity is indicated in Figure 5-17, with the highest flow rates at high transmissivity. An exception is section 473.3–476.3 m borehole length (466.5–469.5 m vertical depth) in deformation zone DZ9 where the flow rate is higher than the transmissivity

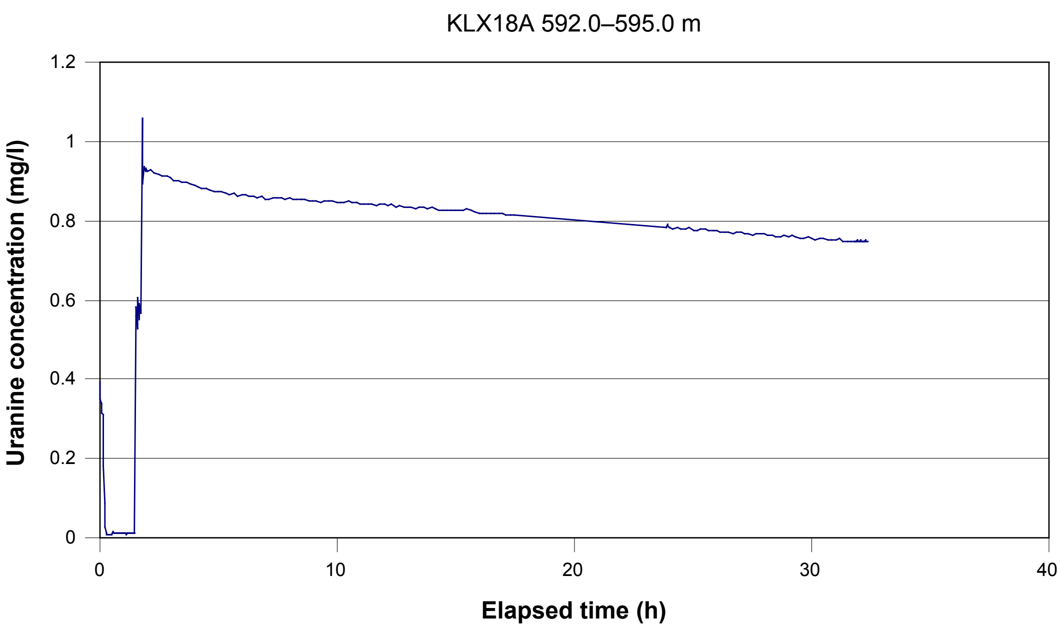

Figure 5-12. Dilution measurement in borehole KLX18A, section 592.0–595.0 m. Uranine concentration versus time.

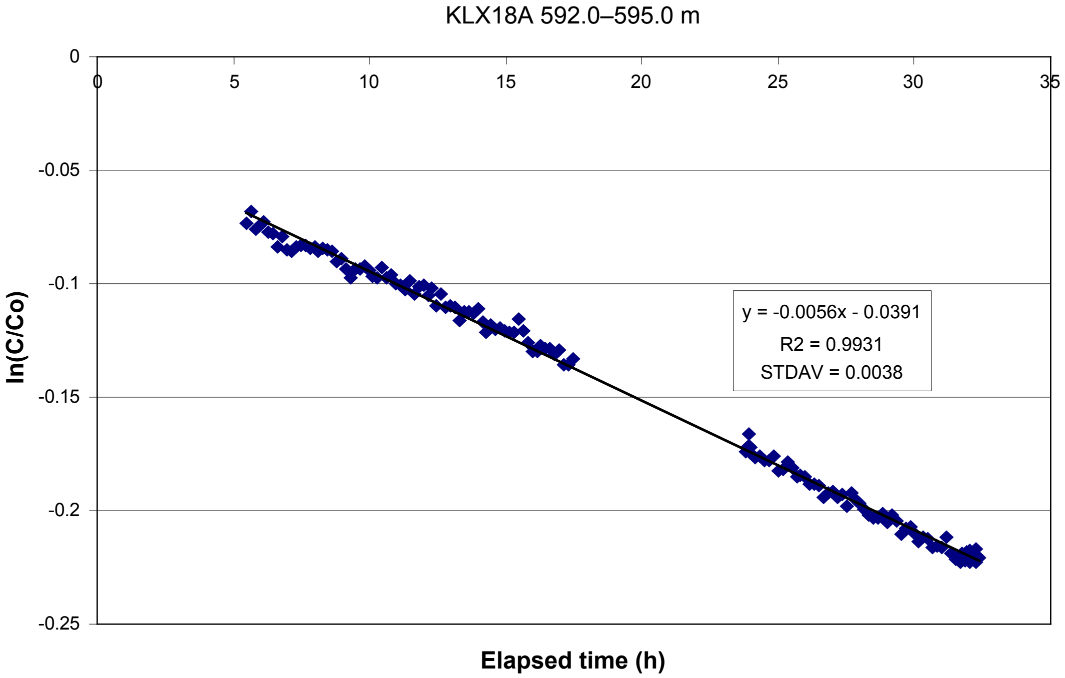

Figure 5-13. *Linear regression best fit to data from dilution measurement in borehole KLX18A, section 592.0–595.0 m.*

Table 5-1. Groundwater flow rates, Darcy velocities and hydraulic gradients for all measured sections in borehole KLX18A.

Borehole	Test section (m)+	Number of flowing fractures*	T (m^2/s)*	Q (ml/min)	Q (m^3/s)	Darcy velocity (m/s)	Hydraulic gradient
KLX18A	146.0–149.0 (144.2–147.2)	4	4.61E–07	0.089	1.5E–09	3.3E–09	0.021
KLX18A	359.0–362.0 (354.0–357.0)	2	2.34E–07	0.022	3.7E–10	8.1E–10	0.010
KLX18A	473.3–476.3 (466.5–469.4)	3–4	4.33E–08	0.041	6.9E–10	1.5E–09	0.10
KLX18A	562.0–565.0 (553.7–556.6)	2–3	5.07E–07	0.20	3.3E–09	7.2E–09	0.043
KLX18A	592.0–595.0 (583.1–586.1)	3–4	9.52E–07	0.18	3.0E–09	6.5E–09	0.021

* /SICADA/.

+ Test section vertical depth (metre above sea level) is given within brackets.

indicates. The hydraulic gradient, calculated according to the Darcy concept, is large in the section at c. 473 m, Figure 5-16. In the other measured sections the hydraulic gradients are within the expected range. It is not clear if the large gradient are caused by local effects where the measured fractures constitute hydraulic conductors between other fractures with different hydraulic heads or due to wrong estimates of the correction factor, α, and/or the hydraulic conductivity of the fracture. The high particle content and the chemical composition in the water at this depth may give some contribution to the estimated large hydraulic gradient in the section.

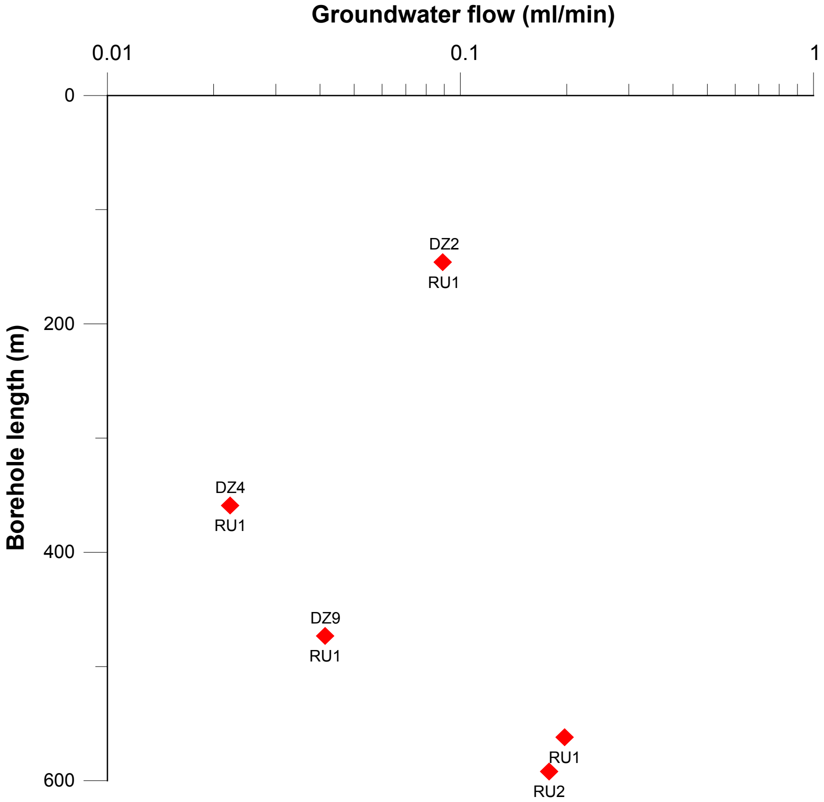

Figure 5-14. *Groundwater flow rate versus borehole length during natural hydraulic gradient conditions. Results from dilution measurements in fracture zones in borehole KLX18A. Labels DZ2, DZ4 and DZ9 refer to minor fracture zone notation and RU1 and RU2 refer to the rock units defined in /Carlsten et al. 2007/.*

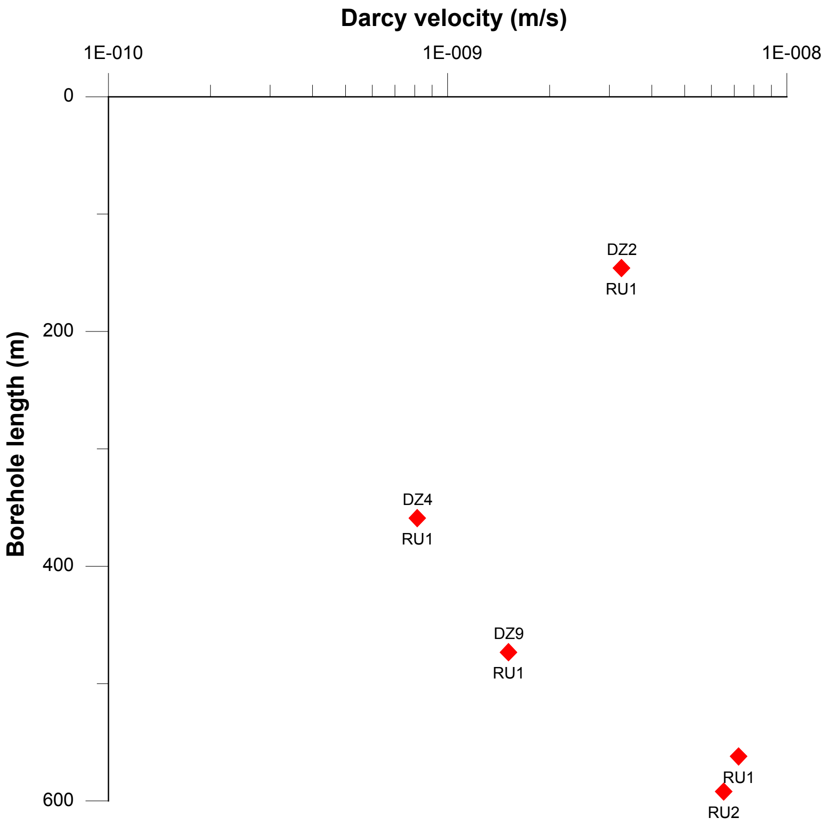

Figure 5-15. *Darcy velocity versus borehole length during natural hydraulic gradient conditions. Results from dilution measurements in fracture zones in borehole KLX18A. Labels DZ2, DZ4 and DZ9 refer to minor fracture zone notation and RU1 and RU2 refer to the rock units defined in /Carlsten et al. 2007/.*

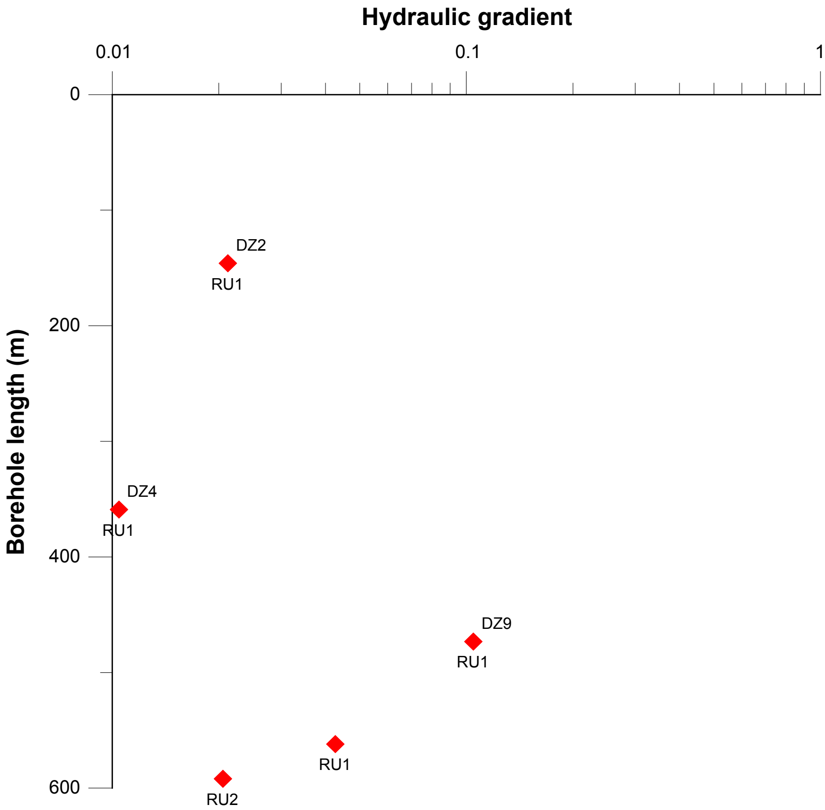

Figure 5-16. *Hydraulic gradient versus borehole length during natural hydraulic gradient conditions. Results from dilution measurements in fracture zones in borehole KLX18A. Labels DZ2, DZ4 and DZ9 refer to minor fracture zone notation and RU1 and RU2 refer to the rock units defined in /Carlsten et al. 2007/.*

