Guidelines for Aquifer Parameter Estimation with Computer Models

Report to the
Water Research Commission

by

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GUIDELINES FOR AQUIFER PARAMETER ESTIMATION WITH COMPUTER MODELS

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EXECUTIVE SUMMARY

GUIDELINES FOR AQUIFER PARAMETER ESTIMATION WITH COMPUTER MODELS

1. Background and Motivation

This report presents the results of research conducted by the Institute for Groundwater Studies for the Water Research Commission on the development of guidelines for aquifer parameter estimation with computer models.

The parameter estimation, analysing hydraulic test data, is based on mathematical models that relate drawdown response to discharge in the abstraction borehole. In fractured rock aquifers, the geometry and permeability of the system have a large influence on the drawdown. However most models are developed for homogeneous porous aquifers and might not be suitable in fractured rock systems. Therefore it is necessary to find an appropriate way, when this kind of models is used.

Consider the geological setup and geometry of the fractured rock aquifers in South Africa (e.g. Karoo Aquifer), in general a three-dimensional groundwater flow must be considered when estimating aquifer parameters with pumping test data. However, most pumping test data are evaluated using analytical solutions such as Theis or Cooper-Jacob with assumptions, which cannot be applied to fractured rock environments. As the estimated parameters are the basis for further investigation, including sustainable management of groundwater resource and groundwater contamination estimation, a better methodology is required.

Because of its high horizontal hydraulic conductivity value, the fracture normally acts like a horizontal production well during a pumping test. The hydraulic head everywhere in the confined fracture drops almost immediately after starting the pump. This causes the drop of the hydraulic head in the matrix at the vicinity of the fracture and water is released from the matrix storage and flows vertically into the fracture at the same rate as the pumping. After having used up this storage, the drawdown wave progresses to a wider range in the matrix to get more storage water and finally to get water from the recharge if the duration of a pumping test is long enough.

In general the spread of the drawdown wave can significantly be affected by several hydrogeological parameters, including:

- the horizontal hydraulic conductivity of the matrix (k_{hm}),
- the vertical hydraulic conductivity of the matrix (k_{vm}),
- the specific storage coefficient of the matrix (S_{sm}),
- the horizontal hydraulic conductivity of the fracture (k_{hf}),
- the vertical hydraulic conductivity of the fracture (k_{vf}) and
- the specific storage coefficient of the fracture (S_{sf}).

Because Theis or Cooper-Jabcob methods can only provide an estimate of the transmissivity (a mixture of k_{hm}, k_{vm}, k_{hf}, k_{vf} and aquifer thickness) and storage coefficient (a mixture of S_{sm}, S_{sf} and aquifer thickness), a more sophisticated method is needed. Using numerical groundwater models and inverse modelling technique should solve this problem.

2. Statement of Objectives

The objectives of this research project are:

- To provide guidelines for estimating aquifer parameters, which are essential for:
  - determining the degree and potential of groundwater contamination; and
  - sustainable use and management of groundwater resources.
- The guideline will include:
  - a method to estimate aquifer parameters of the fracture and the matrix from a pumping test using a computer model
  - pre-built models for different scenarios
  - a guideline how to use these models
- To provide pre-built groundwater models for different scenarios to facilitate the use of the guidelines.
- To provide a better understanding of the aquifer parameters, especially the Karoo aquifer.

3. Meeting the Objectives

All above-mentioned objectives of this project have been reached. In addition to these objectives the following works have been done:

- Although only one hydraulic test on one single site was planned, the project team conducted and analysed different hydraulic tests at two test sites, representing two fractured rock aquifer systems in South Africa:
  i. Horizontal, bedding-plane fracture on the Campus Test Site at the University of the Free State
  ii. Vertical fracture parallel to a dyke on the Meadhurst Test Site in the surrounding of Bloemfontein
- One of the initial objectives of the project was to provide a guideline for aquifer parameter estimation with computer model. However the project team included:
  i. A guideline for aquifer parameter estimation with analytical methods for aquifers with a horizontal, bedding-plane fracture
  ii. For aquifers with a vertical fracture parallel to a dyke the relation between the results of the numerical model and of analytical methods is described. A recommendation for using analytical methods is given.
  iii. Recommendations on conducting hydraulic tests, so that the results can be used in both analytical and numerical models

4. Summary of Methods and Results

Theoretically the best method to obtain fractured rock aquifer parameters is a three-dimensional numerical flow model. However, its required data are usually not available and the use of a numerical model requires a certain level of training. The emphasis of the guideline is therefore on simplifying the parameter estimation process by using pre-build models or analytical methods, whenever applicable.

The methods to achieve the research objectives were:

- A literature survey
- Installing of additional boreholes with piezometers in different depth
- Conducting a number of pumping tests at different boreholes and test sites
- Computational model of the test sites for parameter estimation

The hydraulic test data have been analysed with both numerical and analytical methods. The three dimensional groundwater flow model MODFLOW from the U.S. Geological Survey (McDonald et al. 1996) and the simulation system PMWIN (Chiang and Kinzelbach, 2001) as well as the inverse model PEST (Doherty, 2000) have been used to analyse the hydraulic test data numerically. The results from the numerical models are compared with those from analytical methods. Four analytical methods have been used. They are Cooper Jacob I, Cooper Jacob II, Gringarten and Theis.

The comparison between the results of analytical models and the numerical model shows a possibility to simplify the procedure of parameter estimation from hydraulic test data. For the case of a horizontal, bedding-plane fracture the way to apply different analytical methods for the parameter estimation is described in detail.

5. Conclusions

The development of this guideline was driven by the need to establish a scientifically sound and documented approach to estimate aquifer parameters with computer models. The guideline has resulted from several pumping tests, conducted especially for this project, and hours of extensive computer work on methods to analyse these pumping tests.

The guideline for aquifer parameter estimation with computer models describes the correct way to build a numerical model and to use it for the purpose of parameter estimation. It consists of the following steps:

Step 1 Conceptualisation
Step 2 Create a new model
Step 3 Assign the model data and parameters
Step 4 Assign the observation data
Step 5 Perform the flow simulation
Step 6 Assign data and parameters for inverse modelling

It is concluded in this guideline that in order to analyse pumping test data correctly, either with an analytical method or a numerical model, the following points need to be considered:

- A correct conceptual model for the hydrogeological system
- The geometry of the aquifer
- Inner boundary conditions such as well bore storage effects
- Outer boundary conditions, for example no-flow boundaries.
- Characteristics of the flow conditions

The geometry of the aquifer system and the fracture system is often unknown. This can result in a wrong conceptual model and therefore in a wrong parameter estimation, when performing and analysing a pumping test with both analytical methods and numerical models.

6. Recommendations

Although the numerical models better describe the complex aquifer structures, it is obvious that the use of the numerical models require a certain level of training. However, the comparison between the results of analytical models and the numerical model shows a possibility to simplify the procedure of parameter estimation from hydraulic test data.

It is recommended to use the following suggestions to estimate the aquifer parameters with analytical models:

For aquifers with a single horizontal bedding-plane fracture:

- To estimate the **transmissivity of the matrix**, the Cooper-Jacob or Theis method can be used, when the assumptions for applying these methods are valid. That means the drawdown curve must show radial acting flow and there are no boundary effects.
- To estimate the **transmissivity of the fracture**, the drawdown-distance method (known as Cooper-Jacob II) can be used. At least 2 observation boreholes are required in addition to the abstraction borehole.
- To estimate the **storage coefficient of the fracture**, the Cooper-Jacob or Theis method can be used. It requires an observation borehole, which is intersecting the fracture far away from the abstraction borehole. The problem is that the definition of 'far away' is unclear.
- To estimate the **storage coefficient of the matrix:**
  1. The Cooper-Jacob or Theis method: Both methods require an observation borehole, which is intersecting the fracture close to the abstraction borehole. The problem is that the definition of 'close' is unclear. These methods can also be applied by using the effective borehole radius of the abstraction borehole itself. The effective borehole radius must be calculated from the early data of the hydraulic test.
  2. The Cooper-Jacob II methods: Observation data of at least two matrix piezometers are required.
- For the parameters of the matrix **(T, Kv and S)**, the Gringarten method can be used, but it is non-unique and difficult to fit the data without prior information. If the parameters T matrix, S matrix and half-length of the fracture are estimated with other analytical methods, it is possible to get a unique fit of the drawdown data.

In the case of a vertical fracture, situated on a dyke, the comparison of the results from the numerical model with the analytical methods, as described in section 3.3.2, shows the relationship between the different aquifer features. To use analytical methods for parameter estimating in a case of a vertical fracture is more complicated than for a horizontal fracture, because more than one aquifer system are involved.

- Applying the Cooper-Jacob or Theis method on the hydraulic test data from the abstraction borehole yields a geometric mean of the transmissivity of all aquifer systems.
- Applying the Cooper-Jacob or Theis method on the hydraulic test data from observation boreholes in the fracture yields the transmissivity value of the fracture. Due to its distance dependency, the storage coefficient of the fracture cannot be obtained.
- An analytical method for estimating the storage coefficient of the matrix could not be determined.

The parameter estimation runs described in chapter 4 show that it is not possible to fit the drawdown curves in all piezometers simultaneously. The reasons for this phenomenon are given below. In most cases, these reasons also apply to analytical methods.

- The geometry of the aquifer is not well known and is simplified in the model (e.g., constant thickness over the whole model) and the real extent of the fracture is unknown.
- The drawdown behaviour in the abstraction borehole cannot be simulated correctly with the numerical model due to effects like well bore storage and well bore skin. The radius of the borehole and the cell size in the model are often different, therefore it is only possible to get the same trend of the curve, but not the same values.
- Secondary horizontal and vertical fractures, which intersect the main fracture, and the resulted semi-confined or unconfined conditions are not considered.
- Heterogeneity in both matrix and fracture systems is unknown and not considered. The unknown heterogeneity could even affect the hydraulic test data.

The following points for conducting and analysing hydraulic test data in fractured aquifers are given as recommendation:

- The duration of a hydraulic test should be long enough to reach the radial acting flow phase, when analytical methods are used.
- The discharge rate must be chosen in a way that no fracture will be dewatered during the test. Neither with analytical nor with numerical models it is possible to analyse such a test.
- The discharge rate should be kept constant over the whole period of abstraction. Otherwise no analytical method should be used to estimate the parameter values unless the drawdown is corrected. When using a numerical model, every change in the discharge rate must be considered (in another stress period).
- The measurement of the drawdown must have accuracy of at least 1cm.

- The time intervals of measurement in the beginning of the test should be small, at least less than 1 minute (recommended 10 seconds).
- For estimating vertical hydraulic conductivity, piezometers with short wellscreen should be installed in different depths.
- Parameter r, i.e. the effective borehole radius or half-length of the fracture, must be calculated from early hydraulic test data.
- To estimate the storage coefficient of the aquifer with an analytical method, use the estimated parameter r as distance between abstraction and observation borehole.
- To estimate the storage coefficient of the aquifer in a more accurate way, piezometers in the matrix should be used and the hydraulic test data should be analysed with a numerical model as described in this report.
- Observation boreholes, used for the hydraulic test, should never intersect more than one reacting aquifer system to avoid a mix of observation. If a borehole intersects more than one reacting aquifer system the drawdown data shows a mix of drawdown resulting from different systems and it is difficult to use those data in a numerical or analytical model.

Details of conducting and analysing hydraulic tests in fractured aquifers are given in the “Manual on Pumping Test Analysis in Fractured-Rock Aquifers” (van Tonder et.al., 2001) submitted to the WRC in January 2001 as a final report.

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CHAPTER 1

Introduction

1.1 Preamble

Water resources in South Africa are already being stressed and the country is slowly becoming a water-scarce country (Braune, 1996). This presents a challenge to all water resource managers to ensure that the basic water needs of every South African are met. A good estimation of the aquifer parameter is the basis of managing groundwater resources and understanding groundwater flow and transport processes.

Consider the geological setup and geometry of the fractured rock aquifers in South Africa (e.g. Karoo Aquifer), in general a three-dimensional groundwater flow must be considered when estimating aquifer parameters with pumping test data. However, most pumping test data are evaluated using analytical solutions such as Theis or Cooper-Jacob with the assumptions, which cannot be applied to fractured rock environments (van Tonder et.al., 2001). As the estimated parameters are the basis for further investigation, including sustainable management of groundwater resource and groundwater contamination estimation, a better methodology is required.

The aim of this research is to develop a guideline to estimate the aquifer parameters from a hydraulic test with computer models. The guideline will include:

- a method to estimate aquifer parameters of the fracture and the matrix from a pumping test using a computer model
- pre-built models for different scenarios
- a guideline how to use these models

Because of its high horizontal hydraulic conductivity value, the fracture normally acts like a horizontal production well during a pumping test. The hydraulic head everywhere in the confined fracture drops almost immediately after starting the pump. This causes the drop of the hydraulic head in the matrix at the vicinity of the fracture and water is released from the matrix storage and flows vertically into the fracture at the same rate as the pumping. After having used up this storage, the drawdown wave progresses to a wider range in the matrix to get more storage water and finally to get water from the recharge if the duration of a pumping test is long enough.