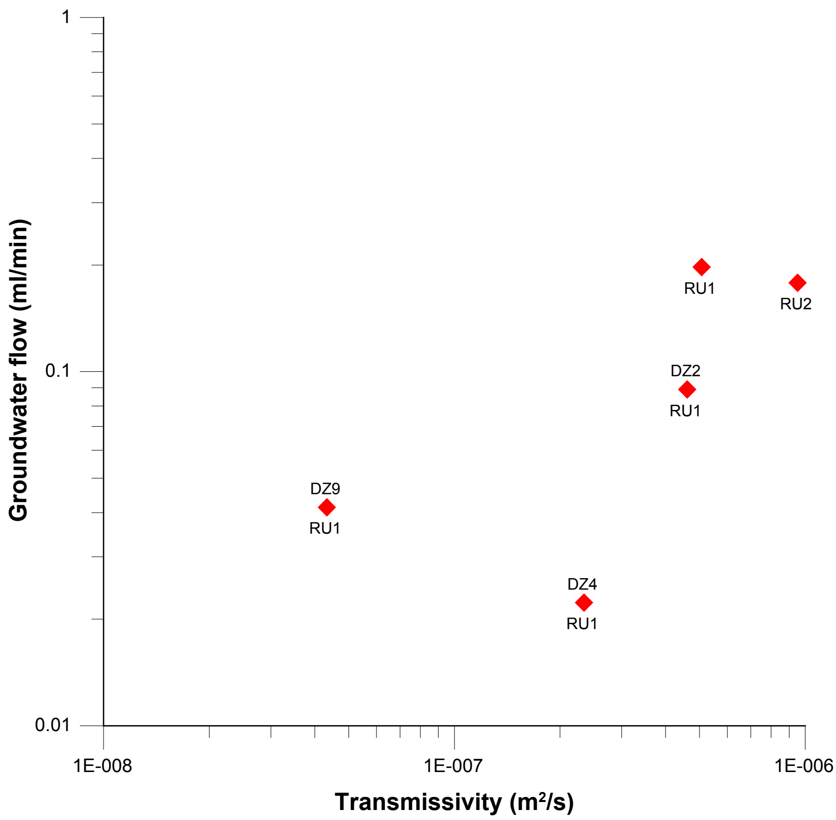

Figure 5-17. *Groundwater flow rate versus transmissivity during undisturbed, i.e. natural hydraulic gradient conditions. Results from dilution measurements in fracture zones in borehole KLX18A. Labels DZ2, DZ4 and DZ9 refer to minor fracture zone notation and RU1 and RU2 refer to the rock units defined in /Carlsten et al. 2007/.*

5.2 SWIW tests

5.2.1 Treatment of experimental data

The experimental data presented in this section have been corrected for background concentrations. Sampling times have been adjusted to account for residence times in injection and sampling tubing. Thus, time zero in all plots refers to when the fluid containing the tracer mixture begins to enter the tested borehole section.

5.2.2 Tracer recovery breakthrough in KLX18A, 473.3–476.3 m

Durations and flows for the various experimental phases are summarised in Table 5-2. The experimental breakthrough curves from the recovery phase for Uranine, cesium and rubidium respectively, are shown in Figures 5-18a to 5-18c. The time coordinates are corrected for residence time in the tubing, as described above, and concentrations are normalised through division by the total injected tracer mass.

Normalised breakthrough curves (concentration divided by total injected tracer mass) for all three tracers are plotted in Figure 5-19. The figure shows that the tracers behave in different ways, presumably caused by different sorption properties. The breakthrough curves approximately conform to what would be expected from a SWIW test using tracers of different sorption properties. The considerable difference between Uranine and the two other curves may also be seen as an indication of a relatively strong sorption effect for cesium and rubidium. The figure indicates similar tracer behaviour as in KLX03 /Gustafsson et al. 2006a/ and KSH02 /Gustafsson and Nordqvist 2005/.

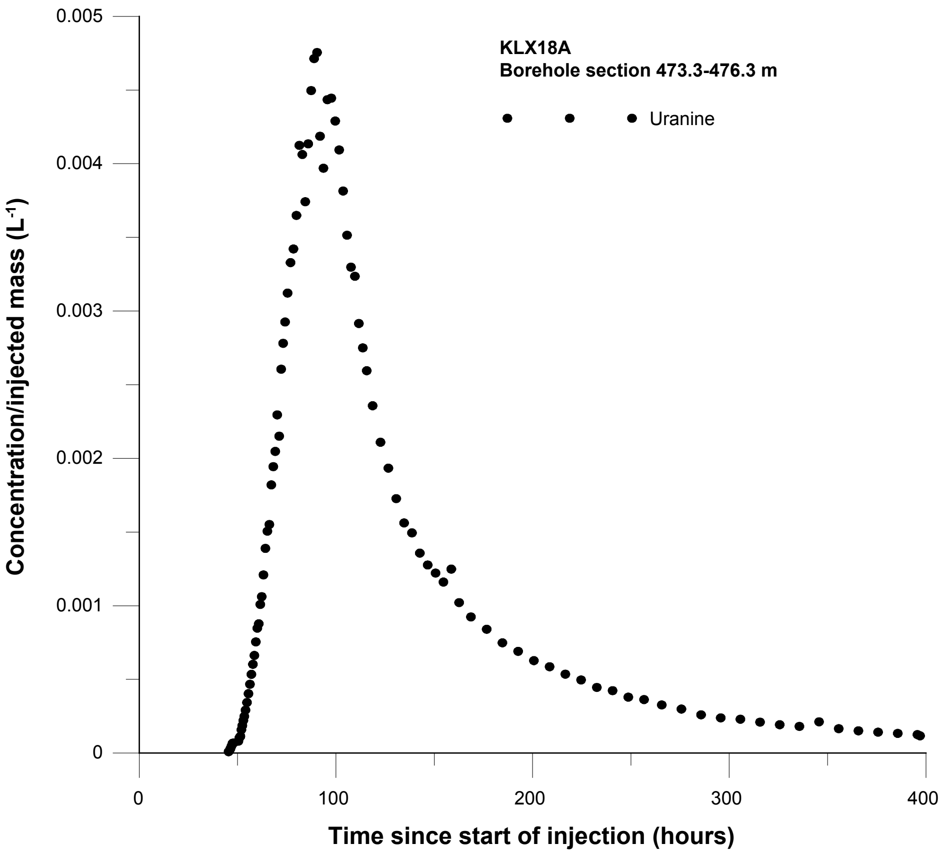

Figure 5-18a. *Normalised withdrawal (recovery) phase breakthrough curve for Uranine in section 473.3–476.3 m in borehole KLX18A.*

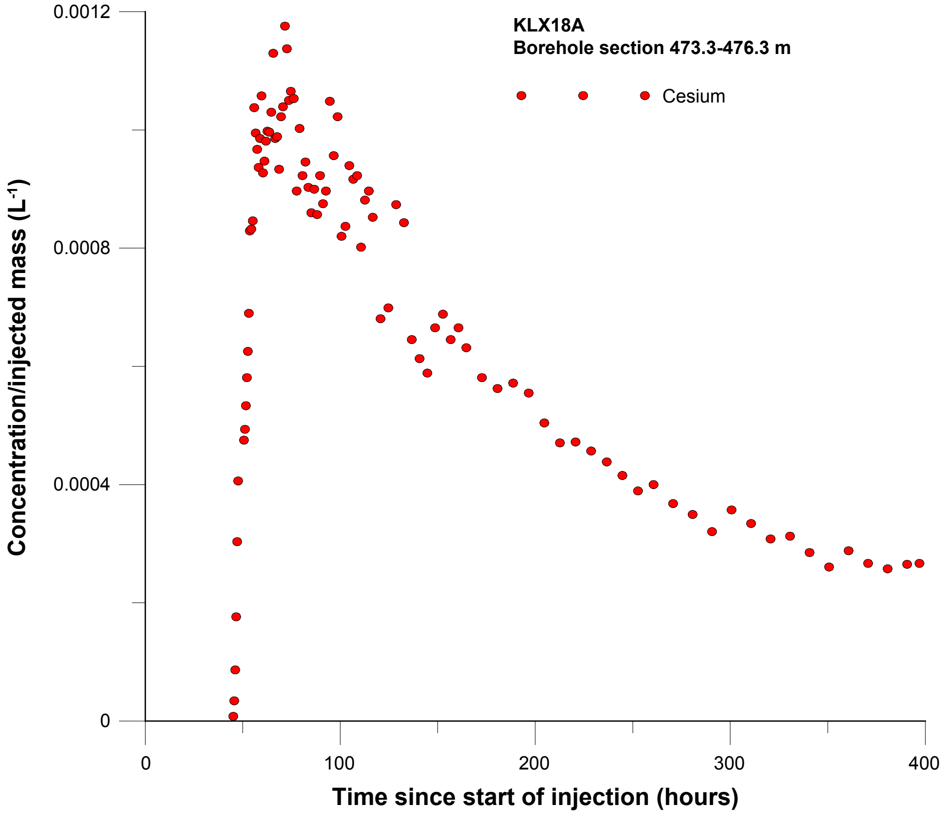

Figure 5-18b. *Normalised withdrawal (recovery) phase breakthrough curve for cesium in section 473.3–476.3 m in borehole KLX18A.*

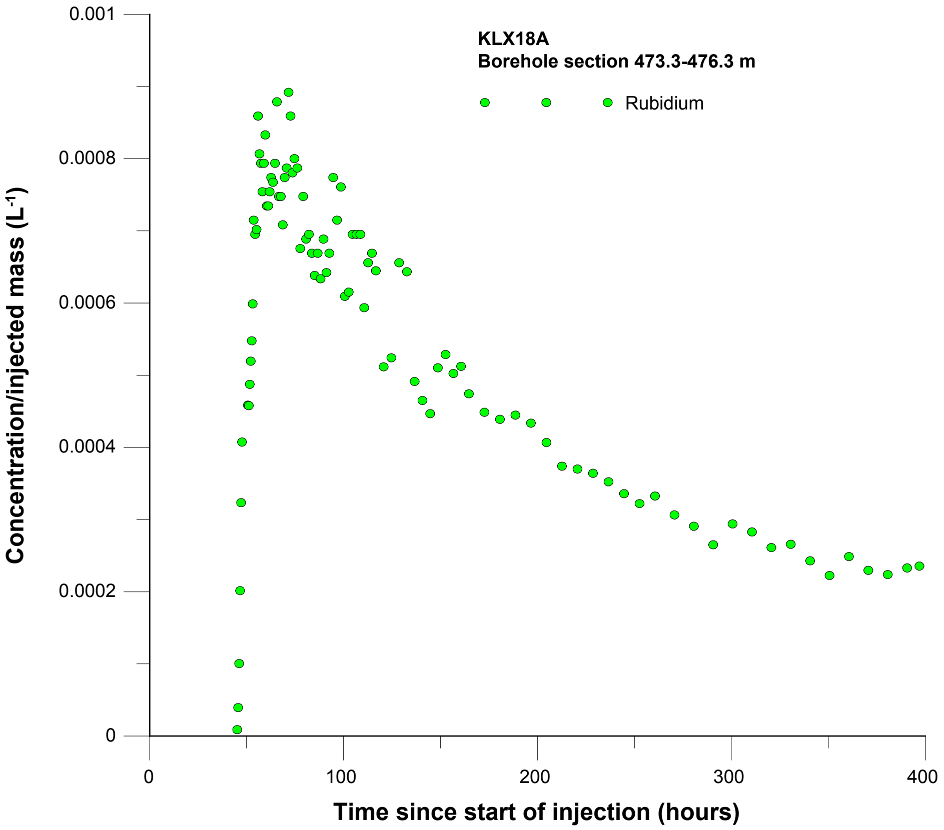

Figure 5-18c. *Normalised withdrawal (recovery) phase breakthrough curve for rubidium in section 473.3–476.3 m in borehole KLX18A.*

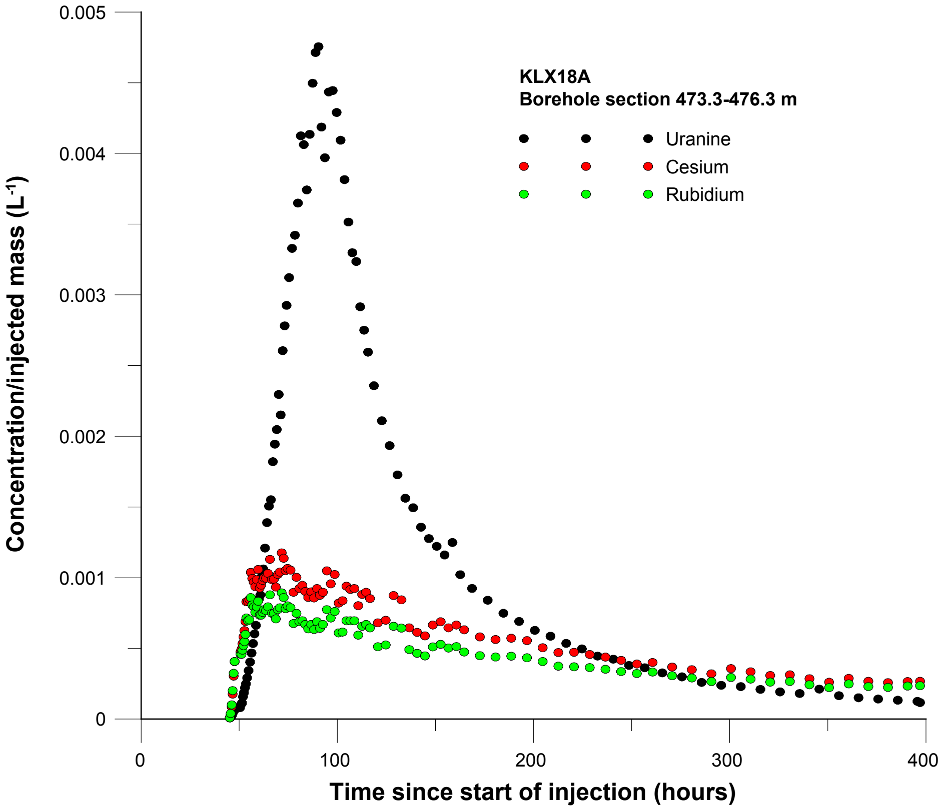

Figure 5-19. Normalised withdrawal (recovery) phase breakthrough curves for Uranine, cesium and rubidium in section 473.3–476.3 m.

Table 5-2. Durations (h) and fluid flows (L/h) during various experimental phases for section 473.3–476.3 m in borehole KLX18A. All times have been corrected for tubing residence time such that time zero refers to the time when the tracer mixture begins to enter the borehole section.

Phase	Start (h)	Stop (h)	Volume (L)	Average flow (L/h)	Cumulative injected volume (L)
Pre-injection	–5.27	0.00	12.65	2.40	12.65
Tracer injection	0.00	4.98	14.35	2.88	27.00
Chaser injection	4.98	45.15	96.71	2.41	123.71
Recovery	45.15	402.80	891.60	2.49	

The tracer recovery from the recovery phase pumping is rather difficult to estimate from the experimental breakthrough curves, because the tailing parts appear to continue well beyond the last sampling time. Preliminary estimation of recovery from the experimental breakthrough curves at the last sampling time yields values of 86.8%, 46.4% and 36.7% for Uranine, cesium and rubidium, respectively. These estimates are based on the average flow rate during the recovery phase.

The peak of the rubidium curve is lower than for cesium, which would indicate stronger sorption capacity.

Final tracer recovery values, i.e. that would have resulted if pumping had been allowed to continue until tracer background values, are difficult to estimate from the experimental curves. However, plausible visual extrapolations of the curves do not clearly indicate incomplete recovery and that the tracer recovery would be different among the three tracers. Thus, for the subsequent model evaluation, it is assumed that tracer recovery is the same for all of the tracers.

5.2.3 Model evaluation KLX18A, 473.3–476.3 m

The model simulations were carried out assuming negligible hydraulic background gradient, i.e. radial flow. The simulated times and flows for the various experimental phases are given in Table 5-2.

From the dilution measurements, the ambient flow through the borehole section was estimated at about 0.041 ml/min, see Table 5-1, which is very small compared with the average flow rates during the SWIW test. The simulated times and flows for the various experimental phases are given in Table 5-2. This borehole section is interpreted to consist of 3–4 flowing fractures, see Table 5-1. In the simulation model, the flow zone is approximated by a 0.1 m thick fracture zone.

The experimental evaluation was carried out by simultaneous model fitting of Uranine and a sorbing tracer as outlined in section 4.4. Thus, separate regression analyses were carried out for simultaneous fitting of Uranine/cesium and Uranine/rubidium, respectively.

For a given regression run, estimation parameters were longitudinal dispersivity (a_L) and a linear retardation factor (R), while the porosity is given a fixed value. Regression was carried out for five different values of porosity: 0.002, 0.005, 0.01, 0.02 and 0.05. For all cases, the fits between model and experimental data are similar. Example of model fits are shown in Figure 5-20a and Figure 5-20b.

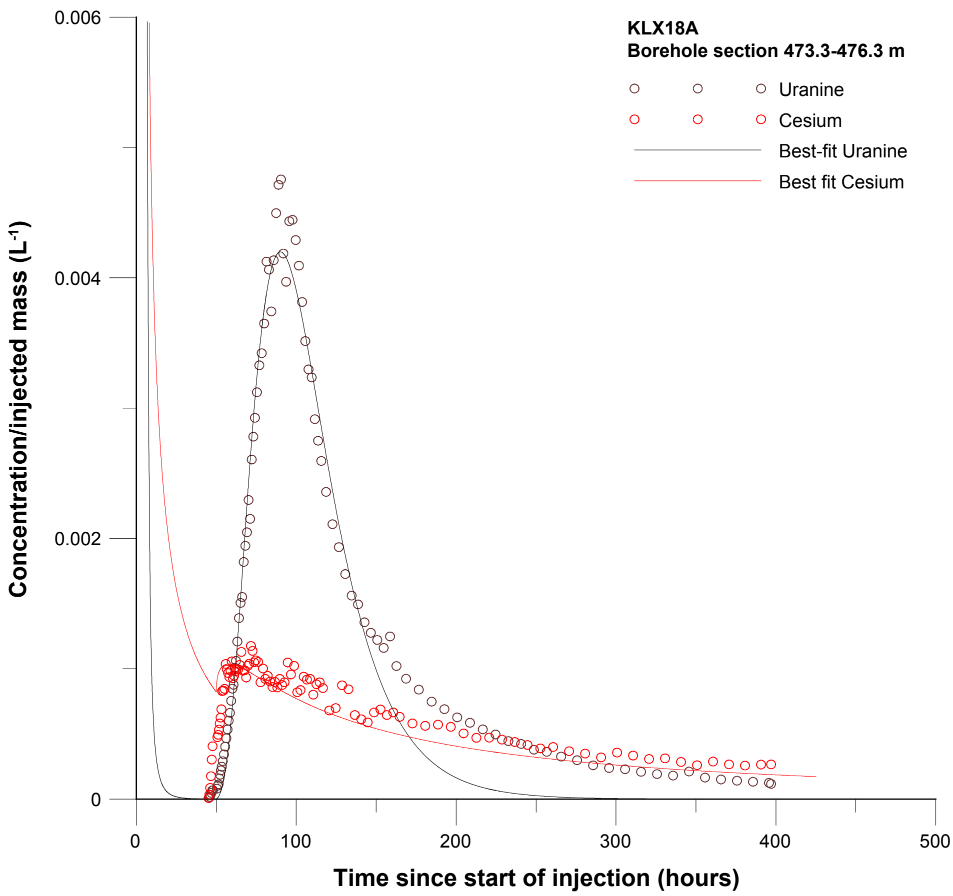

Figure 5-20a. Example of simultaneous fitting of Uranine and cesium for section 473.3–476.3 m in borehole KLX18A. All observation data are given equal regression weights.

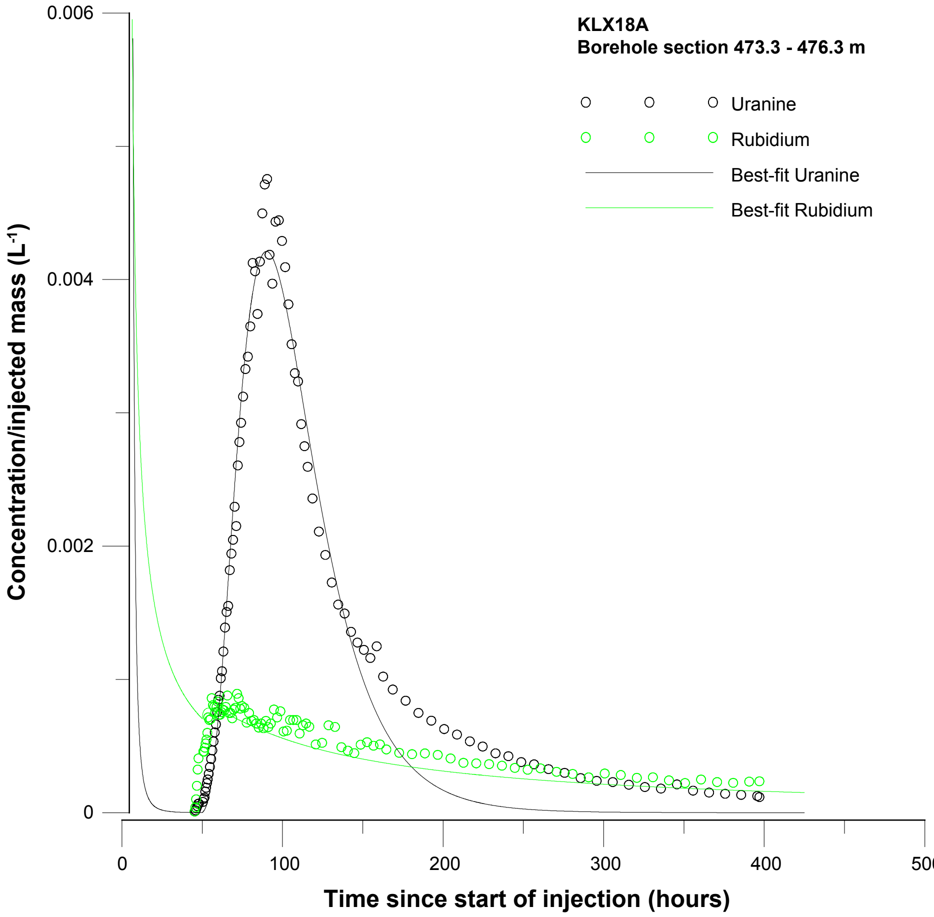

Figure 5-20b. *Example of simultaneous fitting of Uranine and rubidium for section 473.3–476.3 m in borehole KLX18A. All observation data are given equal regression weights.*

The model fits to the experimental breakthrough curves are generally fairly good, especially for the sorbing tracers (cesium and rubidium, respectively). The main discrepancy is observed for the tailing part of the Uranine curve, where the simulated curve levels out to background values faster than the experimental curve.

All of the regression runs (Tables 5-3a and 5-3b) resulted in similar values of the retardation coefficient for each sorbing tracer, while the estimated values of the longitudinal dispersivity are strongly dependent on the assumed porosity value. Both of these observations are consistent with prior expectations of the relationships between parameters in a SWIW test /Nordqvist and Gustafsson 2004, Gustafsson and Nordqvist 2005, Gustafsson et al. 2005, 2006ab/.

The estimated values of R for cesium (852–859) and rubidium (2,503–2,722) indicate very strong sorption effects, and the estimated values are considerable higher compared with previous SWIW tests as well as earlier cross-hole tests. For example, the mean values of R in KLX03 are 235 for cesium and 391 for rubidium, /Gustafsson et al. 2006a/ and in KFM08A 35 for cesium and 21 for rubidium, /Gustafsson et al. 2006b/. Estimated values of R for cesium are lower than for rubidium, although one may consider the values being of similar magnitudes.

Table 5-3a. Results of simultaneous fitting of Uranine and cesium for section 473.3–476.3 m in borehole KLX18A. Approximate values of the coefficient of variation (estimation standard error divided by the estimated value) are given within parenthesis.

Porosity (fixed)	a_L (estimated)	R (estimated)
0.002	0.87 (0.03)	852 (0.15)
0.005	0.55 (0.03)	855 (0.15)
0.01	0.39 (0.03)	857 (0.15)
0.02	0.28 (0.03)	859 (0.15)
0.05	0.17 (0.03)	854 (0.14)

Table 5-3b. Results of simultaneous fitting of Uranine and rubidium for section 473.3–476.3 m in borehole KLX18A. Approximate values of the coefficient of variation (estimation standard error divided by the estimated value) are given within parenthesis.

Porosity (fixed)	a_L (estimated)	R (estimated)
0.002	0.88 (0.03)	2,722 (0.15)
0.005	0.56 (0.03)	2,719 (0.15)
0.01	0.39 (0.03)	2,706 (0.15)
0.02	0.28 (0.03)	2,656 (0.15)
0.05	0.18 (0.03)	2,503 (0.14)

6 Discussion and conclusions

The dilution measurements were carried out in selected fracture zones in borehole KLX18A at levels from 146 to 592 m borehole length (144 to 583 m vertical depth), where hydraulic transmissivity ranged within T = $4.3 \cdot 10^{-8}$ to $9.5 \cdot 10^{-7}$ m^2/s. The borehole intersects some minor local deformation zones that are identified by SKB's single hole interpretation (SHI) of cored boreholes as seen in Table 6-1 /Carlsten et al. 2007/. In the studied sections two rock units are determined, RU1 at 100.81–587.92 m borehole length and RU2 at 587.92–607.43 m borehole length. RU1 are totally dominated by Ävrö granite and RU2 are totally dominated by fine-grained diorite.

The results of the dilution measurements in borehole KLX18A show some variation in the groundwater flow during natural conditions, with flow rates from 0.022 to 0.20 ml/min and Darcy velocities from $8.1 \cdot 10^{-10}$ to $7.2 \cdot 10^{-9}$ m/s ($7.0 \cdot 10^{-5}$ to $6.2 \cdot 10^{-4}$ m/d). These results are in accordance with previous dilution measurements carried out in boreholes KSH02, KLX02 and KLX03. In these boreholes hydraulic transmissivity in the test sections was within T = $1.3 \cdot 10^{-8}$ to $1.3 \cdot 10^{-5}$ m^2/s and flow rate ranged from 0.02–4.2 ml/min and Darcy velocity from $1.4 \cdot 10^{-9}$ to $1.2 \cdot 10^{-7}$ m/s ($1.2 \cdot 10^{-4}$ to $1.0 \cdot 10^{-2}$ m/d) /Gustafsson and Nordqvist 2005/ and /Gustafsson et al. 2006a/.

In KLX18A the highest flow rate and Darcy velocity is measured in the lower part of the borehole, outside the deformation zones. The lowest flow rate and Darcy velocity is measured in the low transmissive section at c. 359 m borehole length (354 m vertical depth). The determined groundwater flow rates are fairly proportional to the hydraulic transmissivity, although the statistical basis is weak.