In general the spread of the drawdown wave can significantly be affected by several hydrogeological parameters, including:

- the horizontal hydraulic conductivity of the matrix (k_{hm}),
- the vertical hydraulic conductivity of the matrix (k_{vm}),
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Because Theis or Cooper-Jabcob methods can only provide an estimate of the transmissivity (a mixture of k_{hm}, k_{vm}, k_{hf}, k_{vf} and aquifer thickness) and storage coefficient (a mixture of S_{sm}, S_{sf} and aquifer thickness), a more sophisticated method is needed. In the "Manual on Pumping Test Analysis in Fractured-Rock Aquifers" (van Tonder et.al., 2001) the use and limits of analytical methods are described. Using numerical groundwater models and inverse modelling technique should solve this problem.

1.2 The Guideline

The aims of the project are

- To provide guidelines for estimating aquifer parameters, which are essential for
  - determining the degree and potential of groundwater contamination and
  - sustainable use and management of groundwater resources.
- To provide pre-built groundwater models for different scenarios to facilitate the use of the guidelines.
- To provide a better understanding of the aquifer parameters, especially of the Karoo aquifer.

To achieve these aims several pumping tests on different sites (typical fractured rock aquifers like horizontal bedding-plane fracture and vertical fractures in a dyke) were conducted. For each site a three-dimensional groundwater model will be constructed and the pumping test data are evaluated using this three-dimensional groundwater model and the inverse modelling technique.

Based on the knowledge (parameter value and aquifer behaviour) obtained in the steps above, groundwater models (pre-built models) and guidelines for evaluating pumping test date in these fractured rock aquifers will be prepared.

The guidelines provide a methodology and steps for estimating the abovementioned aquifer parameters using numerical groundwater models. Pre-built groundwater models will facilitate the use of these guidelines and help users understand the methodology and so prevent misunderstanding.

The report consists of the description of the fieldwork, the computer simulation and the step-by-step guidelines with recommendations for conducting and analysing hydraulic test data. The geology of the test sites and the drilling program is explained in chapter 2. The results of the different hydraulic tests, conducted on the test sites, are presented in chapter 3. The steps to analyse these hydraulic test data and to estimate the aquifer parameters with a numerical model are shown in chapter 4. The results from both the analytical and the numerical methods are compared and recommendations for analysing hydraulic test data are given in chapter 4.3 and chapter 6.

The guideline for analysing hydraulic test data with numerical models, as given in chapter 5, consists of a detailed description of the steps for estimating the aquifer parameters using inverse modelling technique.

CHAPTER 2

Borehole Drillings

2.1 General

The first part of the project was a drilling program on two different test sites to install boreholes, which could be used for the investigation and the field tests of this project. The two test sites are located at the campus of the University of the Free State and Meadhurst in the surrounding of Bloemfontein, respectively. These sites represent the main aquifer types in the Karoo. The Campus Test Site contains a horizontal bedding-plane fracture system and the Meadhurst Test Site includes a vertical fracture along a dyke.

2.2 Campus Test Site

2.2.1 Geology of the Site

The Campus Test Site at the University of the Free State was originally intended as a test site for postgraduate students and covers an area of approximately 180x192m. Before starting this project twenty-five percussion and seven core-boreholes were drilled (see Appendix A, Fig. A.1 and Fig. 2.2.1). Two projects sponsored by the Water Research Commission of South Africa also used this site for research on (a) Karoo Aquifers (Botha *et al*., 1998) and (b) tracer tests in fractured aquifers (Van Wyk *et al*., 2000). The Campus Test Site is underlain by a series of mudstones and sandstones from the Adelaide Subgroup of the Beaufort Group of formations in the Karoo Sequence. Mapping of geological outcrops around the Campus Site reveals the existence of extensional fractures (Mode I) and shearing fractures (Mode II). The dominant type of fractures recognised in the sediments includes sub-horizontal bedding-parallel fractures and orthogonal and diagonal fractures with dominant north-west, north-east and east-west trends.

Five of the seven core-boreholes were drilled vertically and two at an angle of 45 degrees. The two north-easterly fractures detected in core-boreholes CH6 and CH7 are the only subvertical structures intersected during the core drilling and both were calcified. The geological column of the Campus site (Fig. A.2) can be subdivided into five different easily recognisable rock units, each characterised by a unique assemblage of rock types and structures. These lithological units may be subdivided into different lithofacies. The vertical lithofacies represent vertical accretion of deposits in flood-plains (mudstone and siltstone facies), shallow lakes (rhythmite facies) and channels (sandstone facies). A major feature of the core samples is the large number of bedding-parallel fractures whose frequency decreases downward from the upper, more weathered zone, as thicker and more competent units are encountered. The bedding plane fractures in the upper, more weathered part are often transected by large number of orthogonal, oblique and diagonal fractures. These fractures clearly represent secondary fracturing of the rock mass caused by the post-lithification process.

The Mode I fracture is the most significant fracture on the Campus Site and all boreholes with high yields (11 has yields in excess of 3 l/s) intersected this bedding-plane fracture. The yields of the other percussion boreholes are less than 0.6 l/s because the Mode I fracture was not intersected during drilling. It is clear from both the acoustic scan and borehole video of borehole UO23 (Fig A.3 and A.4), that the Mode I fracture, which is situated at about 21 m below surface, consists of a fracture zone with a thickness that varies between 100 and 200 mm (i.e. the fracture zone has developed as consequence of the weathering of the rock between two bedding-plane fractures which were close together).

There are three aquifers present on the Site. The top, a phreatic aquifer, occurs within the upper mudstone layers on the Site. This aquifer is separated from the middle and main aquifer by a layer of carbonaceous shale with a thickness of 0.5 – 4 m, which is about 13 metres below the ground surface. The main aquifer consists of sandstone and has a thickness of about 8 to 10 metres. The bottom aquifer occurs in the mudstone layers (more than 100 m thick that underlies the sandstone unit, Botha *et al*., 1998).

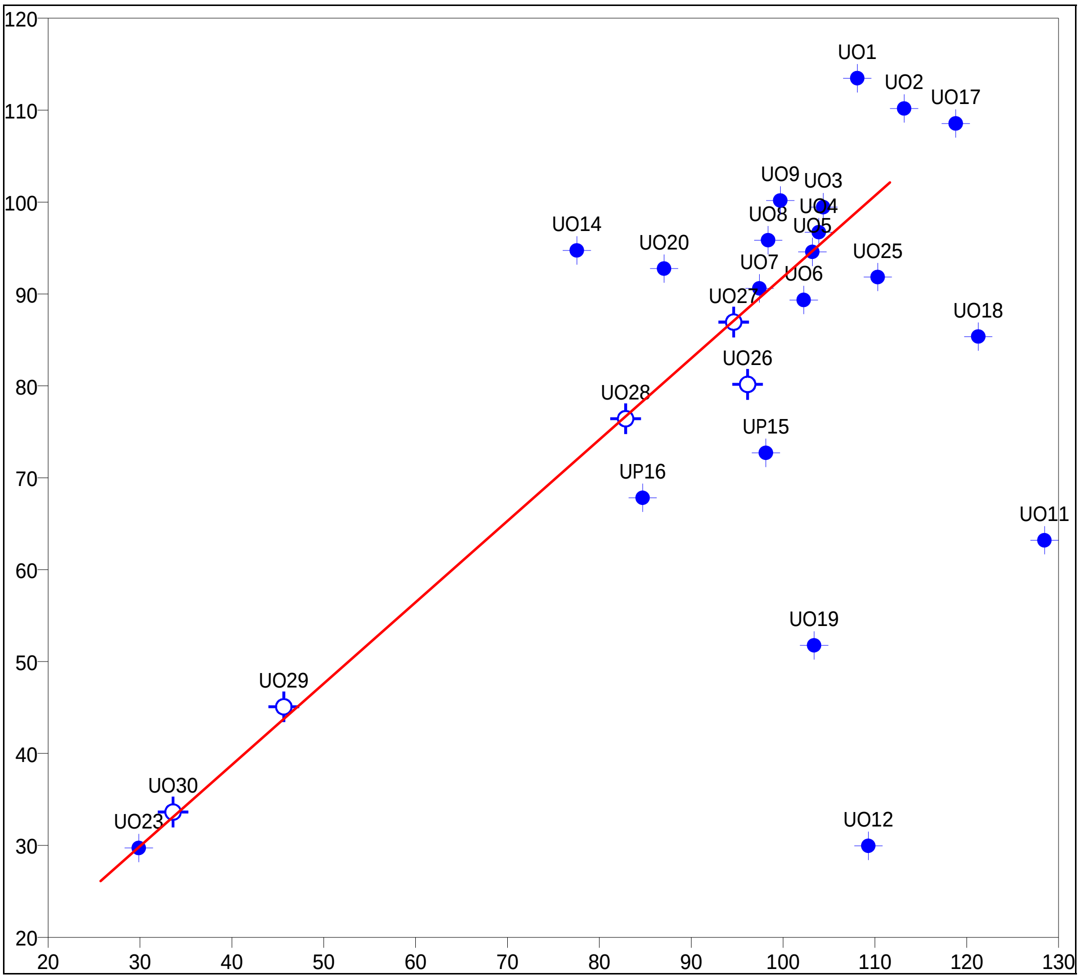


Fig. 2.2.1: Locations of the boreholes at Campus Test Site

2.2.2 Drilling Program

In addition to the existing boreholes on the Campus Test Site five boreholes were drilled in March 2000 to be used especially for this project. The new boreholes are located along a straight line from the centre of the site (UO5) to south-west direction (UO23) as shown on fig. 2.2.1. During the drilling the boreholes UO27 and UO30 were found as low yielded and dry respectively. The other boreholes, named UO26, UO28 and UO29, intersect the Mode I fracture at a depth between 21m and 24 m below surface and yield about 4 l/s. Fig. 2.2.2 shows the borehole log for UO26. The borehole logs for the other boreholes are all very similar and documented in Appendix B.

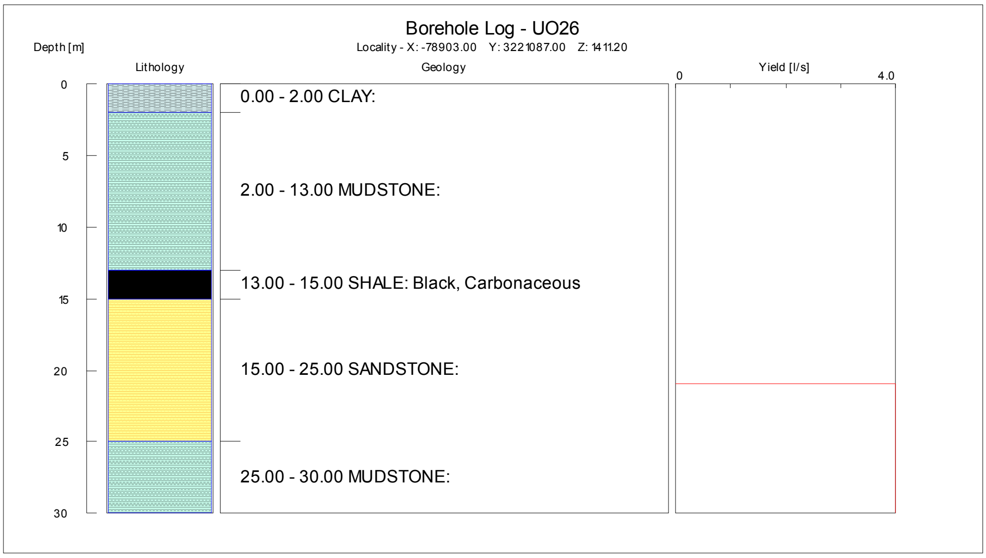


Fig. 2.2.2: Borehole Log for UO 26 (The blow yield of 4l/s starts at 21 m below surface)

To estimate the specific yield of the boreholes and to allocate the correct positions of the fracture zone in each borehole, different tests (e.g. constant rate tests, tracer tests, borehole fluid logs) were conducted.

- A constant rate test, conducted at UO26 with a discharge of about 0.8 l/s, shows the good hydraulic contact between the boreholes UO26, UO27, UO28 and UO29. The drawdowns in all observation boreholes were very similar and in the same range (see also chapter 3.2).
- A constant rate test, conducted at UP16 with a discharge of about 3 l/s, shows a similar behaviour of the observed boreholes in the beginning of the test. When the water level in the abstraction borehole reached the position of the fracture (about 21 m below surface) the water levels in UO29 and UO30 reached the same position (20.84 m and 20.67 m below surface respectively), which is estimated as the position of the fracture zone. The water levels in the other observed boreholes stabilized between 18.54 m and 19.24 m below surface, which lies above the fracture.
- Radial convergent tracer tests, conducted between UO28 and UO26 give an estimate for the flow thickness (i.e. hydraulic effective thickness of the fracture zone) and the porosity of the fracture zone, which are needed for the computer model.

- Borehole conductivity logs, measured with an EC-meter under natural conditions, give a good estimation of the depth of the fracture zone. By using salt as a tracer the estimated position of the fracture can be verified. The results of the borehole conductivity logs are shown in Appendix B.2. Fig. 2.2.3 shows the EC-profile in UO28 with two fracture zones at 20.5 m and 22 m respectively as seen from the jump in the EC-concentration.