Hydraulic gradients in KLX18A, calculated according to the Darcy concept, are within the expected range (0.001–0.05) in four out of five measured test sections. In the section at c. 473 m borehole length (466 m vertical depth) the hydraulic gradient is considered to be large. Local effects where the measured fractures constitute a hydraulic conductor between other fractures with different hydraulic heads or wrong estimations of the correction factor, α, and/or the

Table 6-1. Intersected zones, groundwater flow rates, Darcy velocities and hydraulic gradients for all measured sections in boreholes KLX18A.

Borehole	Test section (m)+	Rock types and zones**	Number of flowing fractures*	T (m^2/s)*	Q (ml/min)	Q (m^3/s)	Darcy velocity (m/s)	Hydraulic gradient
KLX18A	146.0–149.0 (144.2–147.2)	RU1/Ävrö granite DZ2	4	4.61E–07	0.089	1.5E–09	3.3E–09	0.021
KLX18A	359.0–362.0 (354.0–357.0)	RU1/Ävrö granite DZ4	2	2.34E–07	0.022	3.7E–10	8.1E–10	0.010
KLX18A	473.3–476.3 (466.5–469.4)	RU1/Ävrö granite DZ9	3–4	4.33E–08	0.041	6.9E–10	1.5E–09	0.105
KLX18A	562.0–565.0 (553.7–556.6)	RU1/Ävrö granite	2–3	5.07E–07	0.20	3.3E–09	7.2E–09	0.043
KLX18A	592.0–595.0 (583.1–586.1)	RU2/ Fine-graned diorite	3–4	9.52E–07	0.18	3.0E–09	6.5E–09	0.021

* /SICADA/.

** /Carlsten et al. 2007/.

+ Test section vertical depth (metre above sea level) is given within brackets.

hydraulic conductivity of the fracture could explain the large hydraulic gradients. The clogging of the optical device may give some contribution to the measured groundwater flow rate and hence to the large calculated hydraulic gradient. The hydraulic transmissivity of the section is at lower limit of measurement range for the dilution probe which may decrease accuracy in determined groundwater flow rate.

The SWIW experiment in zone DZ9 at 473.3–476.3 m borehole length resulted in high-quality tracer breakthrough data. Experimental conditions (flows, times, events, etc) are well known and documented, as well as borehole geological conditions with BIPS logging (Appendix C). Together they provide a good basis for possible further evaluation.

The results show relatively smooth breakthrough curves. The most significant result is that there is a very clear effect of retardation/sorption of cesium and rubidium.

The model evaluation was made using a radial flow model with advection, dispersion and linear equilibrium sorption as transport processes. It is important that experimental conditions (times, flows, injection concentration, etc) are incorporated accurately in the simulations. Otherwise artefacts of erroneous input may occur in the simulated results. The evaluation carried out may be regarded as a typical preliminary approach for evaluation of a SWIW test where sorbing tracers are used. Background flows were in this case assumed to be insignificant.

The estimated values of the retardation factor for cesium (about 850) and rubidium (about 2,700) in section 473.3–476.3 m indicates strong sorption. A somewhat un-expected result is that rubidium shows stronger sorption than cesium /Andersson et al. 2002/. Rubidium was introduced as an intermediately sorbing tracer between Uranine and cesium.

It should also be pointed out that the lack of model fit in the tailing parts of the curves (most visible for Uranine) appears to be a consistent feature in the SWIW tests performed so far /Gustafsson and Nordqvist 2005, Gustafsson et al. 2005, 2006ab/. Thus, there seems to be some generally occurring process that has not yet been identified, but is currently believed to be an effect of the tested medium and not an experimental artefact. Studies to identify possible causes for the observed discrepancy are ongoing.

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Appendix A

Borehole data KLX18A

SICADA - Information about KLX18A

Title	Value				
	Information about cored borehole KLX18A (2006-09-26).				
Comment:	No comment exists.				
Borehole length (m):	611.280				
Reference level:	TOC				
Drilling period (s):	From date	To date	Secup (m)	Seclow (m)	Drilling type
	2006-02-15	2006-02-21	0.300	99.930	Percussion drilling
	2006-03-29	2006-05-02	99.930	611.280	Core drilling
Starting point coordinate:	Length (m)	Northing (m)	Easting (m)	Elevation	Coord system
	0.000	6366413.390	1547966.345	21.010	RT90-RHB70
	3.000	6366413.400	1547965.930	18.038	RT90-RHB70
Angles:	Length(m)	Bearing	Inclination (- = down)		Coord System
	0.000	271.402	-82.040		RT90-RHB70
Borehole diameter:	Secup (m)	Seclow (m)	Hole diam (m)		
	0.300	9.300	0.340		
	9.300	11.830	0.254		
	11.830	99.830	0.198		
	99.830	99.930	0.163		
	99.930	101.350	0.086		
	101.350	611.280	0.076		
Core diameter:	Secup (m)	Seclow (m)	Core diam (m)		
	99.930	100.800	0.072		
	100.800	611.280	0.050		
Casing diameter:	Secup (m)	Seclow (m)	Case in (m)	Case out (m)	Comment
	0.000	11.830	0.200	0.208	
	0.300	9.300	0.311	0.323	
Cone dimensions:	Secup (m)	Seclow (m)	Cone in (m)	Cone out (m)	
	96.530	101.350			
Grove milling:	Length (m)	Trace detectable			
	110.000	Yes			
	150.000	Yes			
	200.000	Yes			
	250.000	Yes			
	300.000	Yes			
	350.000	Yes			
	400.000	Yes			
	450.000	Yes			
	500.000	Yes			
	550.000	Yes			
	602.000	Yes			
Installed sections:	Section no	Start date	Secup (m)	Seclow (m)	
Section status:	Packers are released.				
Valve status:	(No valve installation/removal)				

End of additional information.

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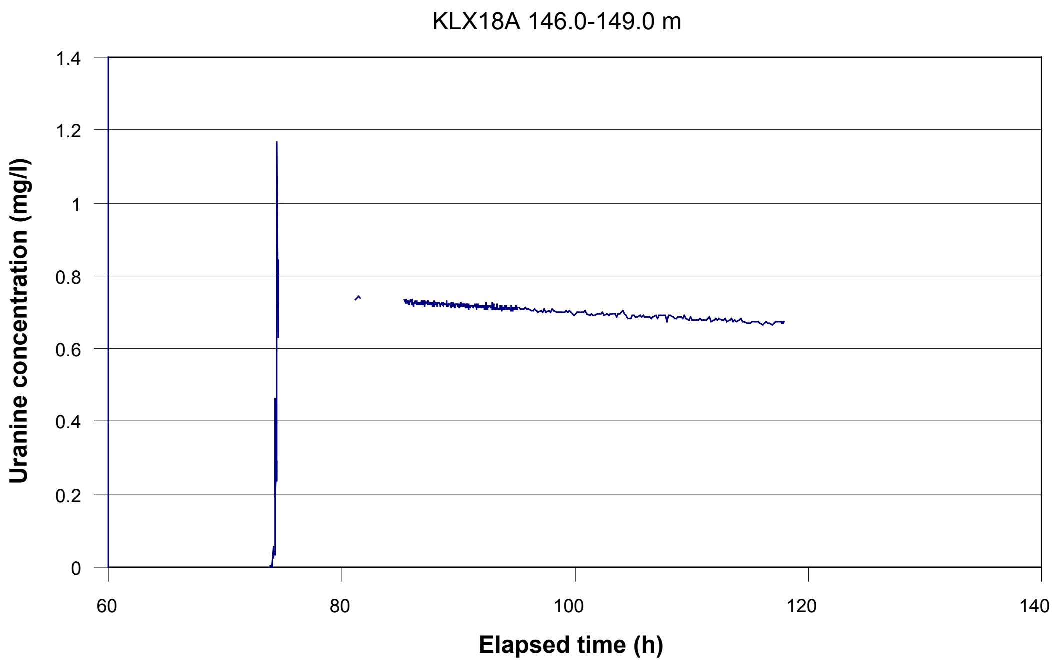
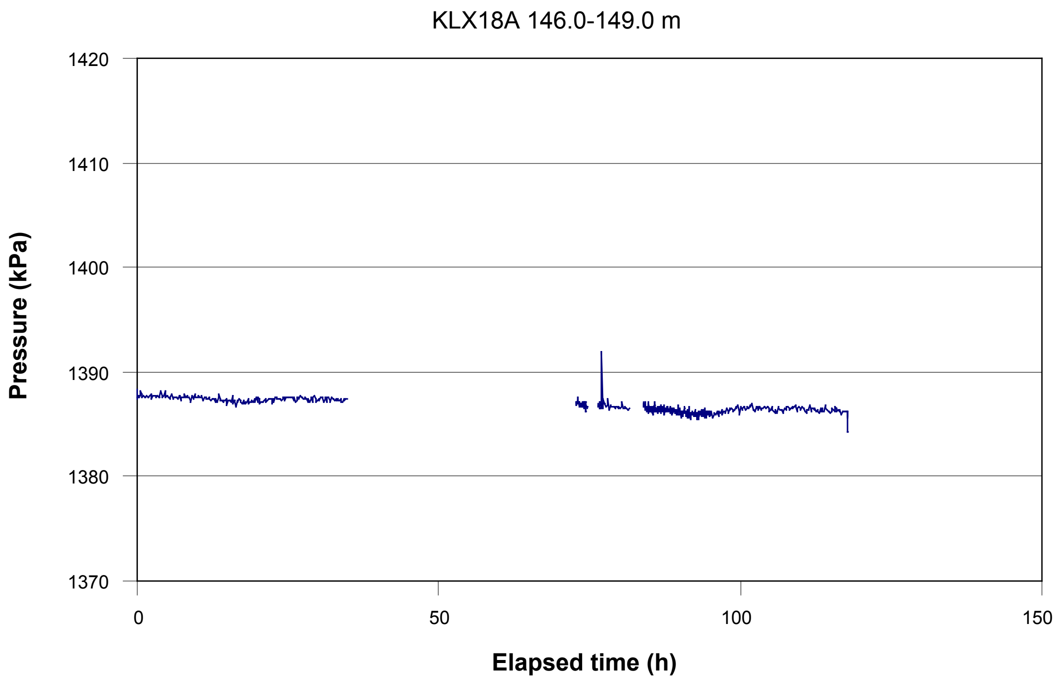
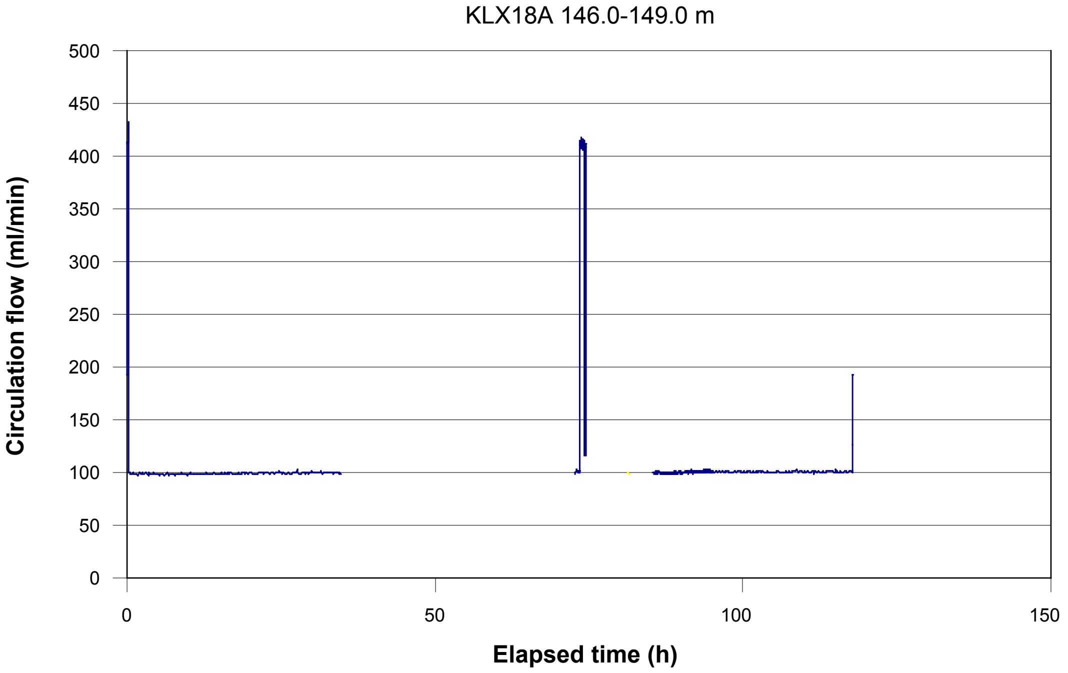
Dilution measurement KLX18A 146.0–149.0 m



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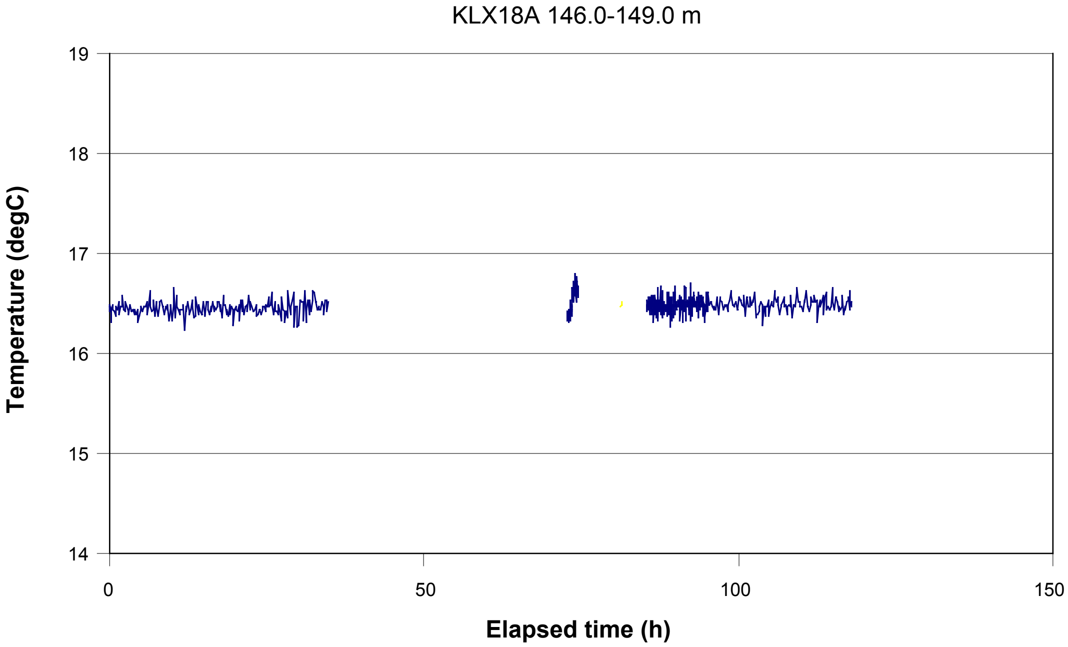
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16
17
18
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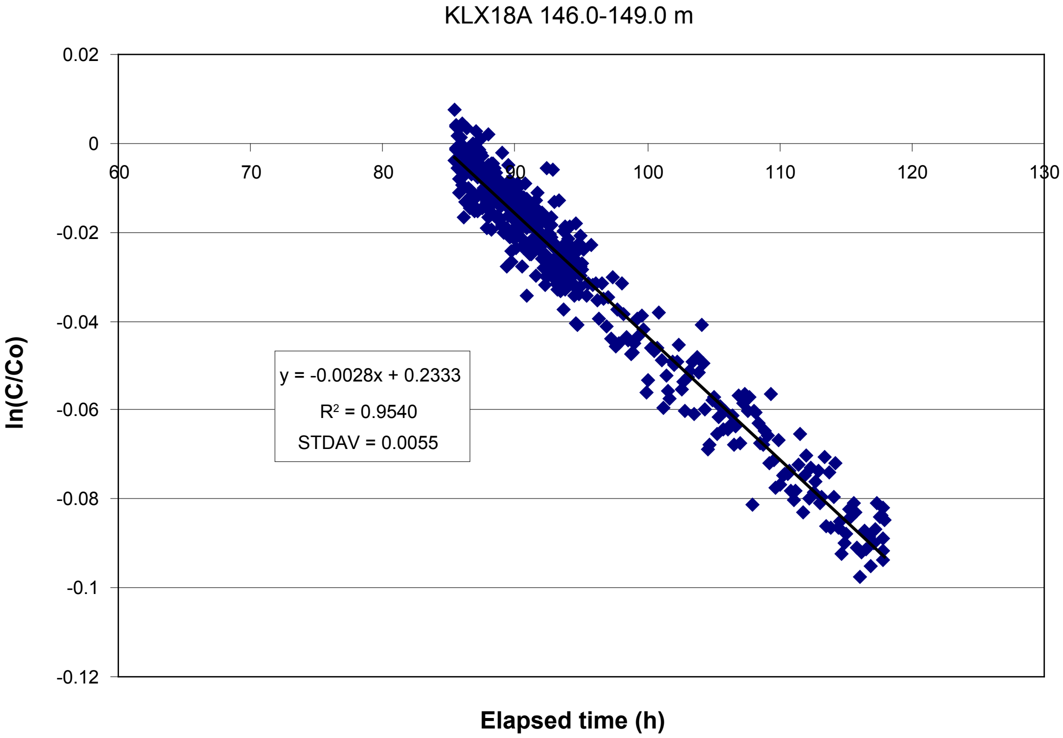
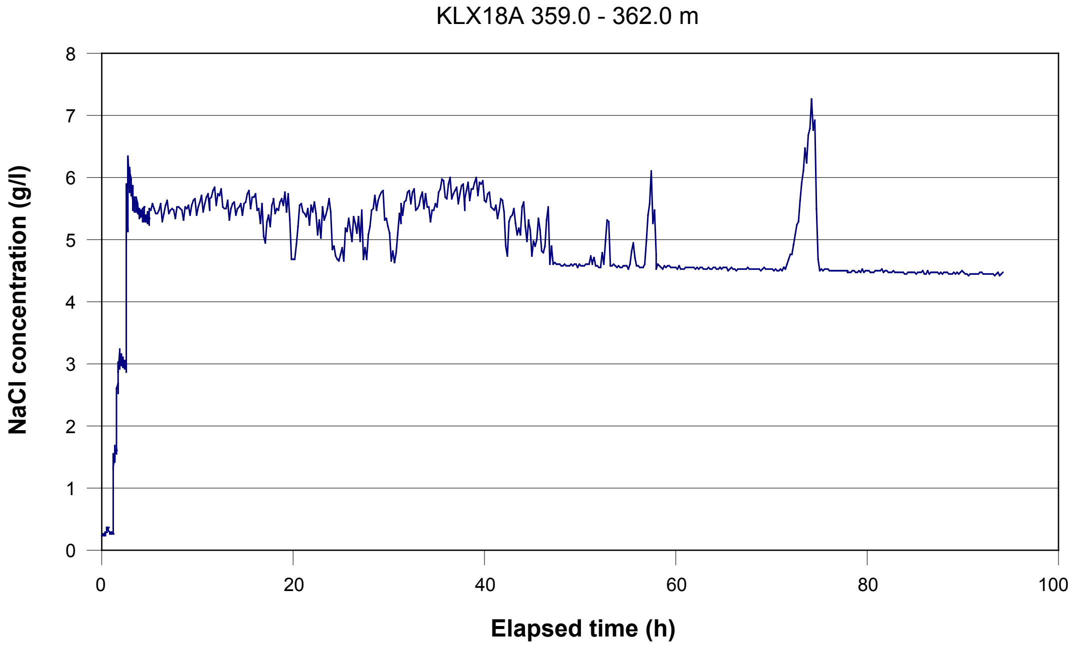
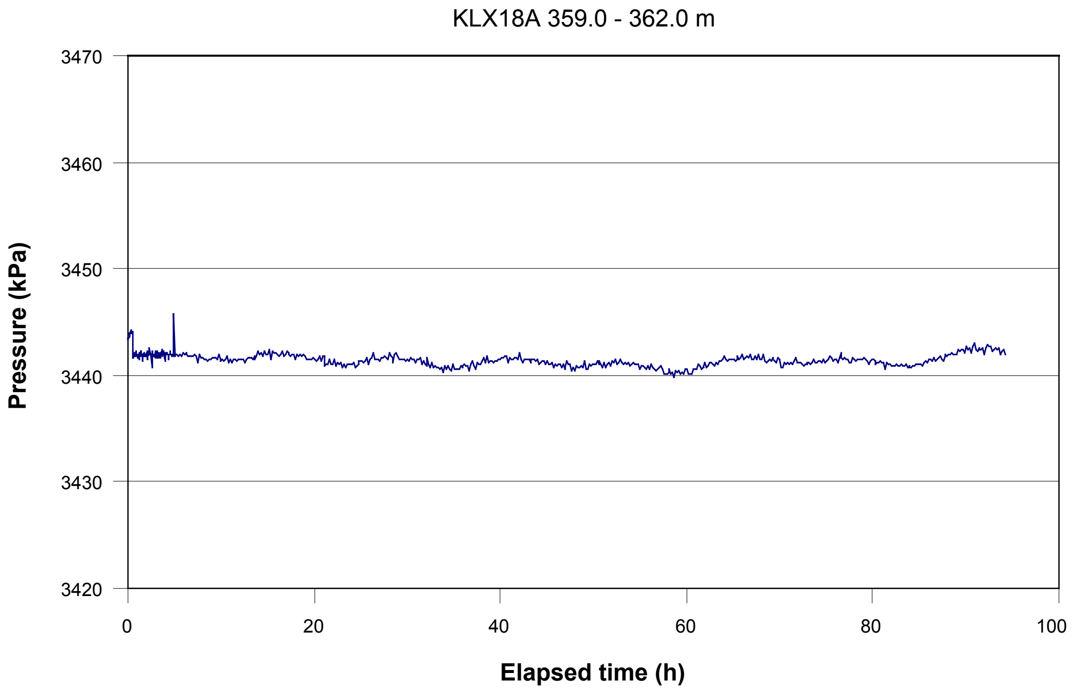


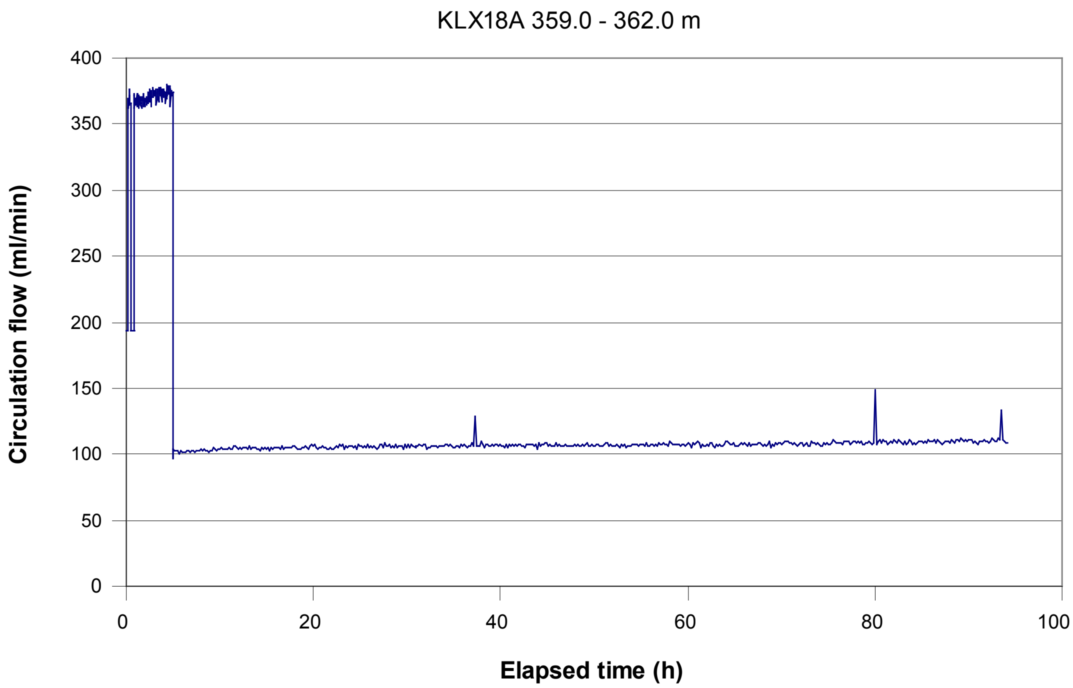
Part of dilution curve (h)	V (ml)	ln(C/Co)/t	Q (ml/h)	Q (ml/min)	Q (m³/s)	R2-value
85 - 117	1909	-0.0028	5.35	0.089	1.48E-09	0.954

Part of dilution curve (h)	K (m/s)	Q (m³/s)	A (m²)	v(m/s)	I
85 - 117	1.54E-07	1.48E-09	0.4560	3.26E-09	0.021