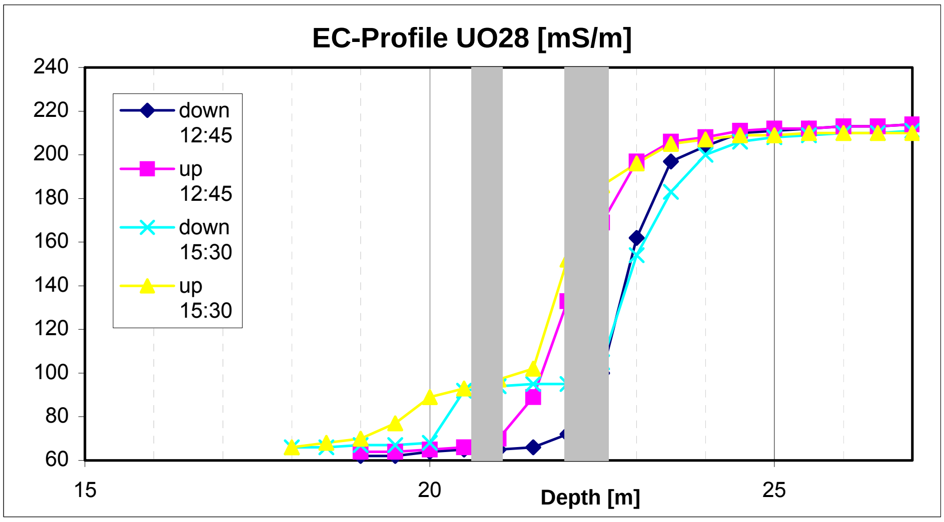


Fig. 2.2.3: Borehole Conductivity Log of UO28, showing the position of the fractures at 20.5m and 22m

The results from the tests, which are important for the following steps of this project, are listed in table 2.2.1. For complete results see the appendix.

Table 2.2.1: Depth of the fracture zone in the new boreholes (m under surface)

Borehole	**Depth of fracture**	**Method of estimation**
UO23	21 m	Borehole video
UO26	24 m	Tracer test, borehole conductivity log
UO27	21 m	Tracer test, borehole conductivity log
UO28	20.5 m and 22 m	Tracer test, borehole conductivity log
UO29	21 m	Tracer test, borehole conductivity log
UO30	21 m	Tracer test, borehole conductivity log

After drilling and testing the boreholes with the abovementioned tests the piezometers were installed in the boreholes UO23, UO29, UO28 and UO27, lying exactly on one line with the borehole UO5, which should be used for the abstraction during the hydraulic tests. In each of the boreholes three piezometers were installed in the following way:

- one piezometer in DN 32 about 1.5m (UO23) or 2.5m above the fracture,
- one piezometer in DN 50 in the fracture zone with a wellscreen length of 1m (UO23), 2m (UO27 and UO29) and 3m (UO28),
- one piezometer in DN 32 about 1,5m (UO23) or 2.5 m below the fracture.

Between the piezometers a sealing of bentonite was put to avoid a flux or pressure contact between the three zones (Fig. 2.2.4). On the bottom of the bentonite sealing a thin layer of cement was installed to avoid a contact between the bentonite and the piezometer.

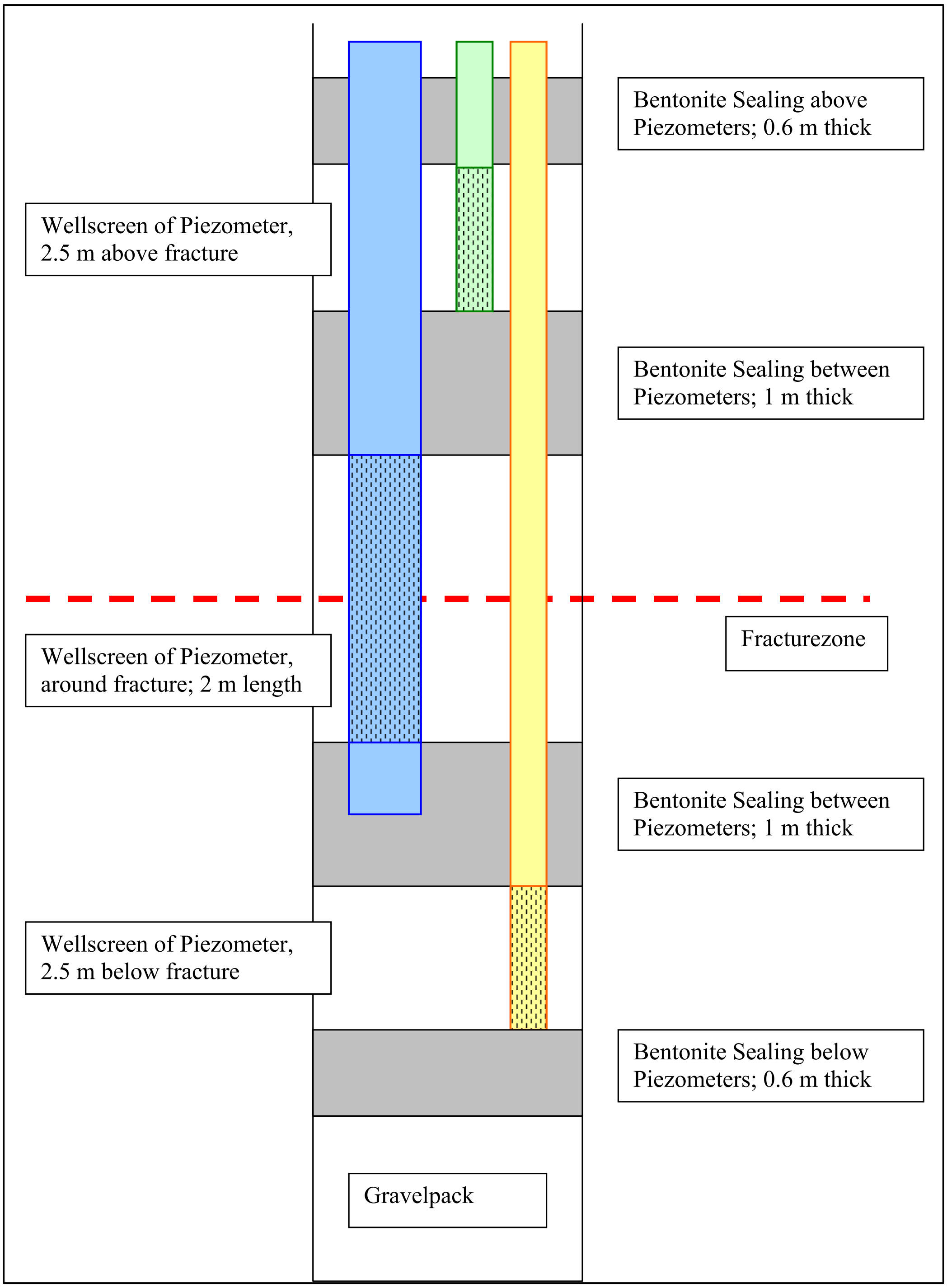


Fig. 2.2.4: Scheme of installing the piezometers into the boreholes

2.3 Meadhurst Test Site

2.3.1 Geology of the Site

The Meadhurst Test Site is situated approximately 16 km outside of Bloemfontein in the Bainsvlei smallholdings area. On the whole site there exist about 30 boreholes, which are located in different subsites (see Appendix A, fig. A.5). Some of them are used by the owners for domestic and irrigation purposes. The investigation for this project was situated on the site A, which is located in the south of the whole site and consists of 10 boreholes along the dyke and on both sides of the dyke respectively. The locations of the boreholes are shown in fig. 2.3.1.

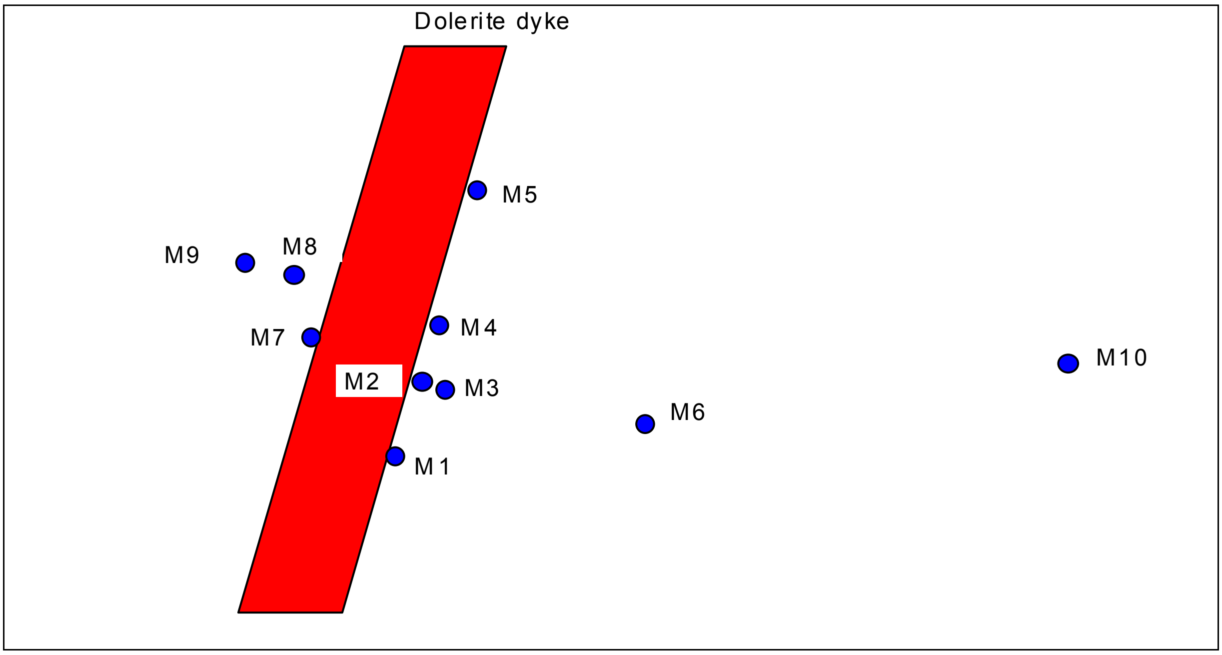


Fig. 2.3.1: Locations of the boreholes at Site A, Meadhurst Test Site

The general Geology of the area is mainly made up of Karoo sandstone, dolerite sills and dykes and mudstone. The top layer consists of red and orange-red soil and sand with a thickness of approximately 20m. It is underlie by a dolerite, which is mostly weathered. Under this aquifer follows a thick layer of mudstone. The mudstone and the dolerite layer are cut by a dolerite dyke, which falls with about 45° to south-east, as shown in the borehole log of M1 in fig. 2.3.2).

The water strikes occur in the weathered dolerite (about 0.4 l/s) and in parallel fractures in the dyke and the contact zone between dyke and mudstone (up to 3 l/s). Due to the width of the dyke the yield of the boreholes, placed direct on the dyke, varies between 0.7 and 3 l/s.

2.3.2 Drilling Program

For the development of this site ten boreholes were drilled. During this project only the boreholes intersecting the dyke are used for the investigation. The borehole log of M1, as shown in fig. 2.3.2, is typical for the boreholes along the dyke. The borehole logs of all boreholes including the water strikes and blow yield are documented in Appendix B.3.

On this site no piezometers for the fracture and the matrix are installed.

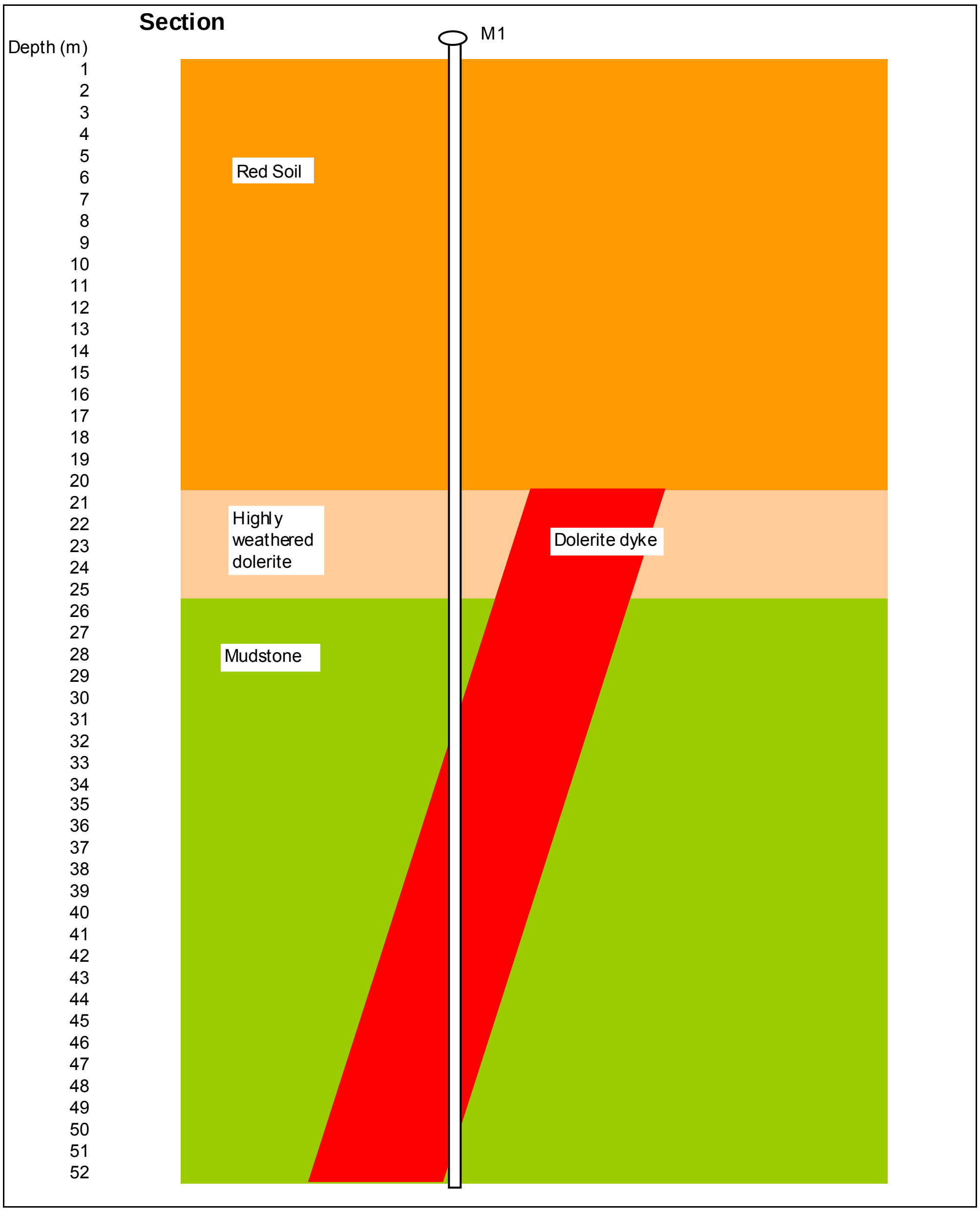


Fig. 2.3.2: Borehole log of M1, intersecting the dolerite dyke

CHAPTER 3

Field Tests

3.1 General

After completing the drilling program as described in chapter 2 on both sites hydraulic tests were conducted to estimate the aquifer parameters. Below the conducted tests were described and the results documented.