Dilution measurement KLX18A 359.0–362.0 m



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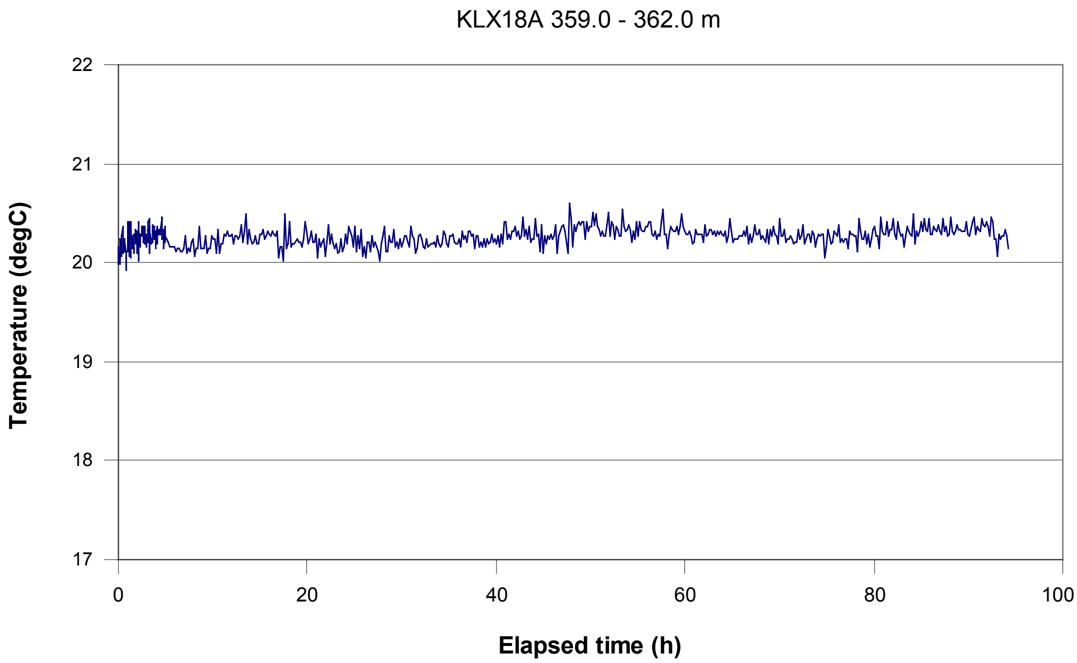
20
40
60
80
100
Elapsed time (h)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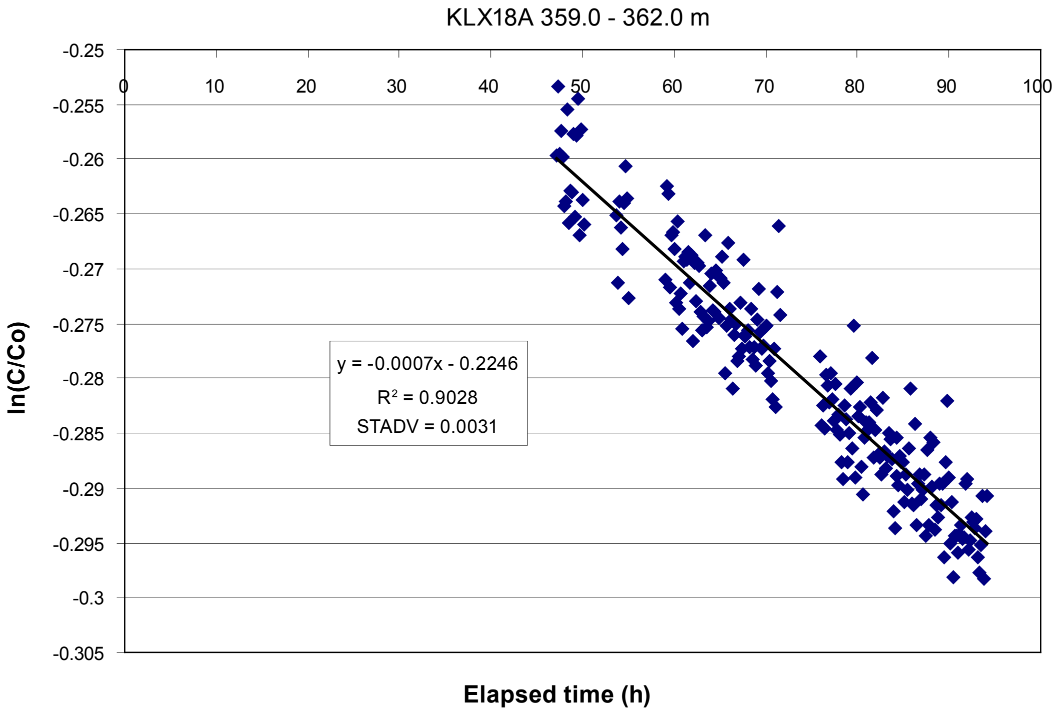
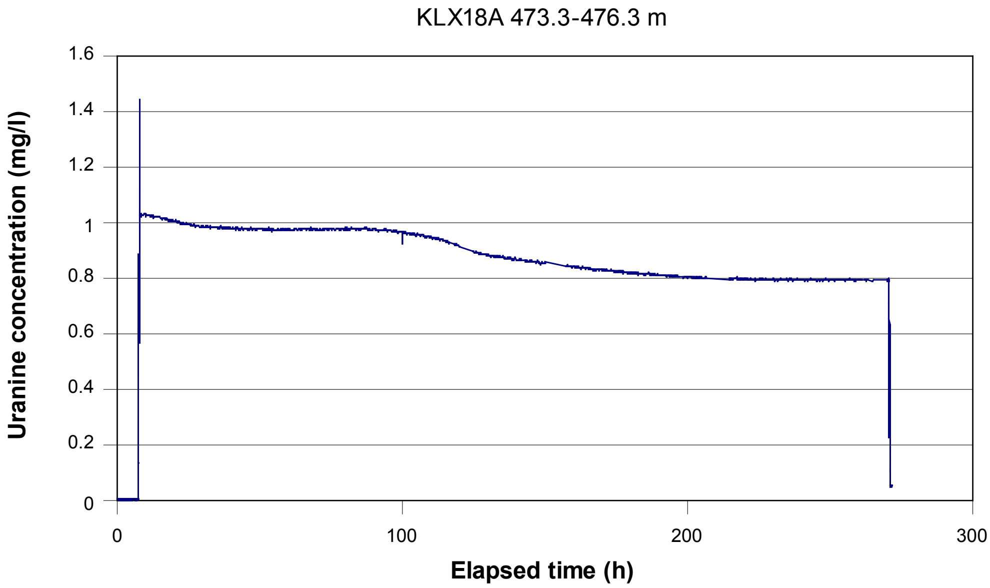
Elapsed time (h)

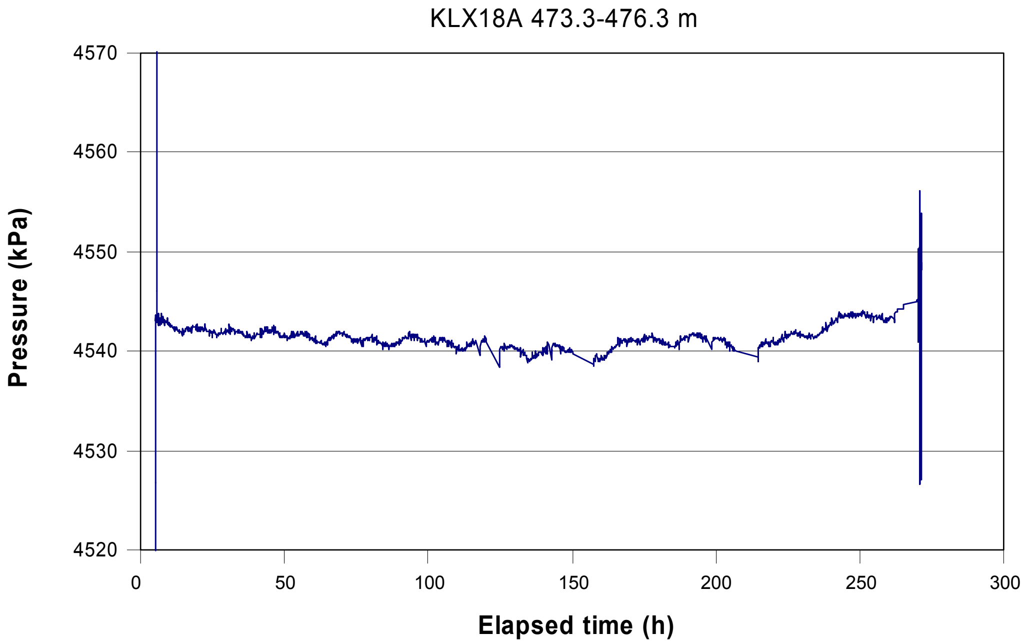


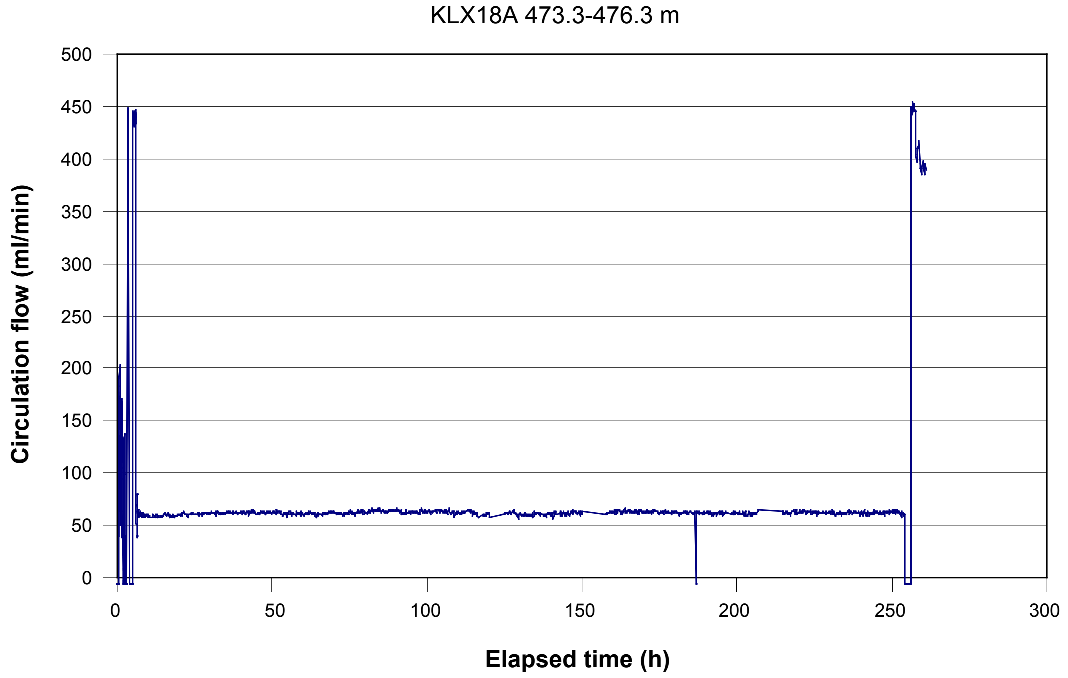
Part of dilution curve (h)	V (ml)	ln(C/Co)/t	Q (ml/h)	Q (ml/min)	Q (m^3/s)	R2-value
47-94	1909	-0.0007	1.34	0.022	3.71E-10	0.9028

Part of dilution curve (h)	K (m/s)	Q (m^3/s)	A (m^2)	v(m/s)	I
47-94	7.80E-08	3.71E-10	0.4560	8.14E-10	0.010

Dilution measurement KLX18A 473.3–476.3 m



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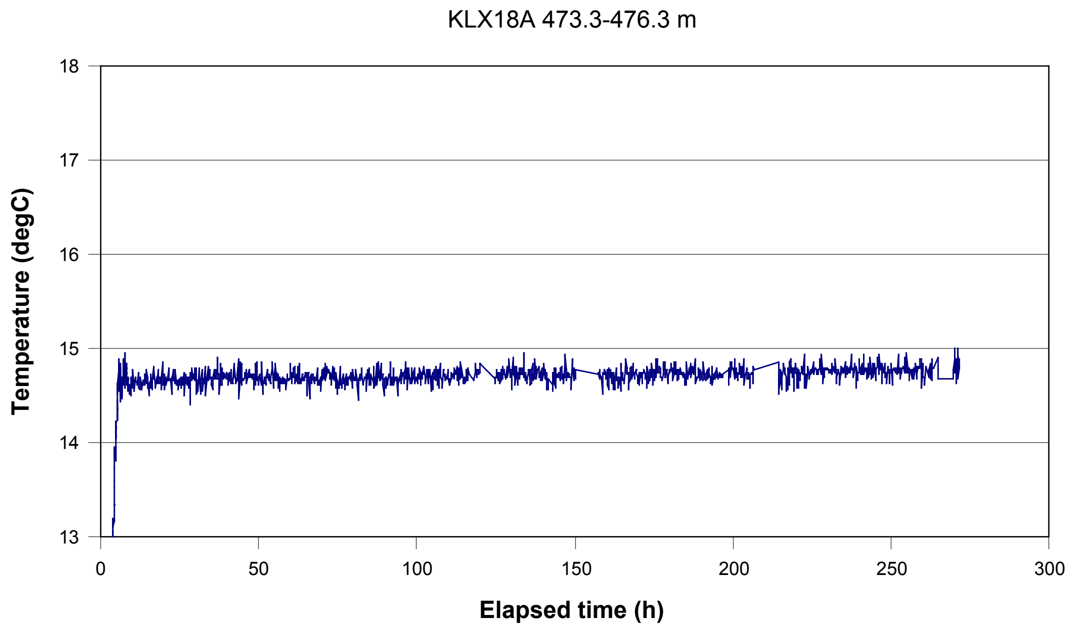
100
150
200
250
300
Elapsed time (h)