3.2 Hydraulic Tests at Campus Test Site

On the Campus Test Site several hydraulic tests were conducted in the last years, including one constant rate test with the new boreholes before installing the piezometers. For this test the borehole UO26 was used for abstracting water and the boreholes UO27, UO28 and UO29 were observed permanently.

The relevant data of the test are shown in table 3.2.1.

The hydraulic tests, using the boreholes with installed piezometers, were conducted in July and September 2000 and are documented in section 3.4. For the abstraction of water the borehole UO5 was used and permanent observations were taken in the piezometers of the boreholes UO27, UO28, UO29 and UO23. The water levels in other boreholes were also measured over the period of the tests.

3.2.1 Constant Discharge Test UO26

As shown in table 3.2.1 the constant discharge test on the Campus Test Site was conducted at the borehole UO26 for the abstraction with a discharge rate of 0.71 l/s for period of 13 hours. The boreholes UO27, UO28 and UO29 were used to observe the water level in the aquifer permanently with a pressure transducer and automatically data logger.

Table 3.2.1: Conditions for the constant discharge test UO26, conducted at Campus Test Site

Abstraction BH	**Discharge Rate**	**Duration of test**	**Observation Boreholes (Distance to UO26 in Brackets)**
UO26	0.71 l/s	780 min	UO27 (7m), UO28 (14m), UO29 (34m)
	Recovery	720 min	

All the boreholes intersected the same Mode I fracture and Fig. 3.2.1 shows the pumping test data in this case. The drawdown values in UO27, UO28 and UO29 were very similar and did not converge to the same drawdown value as the abstraction borehole UO26.

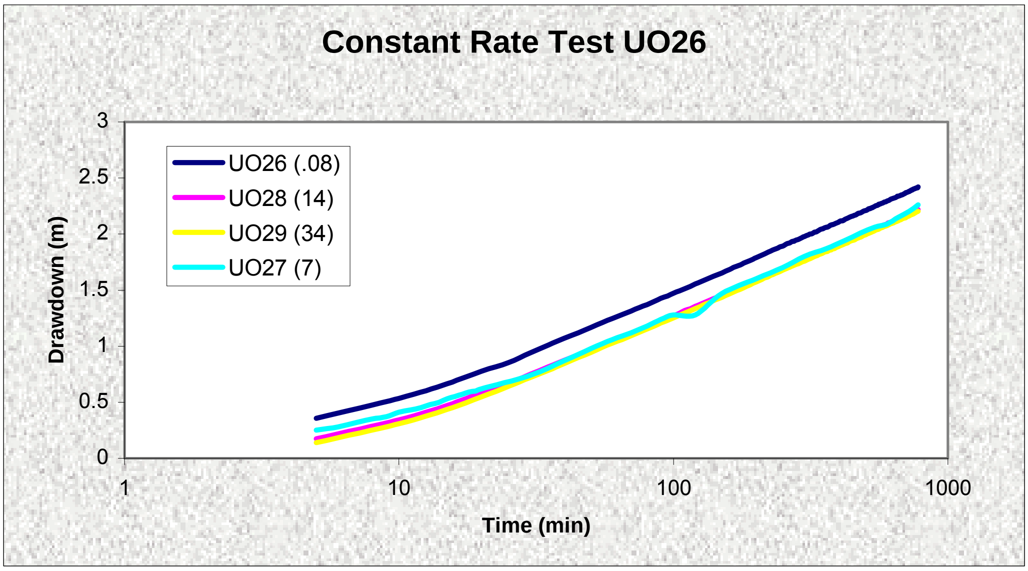


Fig. 3.2.1: Drawdown in the abstraction and observation boreholes during the constant rate test at UO26. The values in parenthesis give the distance between individual boreholes and UO26.

The test data were analysed with different methods to evaluate the aquifer parameter transmissivity T (m^2/d) and storage coefficient S (-). The analysing is documented in appendix C.1 and the results are shown in table 3.2.2. The estimated T-values, using the methods of Cooper-Jacob or Theis, are of the same order of 10 m2/d, but the estimated S-values differ between 3 E-5 and 2E-3 with a distance dependency (the larger the observation distance, the smaller the estimated S-value). **The reason for this phenomenon is the application of a wrong method to the real field situation**. In a fractured aquifer we are dealing with two systems, i.e. fracture and matrix. During a pumping test groundwater is released from matrix, flows vertically to the fracture and than along the fractured zone towards the abstraction borehole (van Tonder et.al., 2001). However, neither the Theis nor Cooper-Jacob methods consider this situation. When applying these methods, only the portion of groundwater, which is released outside of the radius of the observation borehole, is considered by the analytical solution. And this portion is decreasing with the increasing distance of the observation borehole. This explains the decreasing of the S values with the distance. As a result of applying Theis or Cooper-Jacob methods, the estimated T and S values represent a mixture of the matrix and fracture properties.

By using the distance-drawdown-method (known as Cooper-Jacob II, see fig. 3.2.2) the estimated T-value is much higher and the S-value much smaller than with Cooper-Jacob or Theis. With the method Cooper-Jacob II the estimated values represent the fracture zone, while the estimated values with the other methods represent the whole aquifer (fracture + matrix).

From the graphs and the results it can be seen, that the standard methods for estimating aquifer parameter from hydraulic tests (i.e. Theis and Cooper-Jacob) can't be applied correctly to fractured aquifers, because the vertical flux from the matrix to the fracture and the storage of the matrix is nearly neglected in these models. For the numerical model the estimated values are used as initial values of the parameters, which have to be verified and recalculated with the inverse modelling technique.

Table 3.2.2: Results of the evaluated aquifer parameter for the constant rate test UO26

Borehole	Cooper-Jacob Method		Theis Method		Comment
	T (m^2/d)	S (-)	T (m^2/d)	S (-)	
UO26	10.6	2.75 E-5	10	3.30 E-5	S-value calculated with effective BH Radius of 49.7 m
UO27	10.6	2.13 E-3	10	2.45 E-3	T- and S-values valid for whole aquifer (fracture + matrix)
UO28	10.5	5.41 E-4	10	5.80 E-4	
UO29	10.7	8.92 E-5	11	8.60 E-5	
All Boreholes	755	5.87 E-7			Cooper-Jacob II for fracture zone

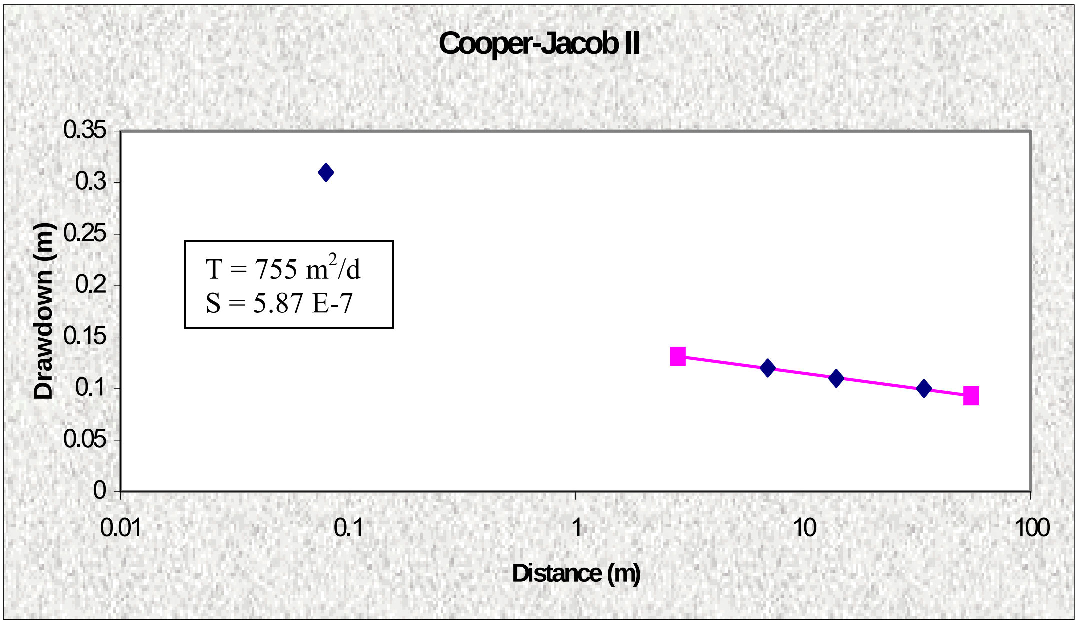


Fig. 3.2.2: Measured drawdown after 2 minutes vs. distance of observation during constant rate test at UO26

3.3 Hydraulic Tests at Meadhurst Test Site

On the Meadhurst Test Site one multirate test with 4 steps and two constant rate tests were conducted. For both tests the borehole M1 was used for abstracting water and the boreholes M2, M3, M5, M6 and M7 were observed permanently. During the tests water level measurements took place in the other boreholes too, but there was no drawdown to register.

The relevant data of the tests are shown in table 3.3.1 and 3.3.2.

3.3.1 Multirate Test M1

As shown in table 3.3.1 the multirate test at borehole M1 was conducted between the 10th and 13th March 2000 with 4 steps rising from 1.4 l/s to 3 l/s. The drawdown curves for each step show a different behaviour depending on the discharge rate (fig. 3.3.1). The higher the discharge the higher is the slope of the drawdown curve at the end of the step. During the step with 3 l/s the discharge decreased to 2.5 l/s after about 60 min. With a high discharge the drawdown reached the first water strike, located in M1 at 26m, and reduced in this way the possible yield of the whole borehole.

Table 3.3.1: Conditions for the multirate test, conducted at Meadhurst Test Site

Abstraction BH	Discharge Rate	Duration of test	Observation Boreholes (Distance to M1 in Brackets)
M1	1.Step: 3.0 l/s	60 min	M2 (21.75m), M3 (21.97m), M4 (34.37m), M5 (80.2m), M6 (35.84m), M7 (55m), M8 (77.5m), M9 (86m)
	2.Step: 2.5 l/s	60 min	
	3.Step: 2.0 l/s	60 min	
	4.Step: 1.4 l/s	60 min	

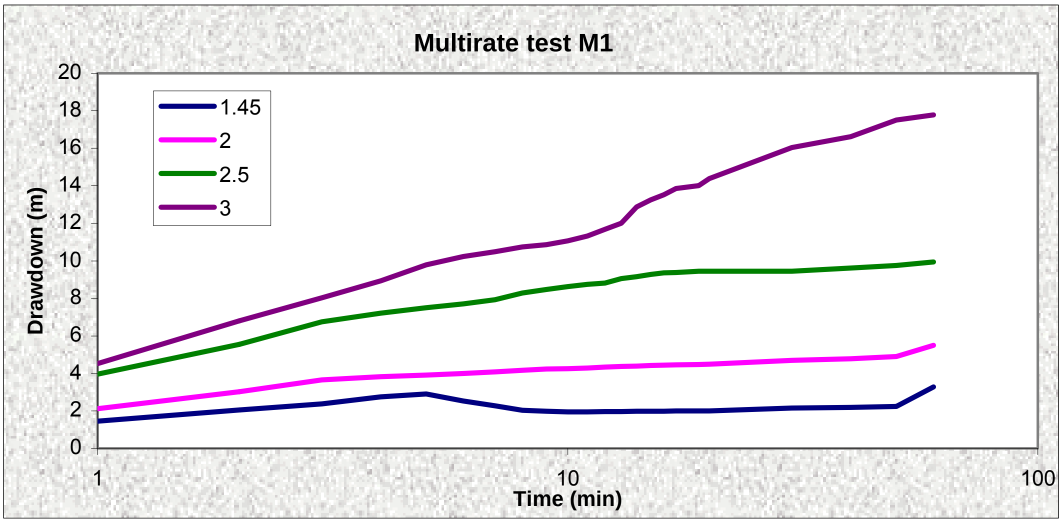


Fig. 3.3.1: Drawdowns in M1 during Multirate Test (values for Q in l/s)

The drawdown measurements in the observation boreholes along the dyke show a similar behaviour, while in the boreholes, which don't intersect the dyke, no relevant drawdown were to observe.