KLX18A 473.3-476.3 m
Temperature (degC)
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15
14
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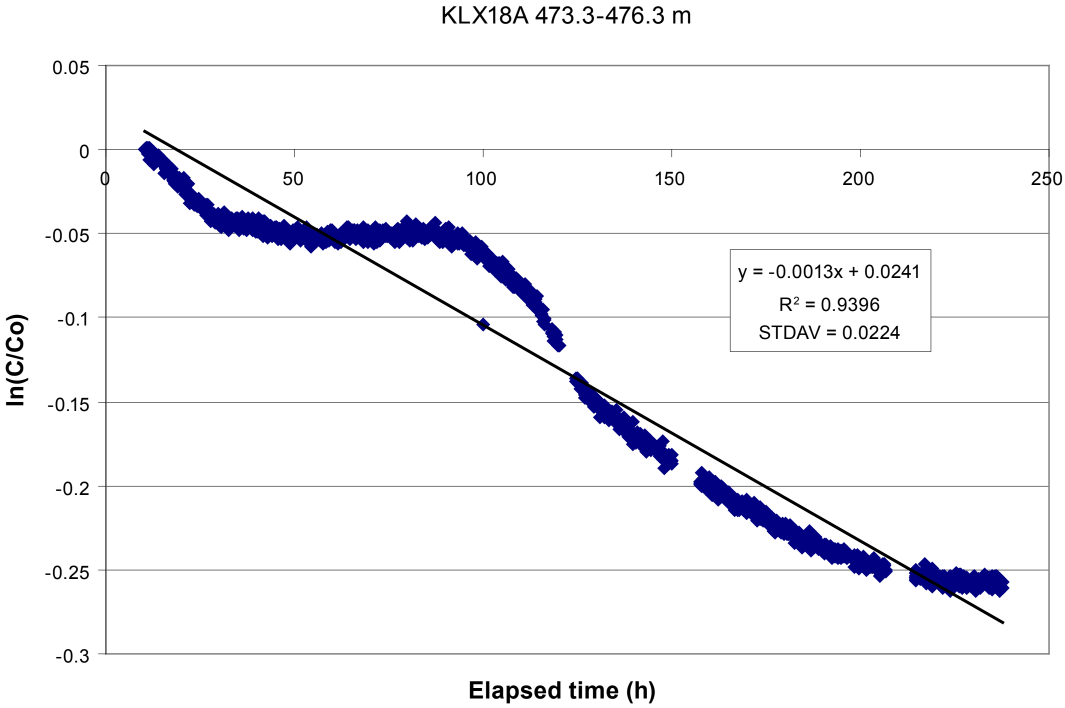
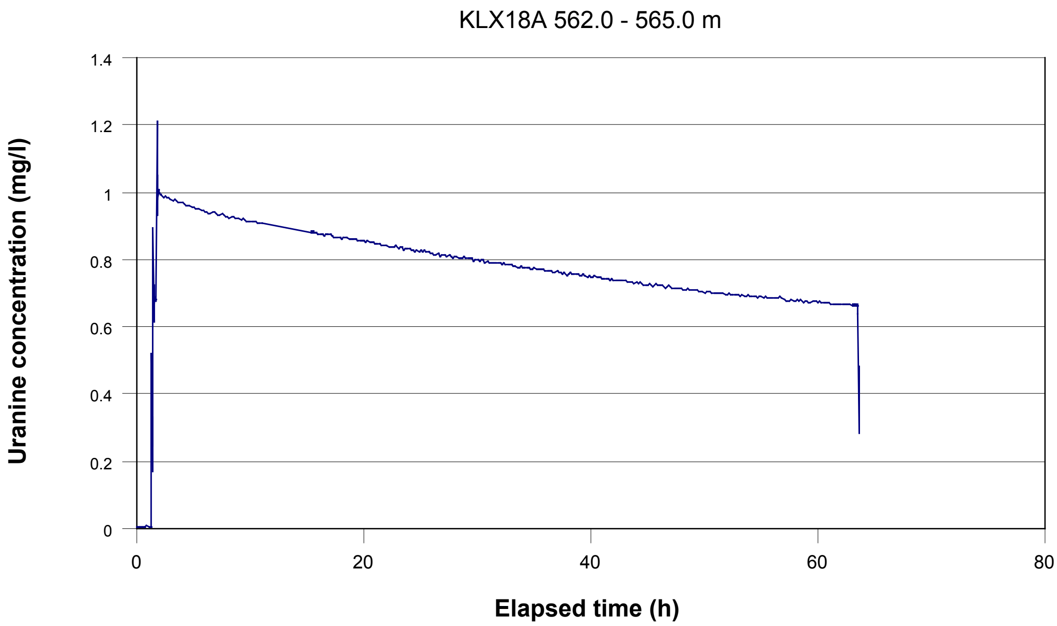
200
250
300
Elapsed time (h)

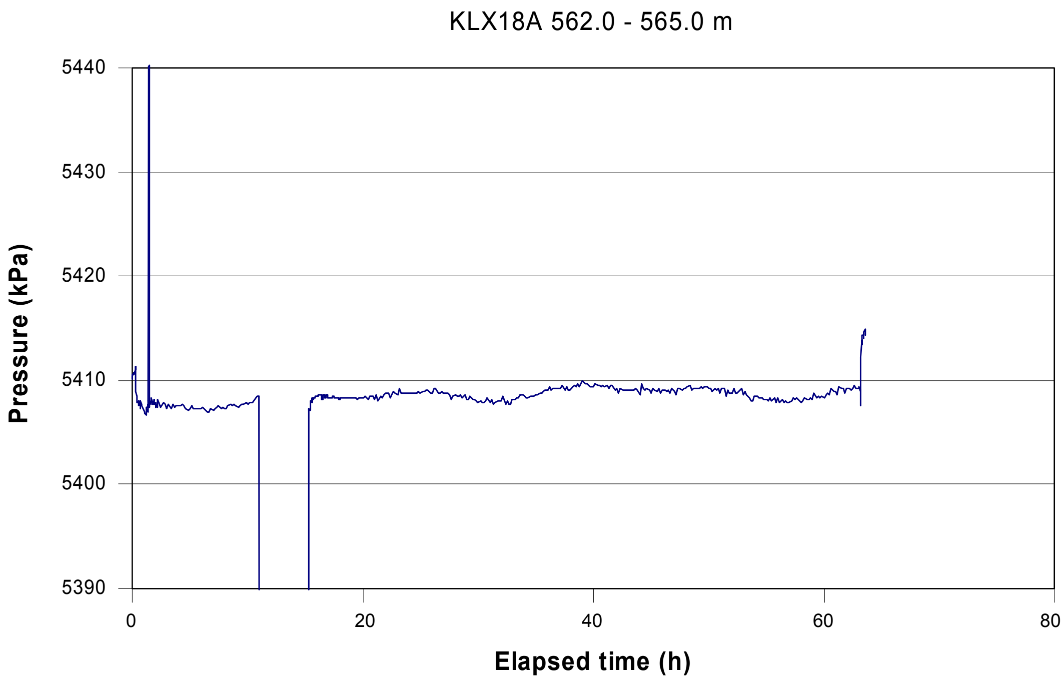


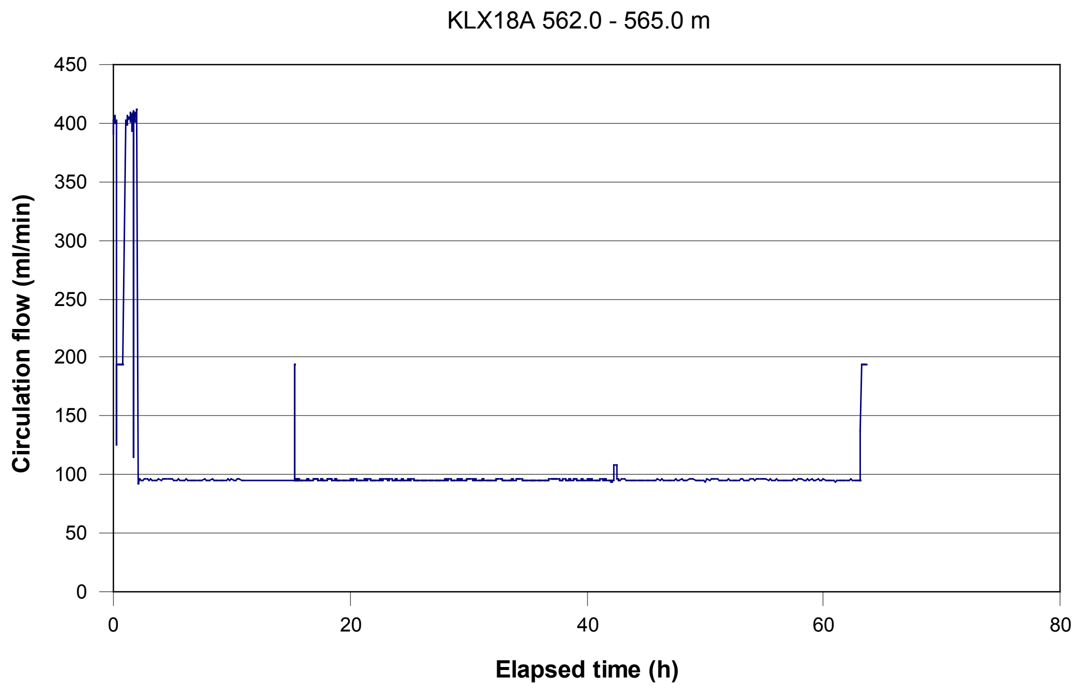
Part of dilution curve (h)	V (ml)	ln(C/Co)/t	Q (ml/h)	Q (ml/min)	Q (m^3/s)	R2-value
10 - 237	1909	-0.0013	2.48	0.041	6.89E-10	0.9396

Part of dilution curve (h)	K (m/s)	Q (m^3/s)	A (m^2)	v(m/s)	I
10 - 237	1.44E-08	6.89E-10	0.4560	1.51E-09	0.105

Dilution measurement KLX18A 562.0–565.0 m






KLX18A 562.0 - 565.0 m
Circulation flow (ml/min)
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300
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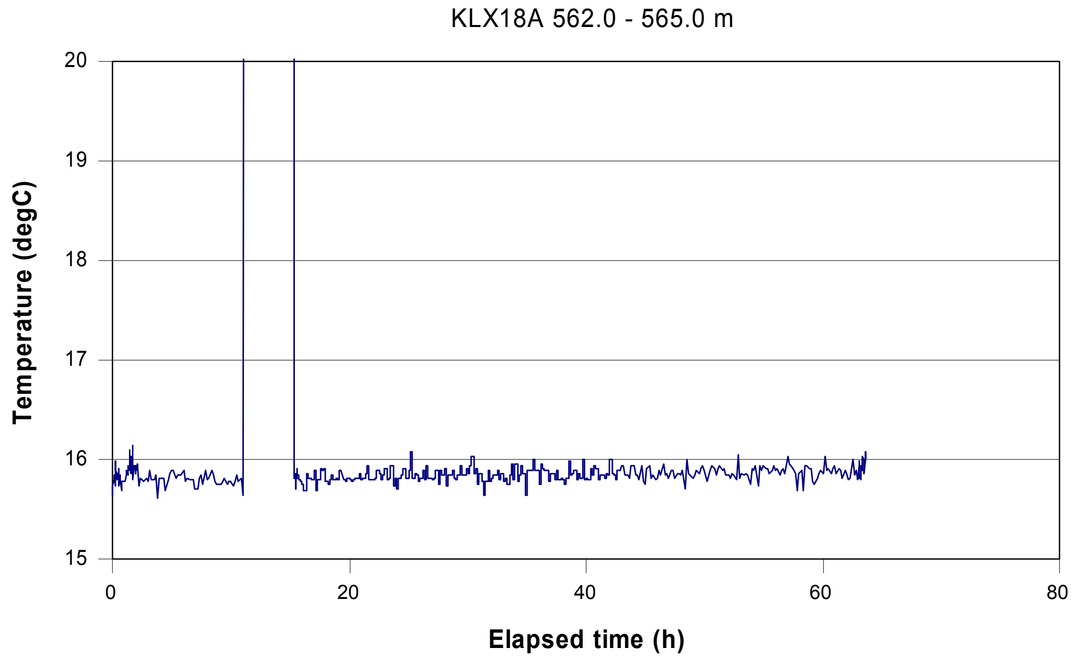
200
150
100
50
0
0
20
40
60
80
Elapsed time (h)


KLX18A 562.0 - 565.0 m
Temperature (degC)
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15
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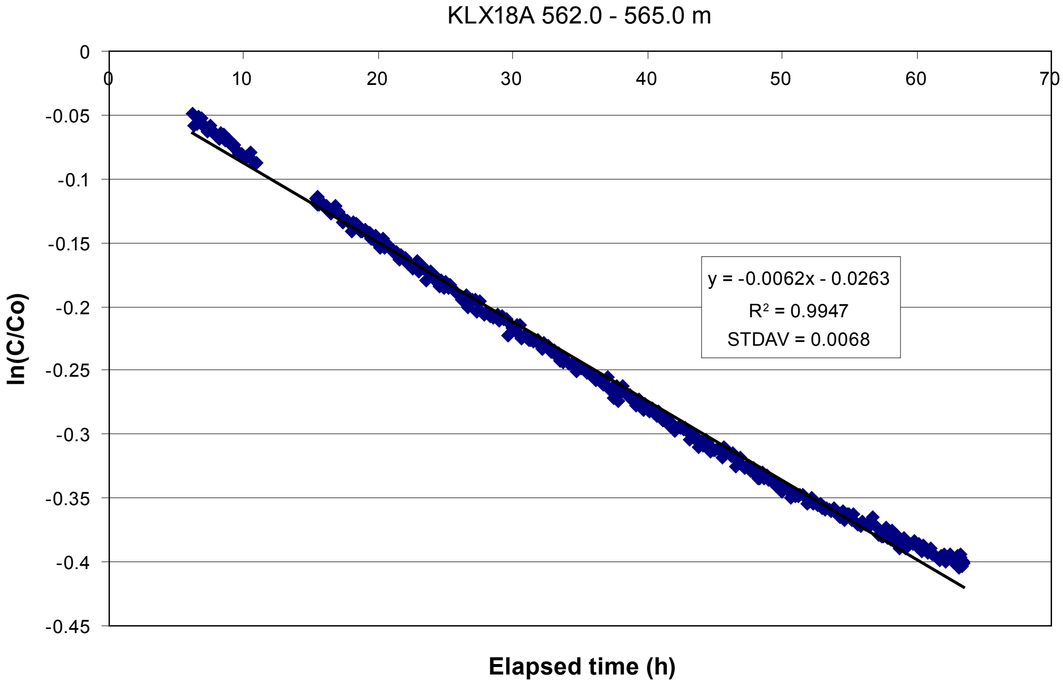
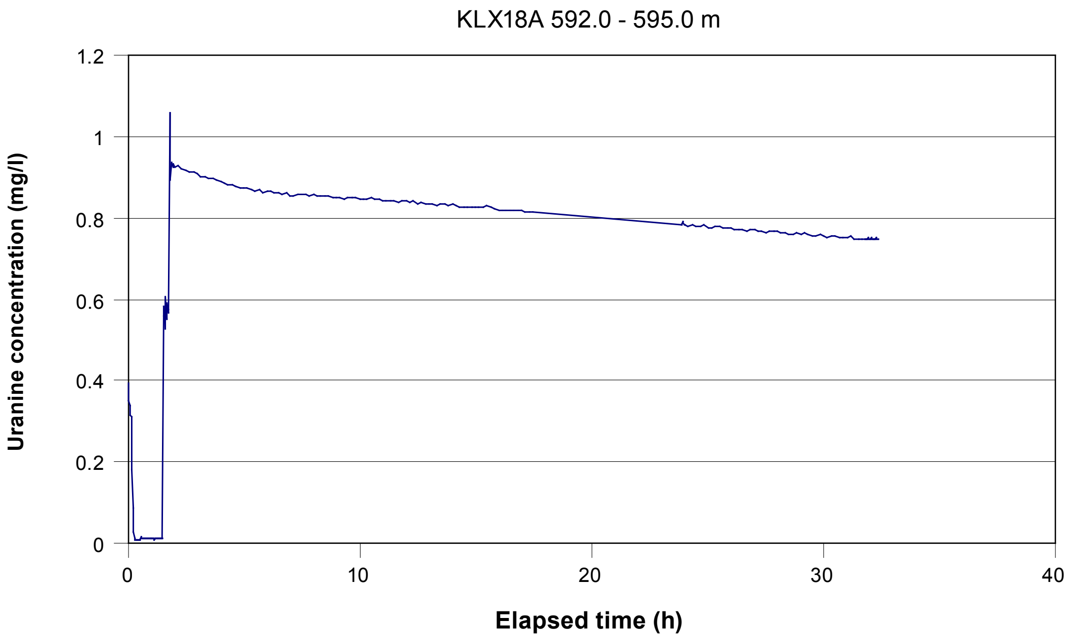
40
60
80
Elapsed time (h)

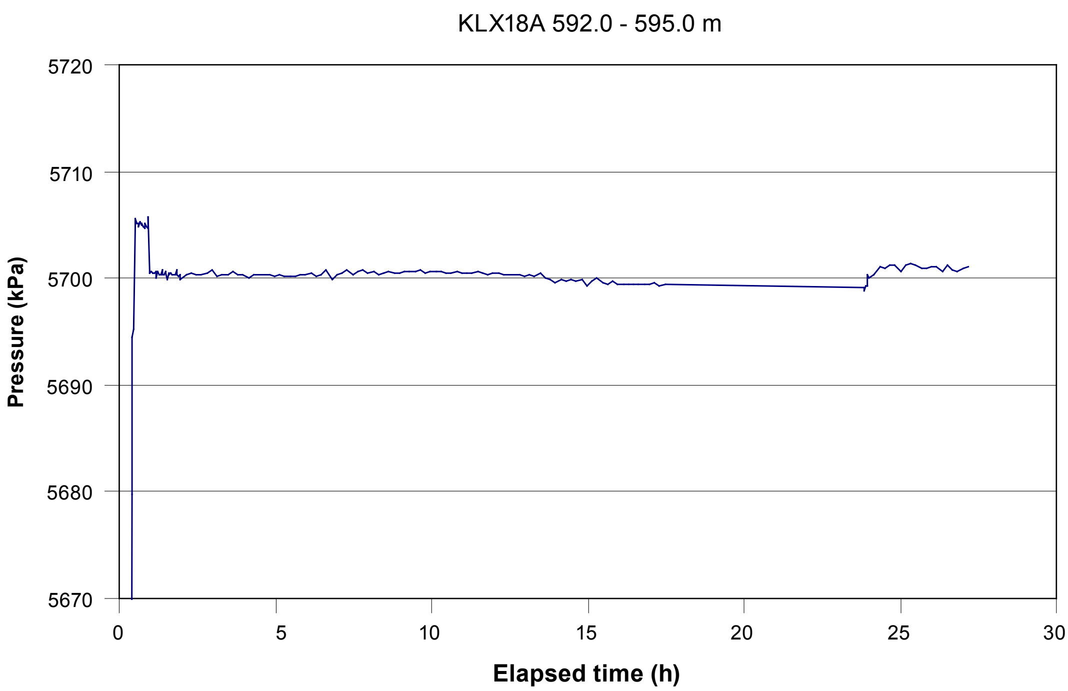


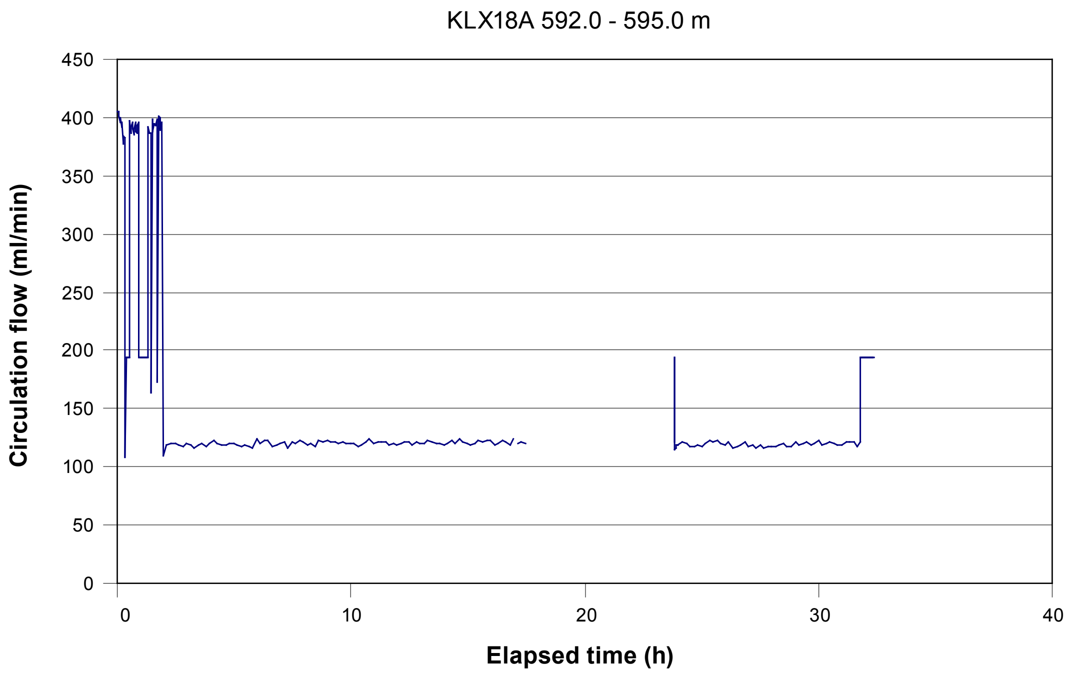
Part of dilution curve (h)	V (ml)	ln(C/Co)/t	Q (ml/h)	Q (ml/min)	Q (m^3/s)	R2-value
6 - 63	1909	-0.0062	11.84	0.197	3.29E-09	0.9947

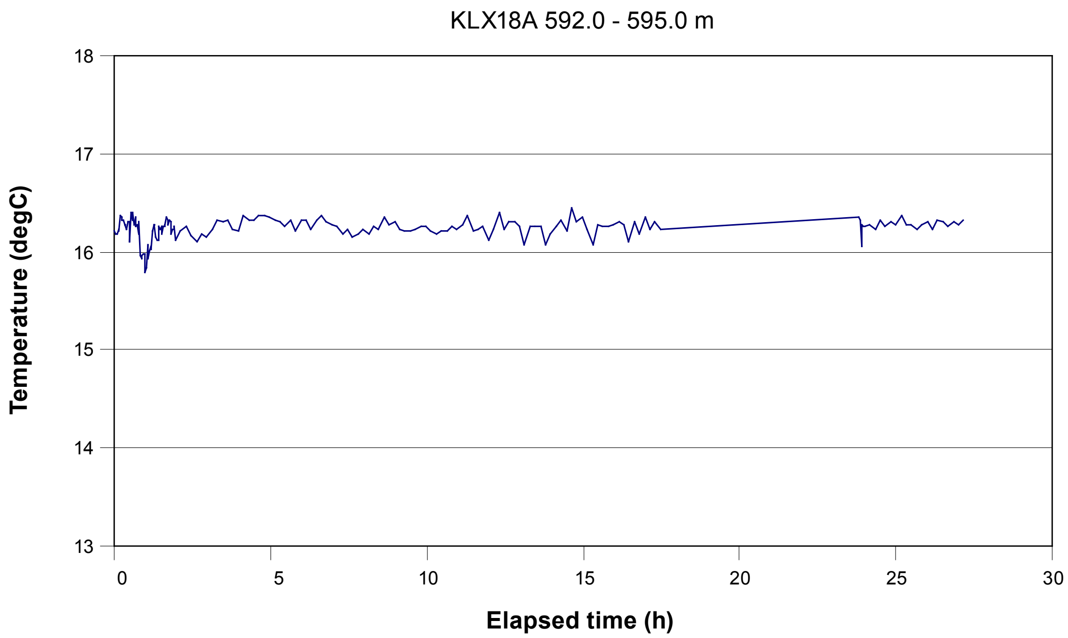
Part of dilution curve (h)	K (m/s)	Q (m^3/s)	A (m^2)	v(m/s)	I
6 - 63	1.69E-07	3.29E-09	0.4560	7.21E-09	0.043

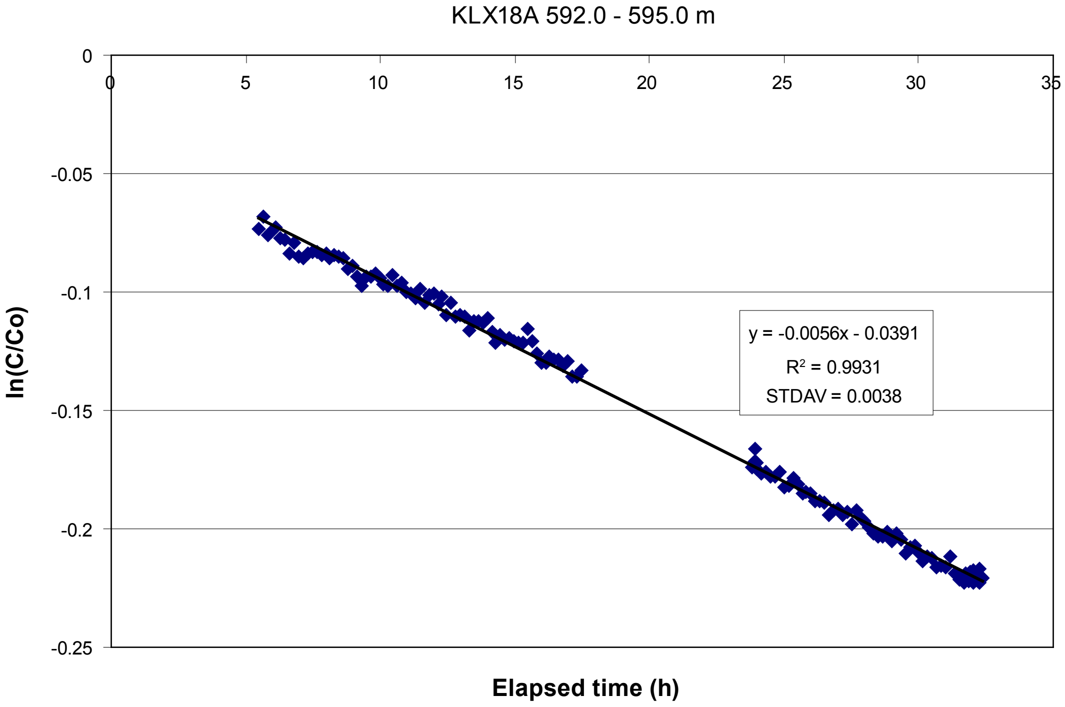
Dilution measurement KLX18A 592.0–595.0 m






KLX18A 592.0 - 595.0 m
Circulation flow (ml/min)
Elapsed time (h)
0
50
100
150
200
250
300
350
400
450
0
10
20
30
40


KLX18A 592.0 - 595.0 m
Temperature (degC)
Elapsed time (h)
13
14
15
16
17
18
0
5
10
15
20
25
30

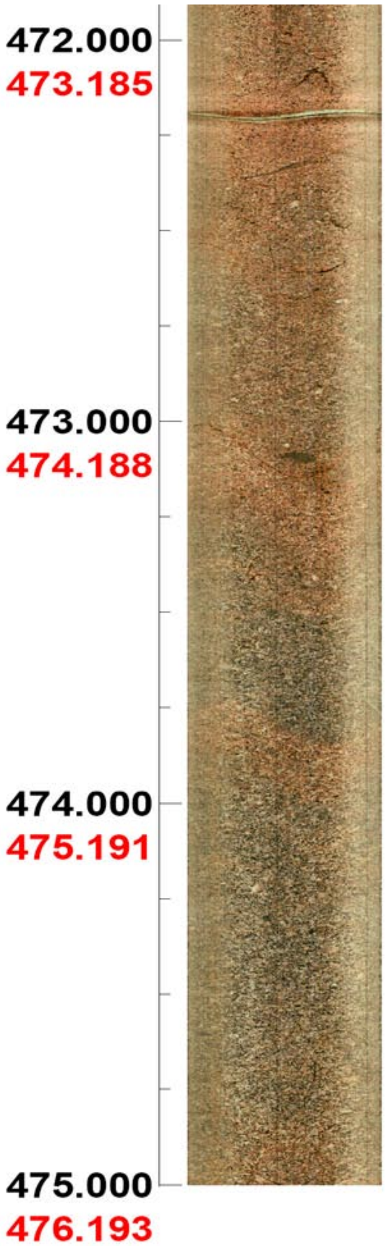


Part of dilution curve (h)	V (ml)	ln(C/Co)/t	Q (ml/h)	Q (ml/min)	Q (m³/s)	R2-value
5 ~27	1909	-0.0056	10.69	0.178	2.97E-09	0.9931

Part of dilution curve (h)	K (m/s)	Q (m³/s)	A (m²)	v(m/s)	I
5 ~27	3.17E-07	2.97E-09	0.4560	6.51E-09	0.021

BIPS logging KLX18A

Adjusted depth range: 473.185-476.185 m



Black number = Recorded depth
Red number = Adjusted depth