3.3.2 Constant Discharge Test M1

As shown in table 3.3.2 the constant discharge tests on the Meadhurst Test Site were conducted at the borehole M1 for the abstraction with a discharge rate of 1.4 l/s and 2.0 l/s respectively for a period of 16 and 18 hours. The boreholes M2, M5 and M6 were used for the 1st test to observe the water level in the aquifer permanently with a pressure transducer and automatically data logger. In the other boreholes listed in table 3.3.2 the water levels were measured with a dipmeter over the whole period of the test. During the 2nd test only the water level in the abstraction borehole was measured.

Table 3.3.2: Conditions for the constant discharge tests, conducted at Meadhurst Test Site

Abstraction BH	**Discharge Rate**	**Duration of test**	**Observation Boreholes (Distance to M1 in Brackets)**
M1	1.4 l/s	960 min	M2 (21.75m), M3 (21.97m), M4 (34.37m), M5 (80.2m), M6 (35.84m), M7 (55m), M8 (77.5m), M9 (86m)
	Recovery	120 min	
M1	2.0 l/s	1080 min	No observation data available
	Recovery	120 min	

Fig. 3.3.2 shows the data and graphs of the 1st test for the abstraction borehole M1 and the nearest observation borehole M2. The behaviour of the drawdown in both boreholes are very similar, even the jump in the drawdown due to the change of the discharge rate after around 8 minutes is clearly to observe in both boreholes.

In the other boreholes, which intersect the dyke, the drawdowns reached maximum 25 cm in the M3 and less than 10 cm in M5 and M6. In the boreholes M8, M9 and M10, which lie outside the dyke and do not intersect the main fracture, no drawdown was observed.

The drawdowns in the boreholes M2 and M3, both intersecting the dyke with a distance of 2m to each other and having almost the same distance to the abstraction borehole M1, show a different behaviour. While drawdown values in M2 and M3 react in the same way as those of the abstraction borehole M1 (fig. 3.3.2 and fig. 3.3.3), the drawdown in M3 is much less (fig. 3.3.3). This shows, that the hydraulic contact between M1 and M2 is better than between M1 and M3. A similar behaviour can be observed in M6.

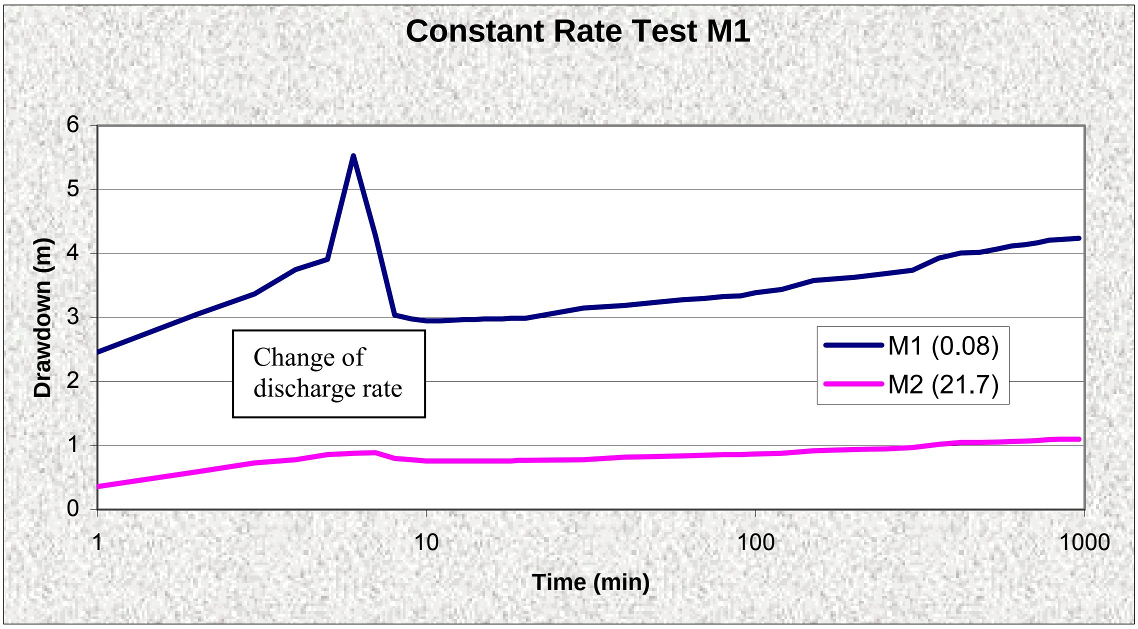


Fig. 3.3.2: Drawdown in the abstraction borehole M1 and the observation borehole M2 during the constant rate test with 1.4 l/s at Meadhurst Test Site

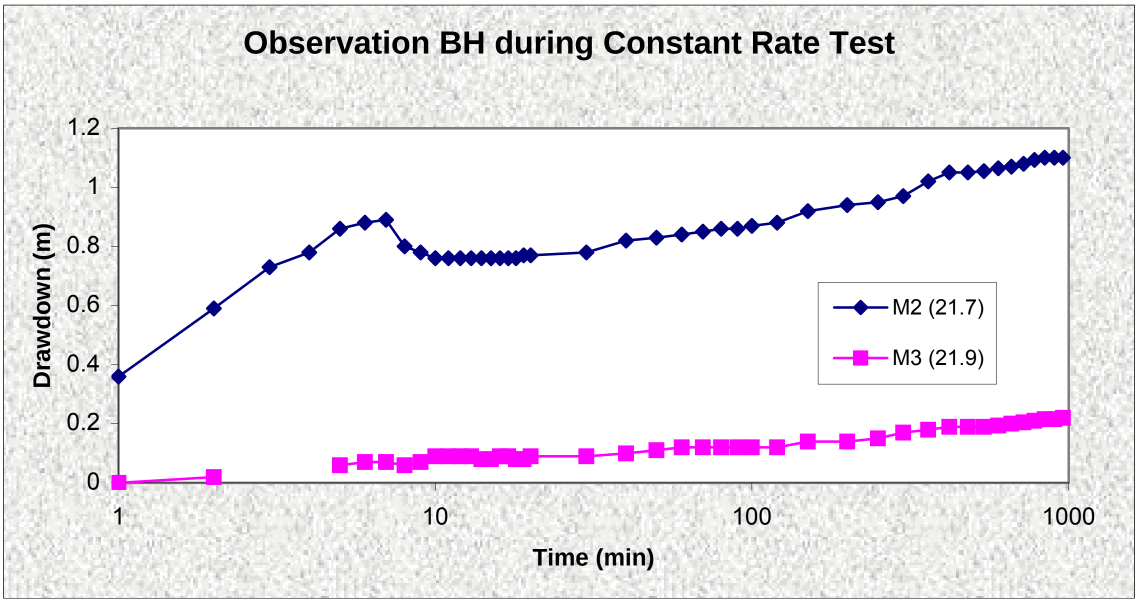


Fig. 3.3.3: Drawdown behaviour of the observation boreholes M2 and M3

The estimation of the transmissivity for the different boreholes, used the methods from Theis and Cooper-Jacob, yield values between 23.8 m^2/d and 294 m^2/d (see table 3.3.3). The high values were estimated for boreholes with a small drawdown like M3, M5 and M6. In the same boreholes large values for the storage coefficient, between 3E-3 and 3E-2, were estimated, while the storage coefficient in the boreholes M1 and M2 was estimated at 2E-5, which makes more sense for the fracture system.

Using the drawdown-distance method (Cooper-Jacob II) an average T-value for the fracture is estimated as 35 m^2/d and an average storage coefficient S as 3E-5. From the graph (see fig. 3.3.4) it can be shown that these values are only valid for the boreholes M1, M2 and M5, while the plots of the boreholes M3 and M6 lie outside of the straight line. This even shows that these boreholes do not have a good hydraulic contact with the fracture system M1 – M2 – M5.

From the graphs in the appendix C.3 and the table 3.3.2 it can be seen clearly that the application of Cooper-Jacob or Theis methods cannot yield correct values in this case due to the different behaviour of the fractured aquifer, because these methods are only valid for porous media and under restrictive assumptions.

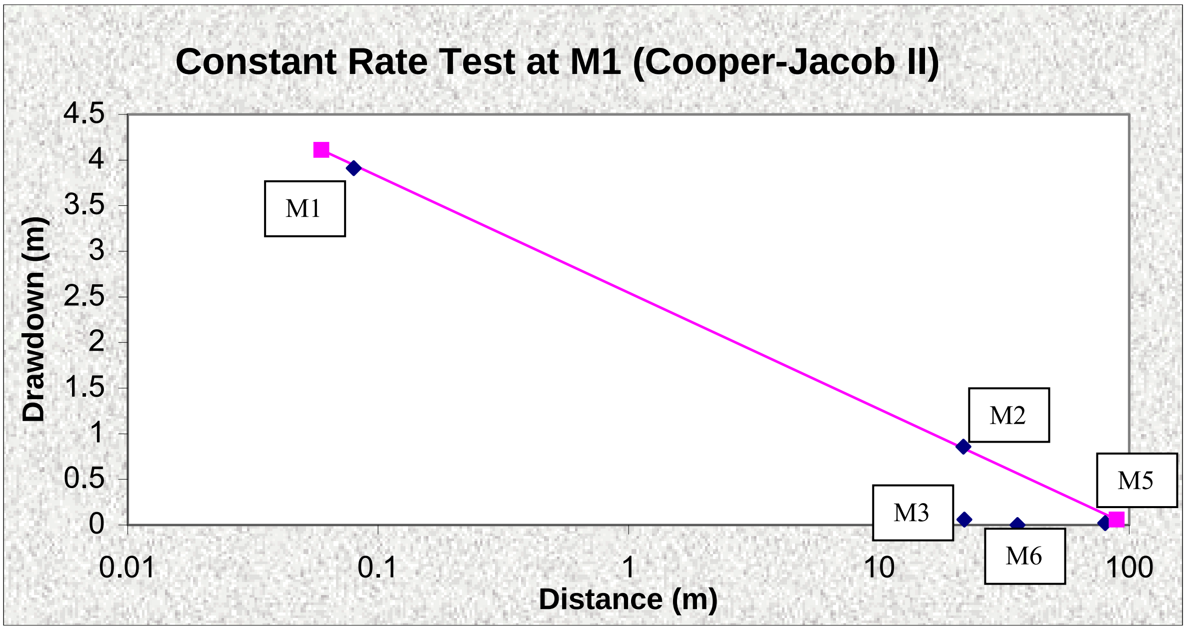


Fig. 3.3.4: Drawdown-distance plot of the constant rate test at Meadhurst Test Site

Table 3.3.2: Results from the Constant Rate Test at Meadhurst Test Site, using the standard methods of Cooper-Jacob and Theis.

	Cooper-Jacob Method		Theis Method		
Borehole	T (m^2/d)	S (-)	T (m^2/d)	S (-)	Comment
M1, 1st	23.8	2.00 E-5	24	1.70 E-5	S-value calculated with effective BH Radius
M1, 2nd	21.3	1.17 E-6	22	1.00 E-6	
M2	82.1	1.90 E-5	82	1.90 E-5	
M3	167.5	1.09 E-2	182	8.50 E-3	T- and S-values are too high for the system
M5	294.4	3.87 E-3	292	4.40 E-3	
M6	273.7	3.19 E-2	273	3.49 E-2	
all	34.75	3.07 E-5			Cooper-Jacob II for fracture zone

3.4 Hydraulic Tests with installed Piezometers at Campus Test Site

After installing the piezometers two hydraulic tests were conducted on the Campus Test Site, both using the borehole UO5 as abstraction borehole with different discharge rates.

3.4.1 Constant Discharge Test UO5, July 2000

As shown in table 3.4.1, the first constant discharge test with installed piezometers on the Campus Test Site was conducted at the borehole UO5 for the abstraction with a discharge rate of 0.51 l/s for a period of 67 hours. The piezometers in the boreholes UO23, UO27, UO28 and UO29 were used to observe the water level in the fracture zone, and the rock matrix permanently with a dip meter. The water levels in the boreholes UO6, UO7, UO20, UO26 and UO30 were also measured during the period of the test.

Table 3.4.1: Conditions for the constant discharge test UO5, conducted at Campus Test Site

Abstraction BH	Discharge Rate	Duration of test	Observation Boreholes (Distance to UO5 in Brackets)
UO5	0.5 l/s	4008 min	UO27a, b, c (each 11.5m); UO28a, b, c (each 27.25m); UO29a, b, c (each 75.9m); UO23a, b, c (each 97.9m); UO6a, b (each 5.3m); UO7 (7.0m), UO20 (16.2m), UO26 (16.1m), UO30 (92.5m)
	Recovery	6000 min	

(a: piezometer above the fracture, b: piezometer below the fracture, c: piezometer in the fracture zone)

The drawdown behaviour in the fracture-piezometers and the boreholes are similar to the abovementioned UO26-test. The water level in all boreholes dropped simultaneously and in the same range as in the abstraction borehole UO5. Fig. 3.4.1 shows the drawdown in the fracture while fig. 3.4.2 shows the drawdown in the matrix-piezometers.

The behaviour of the groundwater flow during the pumping test conducted in the abstraction borehole UO5 can be described as follows:

- The hydraulic head everywhere in the fracture drops simultaneously
- The hydraulic head in the matrix drops later and less than in the fracture; water from the matrix storage flows into the fracture and from there to the abstraction BH
- After stopping the pumping, the drawdown in the matrix continues while the head in the fracture recovers; water still flows from the matrix toward the fracture to refill the system.

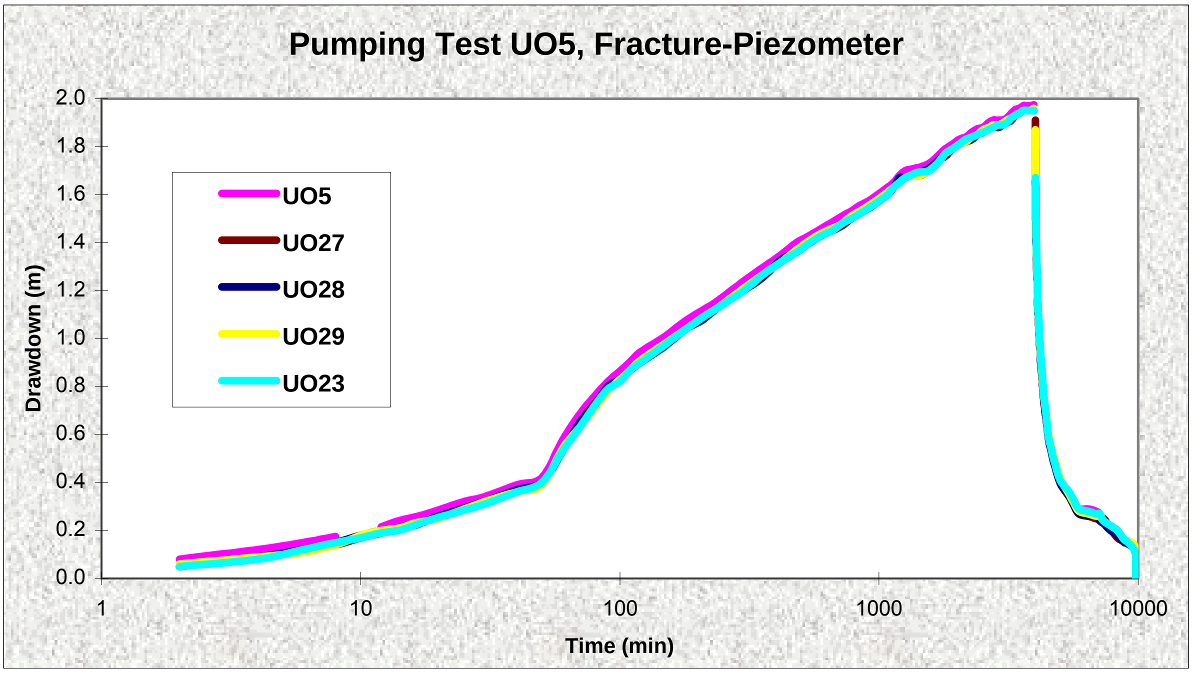


Fig. 3.4.1: Drawdown in the fracture-piezometers during constant discharge test UO5, July 2000

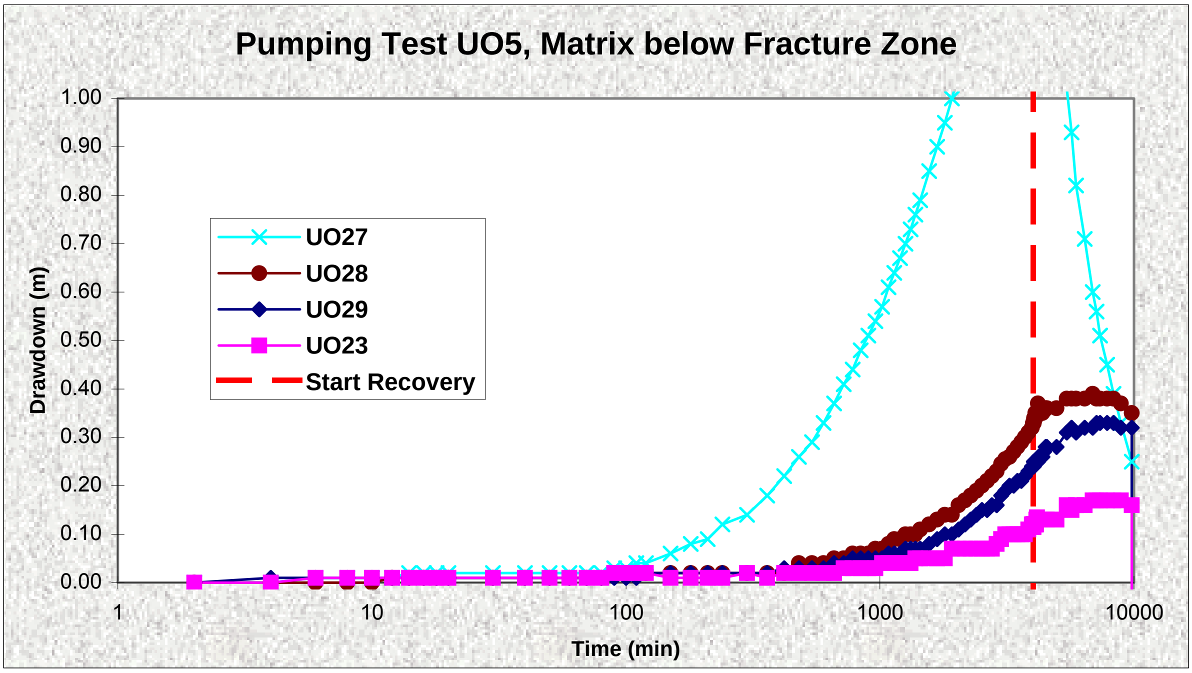


Fig. 3.4.2: Drawdown in the matrix-piezometers below the fracture zone during the constant discharge test UO5, July 2000

The test data were analysed with different analytical methods to evaluate the aquifer parameter transmissivity T (m^2/d) and storage coefficient S (-). The analysis is documented in appendix C.5 and the results are shown in table 3.4.2. The estimated T-values, using the methods of Cooper-Jacob or Theis, are of the same order of 10 m^2/d, as estimated for the constant discharge test UO26. The estimated S-values differ between 1E-5 and 8E-3 with a distance dependency (the larger the observation distance, the smaller the estimated S-value).

This distance dependency will also occur, if applying the Gringarten-method, which is an analytical solution for a horizontal, uniform flux fracture. The estimated values for the transmissivity and the storage coefficient of the aquifer are of the same order than the values estimated with Cooper-Jacob or Theis (see table 3.4.2). Additionally to these parameters the thickness of the aquifer, the vertical hydraulic conductivity, the half-length of the fracture and the fracture height have to be estimated (see table 3.4.3). Without prior information about the aquifer properties this method is a non-unique solution.

By using the distance-drawdown-method (known as Cooper-Jacob II, see fig. 3.4.4) the estimated T-value is much higher and the S-value much smaller than with Cooper-Jacob or Theis. With the method Cooper-Jacob II, the estimated values represent the fracture zone, while the estimated values with the other methods represent the whole aquifer (fracture + matrix).

Table 3.4.2: Results of the evaluated aquifer parameter for the constant rate test UO5, July 2000, obtained from the fracture-piezometers

Bore-hole	Cooper-Jacob I		Theis		Gringarten		Comment
	T (m^2/d)	S (-)	T (m^2/d)	S (-)	T (m^2/d)	S (-)	
UO5	10.6	4.4E-03	9	8.0E-03	15	3.0E-03	S-value calculated with effective BH Radius of 5 m
UO27c	10.7	9.1E-04	11	8.3E-04			Distance: 11.5m
UO28c	10.6	1.6E-04	11	1.5E-04			Distance: 27.2m
UO29c	10.6	2.1E-05	11	1.9E-05			Distance: 76m
UO23c	10.6	1.3E-05	10	1.5E-05	10	2.0E-05	Distance: 98m
All BH	743	2.4E-15					Cooper-Jacob II for fracture zone

Table 3.4.3: Estimated and assumed parameter values from the Gringarten-method for the constant rate test UO5, July 2000

Parameter	UO5 (Abstraction)	UO23 (Observation)	Units
Transmissivity matrix	15	10	m^2/day
Aquifer Thickness	20	20	m
Storage Coefficient	3.0 E-03	2.0 E-05	-
Vertical hydraulic conductivity	3.0 E-03	3.0 E-03	m/day
Fracture half-length	60	60	m
Fracture height	0.2	0.2	m
Fracture Elevation	10	10	m

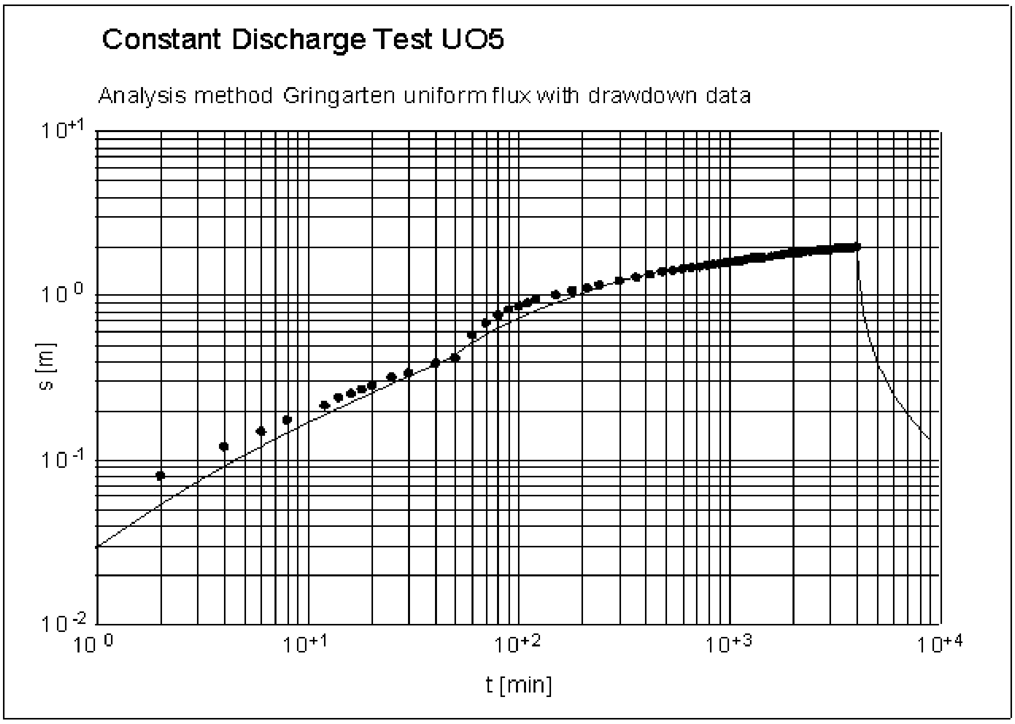


Fig. 3.4.3: Measured drawdown in UO5 (dots) during constant rate test at UO5, July 2000 and fitted curve with Gringarten-method, parameter values from table 3.4.3

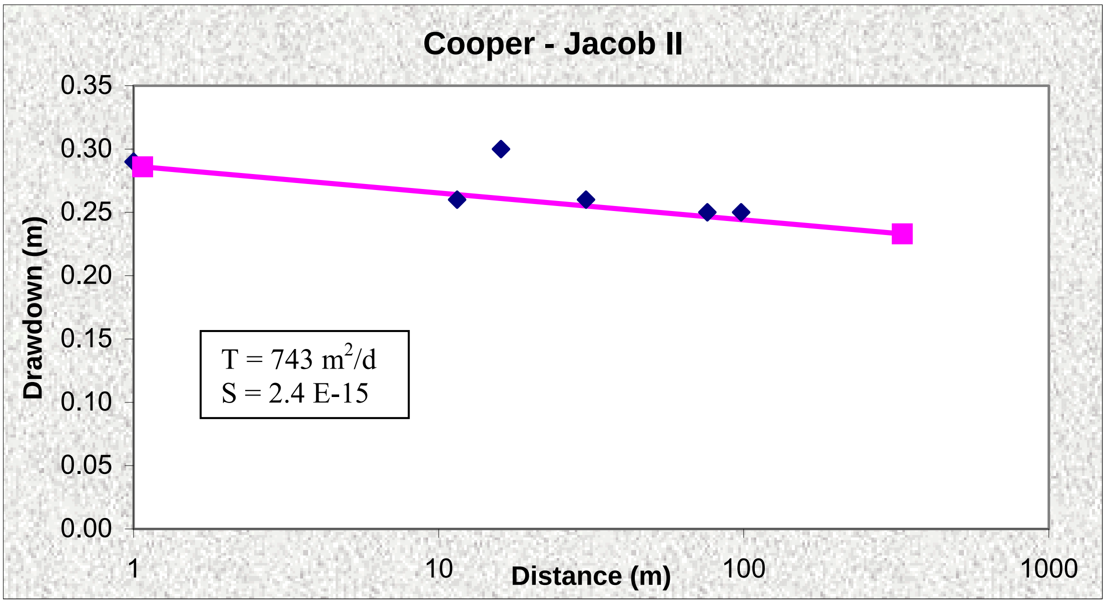


Fig. 3.4.4: Measured drawdown after 20 minutes vs. distance of observation during constant rate test at UO5, July 2000
(The estimated S-value is far too small for the fracture system. If neglecting the abstraction borehole UO5, an S-value of E-10 can be computed, which is even smaller than expected)

If applying the abovementioned methods to the drawdown data obtained from the matrix-piezometers, the estimated values for transmissivity and storage coefficient differ much from the values obtained from the fracture-piezometers and seem too high and unrealistic (see table 3.4.4). The Gringarten-method is not applicable to the data from matrix-piezometers.

Table 3.4.4: Results of the evaluated aquifer parameter for the constant rate test UO5, July 2000, obtained from the matrix-piezometers

	Cooper-Jacob Method		Theis Method		
Borehole	**T (m^2/d)**	**S (-)**	**T (m^2/d)**	**S (-)**	**Comment**
UO27a	88.5	3.28E-01	80	3.0E-01	Distance: 11.5m
UO28a	57.5	8.89E-02	60	9.0E-02	Distance: 27.2m
UO29a	80.0	7.39E-03	90	7.0E-03	Distance: 76m
UO23a	12.5 33.7	5.78E-03 9.85E-03	5	7.4E-03	Distance: 98m
UO27b	4.2	2.89E-02	4	3.3E-02	Distance: 11.5m
UO28b	14.1	3.31E-02	11	4.4E-02	Distance: 27.2m
UO29b	11.5	5.43E-03	12	7.6E-03	Distance: 76m
UO23b	34.5	7.06E-03	65	7.5E-03	Distance: 98m
all above	254	2.28E-02			Cooper-Jacob II
all below	50.8 - 162	1.2 E-02			Cooper-Jacob II

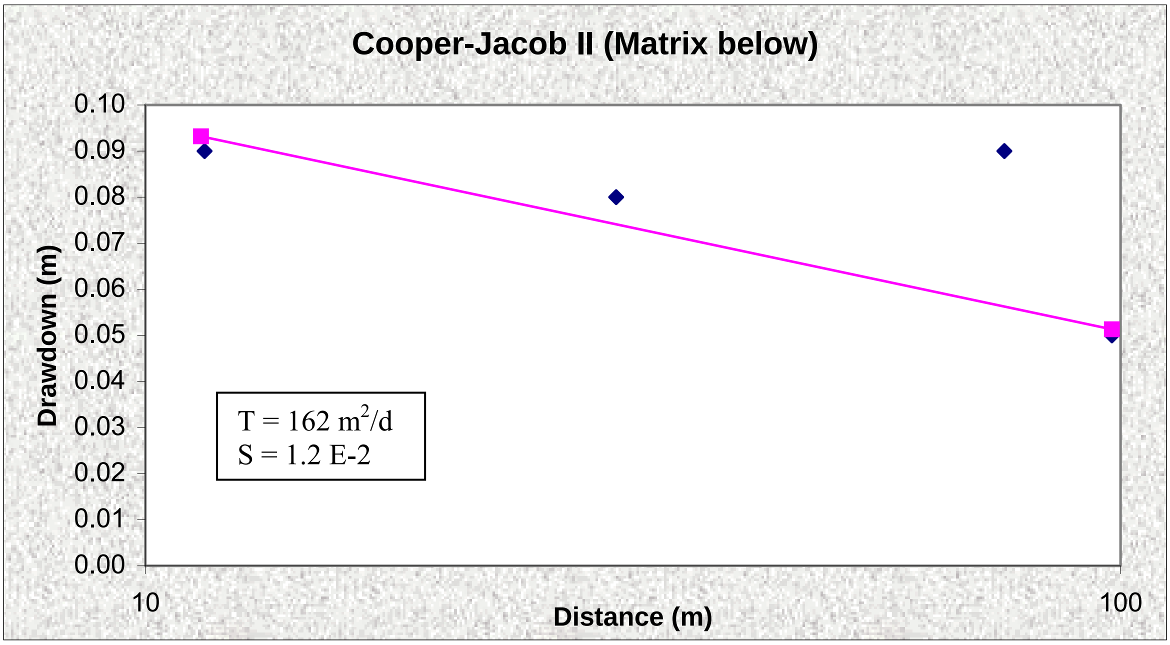


Fig. 3.4.5: Measured drawdown in the matrix-piezometer after 3000 minutes vs. distance of observation during constant rate test at UO5, July 2000

3.4.2 Constant Discharge Test UO5, September 2000

As shown in table 3.4.5, the second constant discharge test with installed piezometers on the Campus Test Site was conducted at the borehole UO5 for the abstraction with a discharge rate of 2 l/s for a period of 24 hours. The piezometers in the boreholes UO23, UO27, UO28 and UO29 were used to observe the water level in the fracture zone, and the rock matrix permanently with a dip meter. The water levels in the boreholes UO6, UO7, UO20, UO26 and UO30 were also measured during the period of the test.

Table 3.4.5: Conditions for the constant discharge test UO5, conducted at Campus Test Site

Abstraction BH	Discharge Rate	Duration of test	Observation Boreholes (Distance to UO5 in Brackets)
UO5	2.0 l/s	1460 min	UO27a, b, c (each 11.5m); UO28a, b, c (each 27.25m); UO29a, b, c (each 75.9m); UO23a, b, c (each 97.9m); UO6a, b (each 5.3m); UO7 (7.0m), UO20 (16.2m), UO26 (16.1m), UO30 (92.5m)
	Recovery	not permanently measured	

(a: piezometer above the fracture, b: piezometer below the fracture, c: piezometer in the fracture zone)

The drawdown behaviour in the fracture-piezometers and the boreholes are similar to the abovementioned UO5-test in July 2000. The water level in all boreholes dropped simultaneously and is in the same range as in the abstraction borehole UO5. Fig. 3.4.6 shows the drawdown in the fracture while fig. 3.4.7 shows the drawdown in the matrix-piezometers.

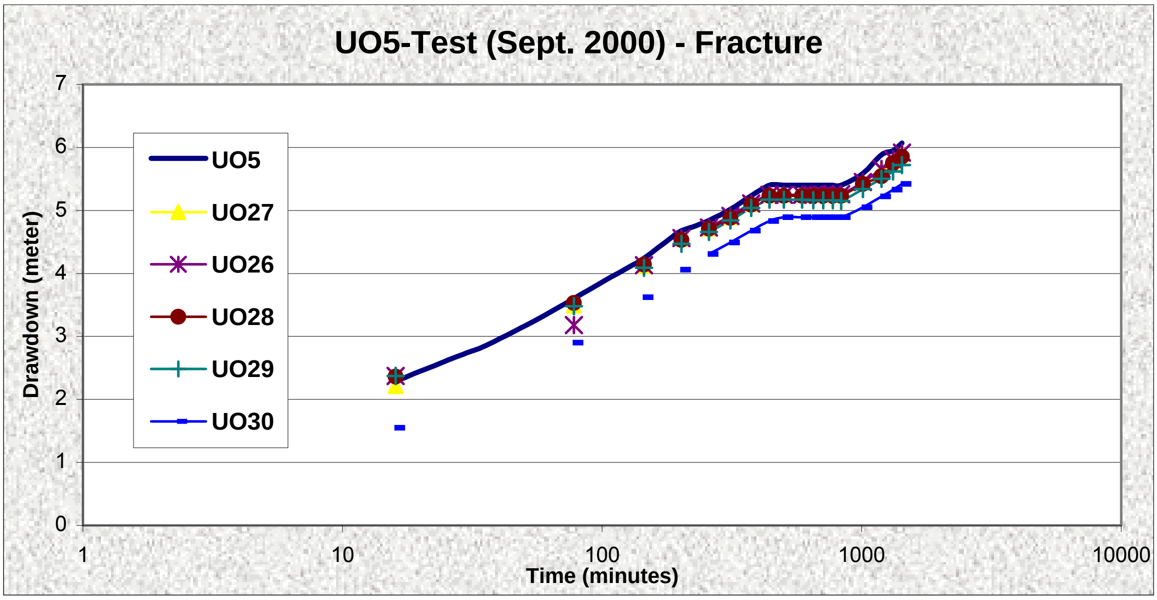


Fig. 3.4.6: Drawdown in the fracture-piezometers during constant discharge test UO5, September 2000

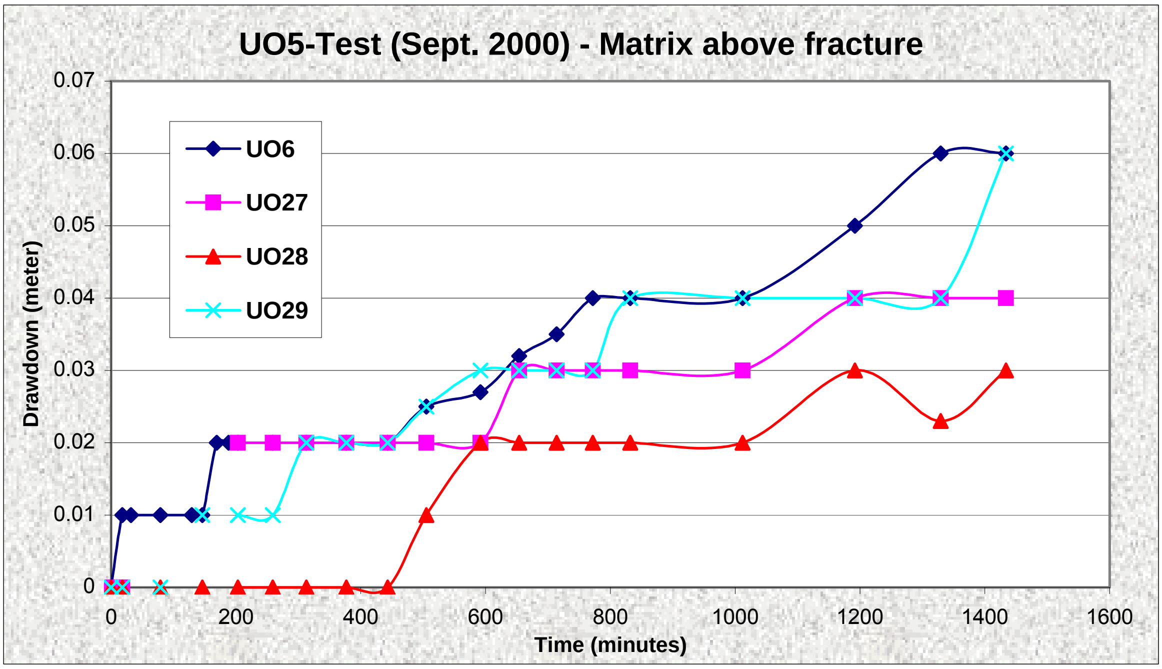


Fig. 3.4.7: Drawdown in the matrix-piezometers during constant discharge test UO5, September 2000

Table 3.4.6: Results of the evaluated aquifer parameter for the constant rate test UO5, September 2000, obtained from the fracture- and the matrix-piezometers

Borehole	Cooper-Jacob Method		Theis Method		Comment
	T (m^2/d)	S (-)	T (m^2/d)	S (-)	
UO5	13.4	1.76E-03	13	2.12E-03	S-value calculated with effective BH Radius of 5 m
UO27c	13.8	3.55E-04	14	3.46E-04	Distance: 11.5m
UO23c	13.7	6.22E-06	13	7.00E-06	Distance: 98.0m
fracture	534	5.73E-40			Cooper-Jacob II
matrix above	1754	2.88E-01			Cooper-Jacob II
matrix below	165	5.67E-03			Cooper-Jacob II

Since there is no analytical solution to describe this behaviour properly, a numerical model has to be applied to estimate the aquifer parameter for the fracture and the matrix as described in chapter 4.

CHAPTER 4

Analyzing the Field Tests with Numerical Models

As shown in chapter 3, applying analytical methods to estimate the aquifer parameters from hydraulic tests will yield different and inherent values. The analytical methods seem not to be suitable. Therefore a numerical model was used to estimate the aquifer parameters. The further tasks of using a numerical model are:

a) To verify the impact the geometry of the aquifer and the fracture has on the estimated values,
b) To simplify the procedure of using a numerical model to estimate the aquifer parameters,
c) To find a way, how analytical methods can be used correctly for estimating the aquifer parameters.

For the applying of numerical models a constant rate test was chosen from both sites, described in chapter 2. On the Campus Test Site the data of the UO5 test, conducted in July 2000 (see section 3.4.1), are used for the numerical model, while the data of the M1 test are used at the Meadhurst Test Site (see section 3.3.2).

4.1 Campus Test Site

4.1.1 Conceptual model

A conceptual model is used to denote the parameters (such as hydraulic conductivity) and conditions (such as boundary conditions) needed to solve the governing equations in a mathematical model.

The conceptual model for the Campus Test Site is based on the geology and hydrogeology of the site as described in Botha et.al. (1998). The main aquifer is situated in a horizontal layer of sandstone with a bedding-plane fracture zone at a depth of approximately 21 m (see also chapter 2.2). The thickness of the sandstone layer is between 15m and 20m. The extent of the fracture zone is unknown, but at least some hundred meters.

Comparing to the high hydraulic conductivity of the fracture, the hydraulic conductivity of the matrix is small. But the storage of the matrix is much higher than that of the fracture. During the pumping in the fracture groundwater is released from the matrix, flows vertically to the fracture and then horizontally to the pump. These conditions must be considered by the numerical model.

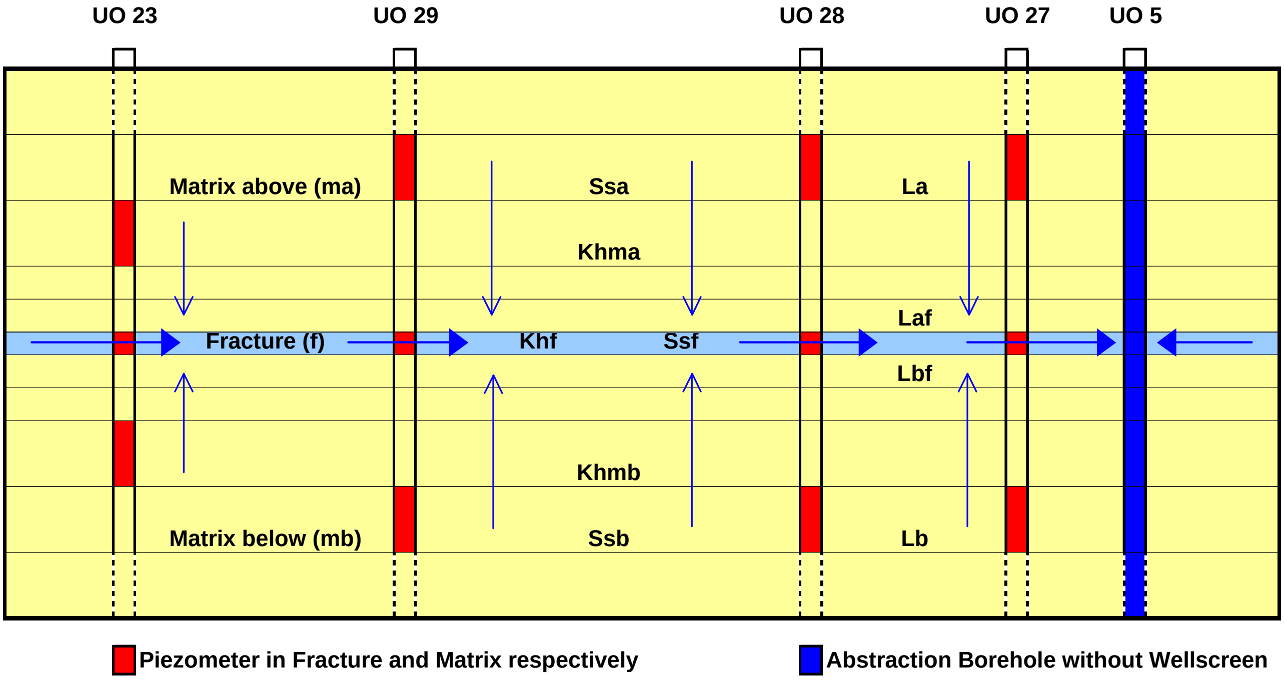


Fig. 4.1.1: Conceptual model of the flow in the sandstone aquifer of the Campus Test Site with the relevant parameters (explanation of the abbreviations in table 4.1.1)

Table 4.1.1: Complete list of parameters for PEST-calibration

Aquifer / Layer	**Parameter Description**	**Abbreviation**
Matrix above (ma)	Leakage of the matrix above	La
	Leakage from the matrix above to the fracture	Laf
	Hydraulic Conductivity of the matrix above	Khma
	Specific Storage of the matrix above	Ssa
Fracture (f)	Hydraulic Conductivity of the fracture	Khf
	Specific Storage of the fracture	Ssf
Matrix below (mb)	Leakage of the matrix below	Lb
	Leakage from the matrix below to the fracture	Lbf
	Hydraulic Conductivity of the matrix below	Khmb
	Specific Storage of the matrix below	Ssb

4.1.2 Numerical model

For this study a numerical model is built by using PMWIN (Chiang & Kinzelbach, 2001), which is a user friendly, graphical pre- and postprocessor and includes MODFLOW for the flow modelling and PEST as the inverse modelling technique.

The first step in analysing the groundwater flow in an aquifer with a numerical model is to develop a suitable mesh or grid for the aquifer. The finite difference mesh used in the present model consists of 88 rows, 115 columns and 23 layers of nodes. The horizontal extent of the model chosen was large enough to avoid boundary effects (6200m x 6200m). The grid size varies from 400m at the outer part to 2m in the surrounding of the abstraction borehole UO5.

The 12th layer of the model represented the fracture. The other layers represented the sandstone matrix above and below the fracture. The two layers directly above and below the fracture were each assigned a thickness of 0.5 m, and the other layers a thickness of 1 m (see also Fig. 4.1.1). This fine vertical discretization was necessary to account for the vertical drawdown in the rock matrix.

As mentioned in chapter 2.2, the fracture zone has an aperture of 0.2 m, while its horizontal extent was estimated as 150 m x 200 m, based on the geological profiles of the boreholes. The impact this size has on the estimated parameter values will be discussed in section 4.1.5. The abstraction borehole UO5 and the observation boreholes (UO27, UO28, UO29 and UO23) were also placed in the mesh within the fracture and the matrix respectively.

To calibrate the model with the pumping test data, the inverse model PEST (Doherty, 2000) is used. The criterion for the automatic parameter estimation with inverse modelling technique is the sum of squared residuals (called phi), where residuals are the differences between the measured and calculated data (e.g. hydraulic head or drawdown).

In this case the drawdown observations during the hydraulic test were used as measured data. Because of the big difference of the values in the fracture and in the matrix, the matrix observations were assigned a weighting factor between 5 and 10, which was calculated from the maximum drawdown in the piezometer vs. maximum drawdown in the fracture (e.g. maximum drawdown in the fracture-piezometers = 2m and maximum drawdown in UO28a = 0.2m, weighting factor for the observation data of UO28a = 10).

The parameters to estimate were assigned different parameter numbers. For each parameter initial values, upper and lower bounds were defined. For the first calibration runs the estimated parameters from the existing numerical model of the Campus Test Site (Chiang et. al., 1999) were used as initial values, while the bounds were chosen as big as reasonable while avoiding any effects.

4.1.3 Model results

To estimate the unknown parameters with the inverse modelling technique PEST it is essential to get at first a good guess of the initial values (see steps 1 to 3 in the following procedure). Using initial values, which are not suitable for the aquifer system, will lead to a wrong estimation of the parameters. The following procedure has been used to estimate the unknown parameters:

1. Assume initial values and run the model forward – to make sure that the initial values are in reasonable ranges.
2. Estimate initial values for all parameters by running PEST with the assumed initial values (step 1) and bounds, and using only the observation data in the fracture – to update the initial parameter values
3. Fix the parameter values for the fracture, which are obtained from steps 2, and run PEST using the observation data in the matrix piezometers to update the initial values for the matrix parameters.
4. Estimate all parameters by running PEST with the fracture and matrix parameter values obtained from steps 2 and 3 as initial values and using all observation data.
5. Eventually improve the fit by changing parameters individually (change one parameter at a time) and running the model forward (see also section 4.1.4).
6. Use the parameter values from step 5 as initial values and run PEST to get a final estimate of parameter values.
7. Use the parameter values from step 5 as initial values and run the inverse model with different geometry (extent of the fracture, thickness of the matrix), to estimate the impact (parameter sensitivity) due to the unknown geometry (see also section 4.1.4).

As a result of the optimisation runs PEST gives the estimated parameter values and their 95% confidence limits. Additionally some statistical values are given as there are:

- Phi (sum of squared weighted residuals), should be as small as possible
- Correlation coefficient for the whole run, should be close to 1
- Mean value of weighted residuals, should be close to zero
- Maximum weighted residual, should be as small as possible
- Minimum weighted residual, the difference min-max should be as small as possible
- Standard variance of weighted residuals, should be as small as possible
- Standard error of weighted residuals, should be as small as possible

In the following section the results of each step are discussed and finally the calibrated parameters are listed.

Step 1: Forward run with assumed initial values

Using the parameter values estimated with the existing numerical model of the Campus Test Site (Chiang et. al., 1999) the MODFLOW model was run forward and the result is shown in fig. 4.1.2 (run 2). Although the calculated drawdown is much higher than the observed drawdown, MODFLOW was able to complete the simulation with the assumed initial values and therefore they can be used in step 2.

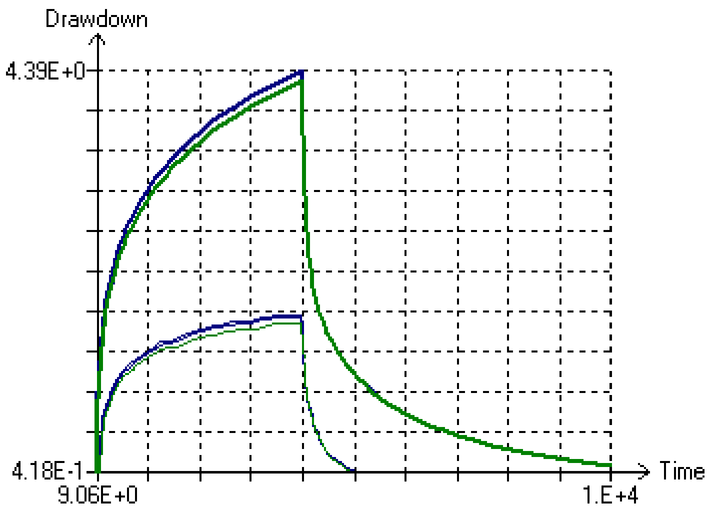


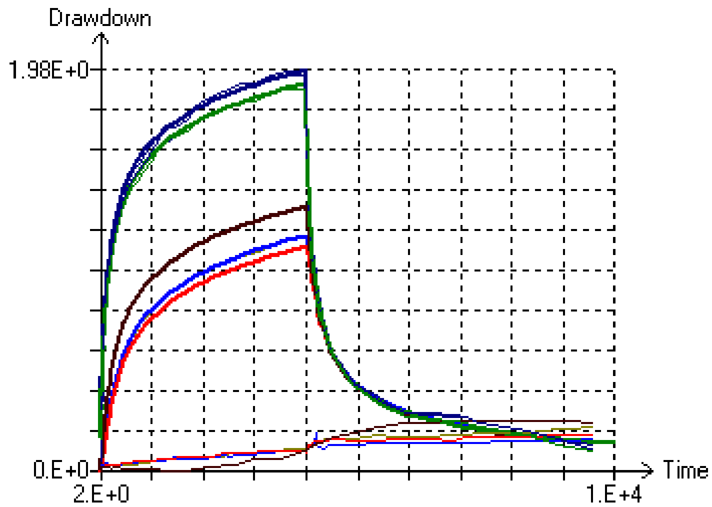
Fig. 4.1.2: Result of forward modelling with assumed initial values as listed in table 4.1.2 (from existing model of the Campus Test Site, Chiang et. al., 1999)

Table 4.1.2: Assumed initial parameter values for forward run (comparison of observed and calculated drawdown shown in fig. 4.1.2)

Parameter (model)	***Value***	**Parameter (aquifer)**	***Value***
Khma = Khmb	1.26E-04 m/min	T matrix (20m)	3.6 m^2/day
Khf	1.38E+00 m/min	T fracture	396 m^2/day
Ssma = Ssmb	1.00E-05 /m	S matrix total (20m)	2.00E-04
Ssf	5.45E-05 /m	S fracture	1.09E-05
La = Lb	1.01E-06 /min	K vertical matrix	1.45E-03 m/day
Laf = Lbf	1.01E-06 /min		

Step2: Inverse modelling with initial values from step 1 and fracture observation only

To get a better estimate for the initial values the inverse model was run with the assumed initial values from step 1 and the observation data of the fracture piezometer (run 6a). The result is graphically shown in fig. 4.1.3 and listed in table 4.1.3. The run gives reasonable values for the parameter of the fracture and the transmissivity of the matrix while the leakage and storage of the matrix result in a too high drawdown in the matrix.



Observed and calculated drawdown in UO5 and UO30

Calculated drawdown in UO23a, UO28a, UO29a

Observed drawdown in UO23a, UO28a, UO29a

Fig. 4.1.3: Result of inverse modelling with observation data of fracture only (estimated values are listed in table 4.1.3)

Table 4.1.3: Estimated parameter values of inverse modelling with observation data of the fracture only (comparison of observed and calculated drawdown shown in fig. 4.1.3)

Parameter (model)	**Value**	**Parameter (aquifer)**	**Value**
Khma = Khmb	4.55E-04 m/min	T matrix (20m)	13.1 m^2/day
Khf	2.15E+00 m/min	T fracture	619 m^2/day
Ssma = Ssmb	2.25E-05 /m	S matrix total (20m)	4.50E-04
Ssf	1.38E-04 /m	S fracture	2.76E-05
La = Lb	7.04E-07 /min	K vertical matrix	1.01E-03 m/day
Laf = Lbf	2.82E-06 /min		

Step 3: Inverse modelling with initial values from step 2 and matrix observation only

As shown in figure 4.1.3, the fit for the drawdown in the matrix piezometer is not good. To improve the fit and get a better estimation of the parameter values for the matrix, the estimated values for the fracture from step 2 were fixed and PEST was run with the observation data of the matrix piezometer only (run 6f). The results are shown in figure 4.1.4 and table 4.1.4. It becomes apparent that a good fit for the drawdown in the matrix piezometer will yield a too high drawdown in the fracture when fixing the parameter of the fracture.

a) b)

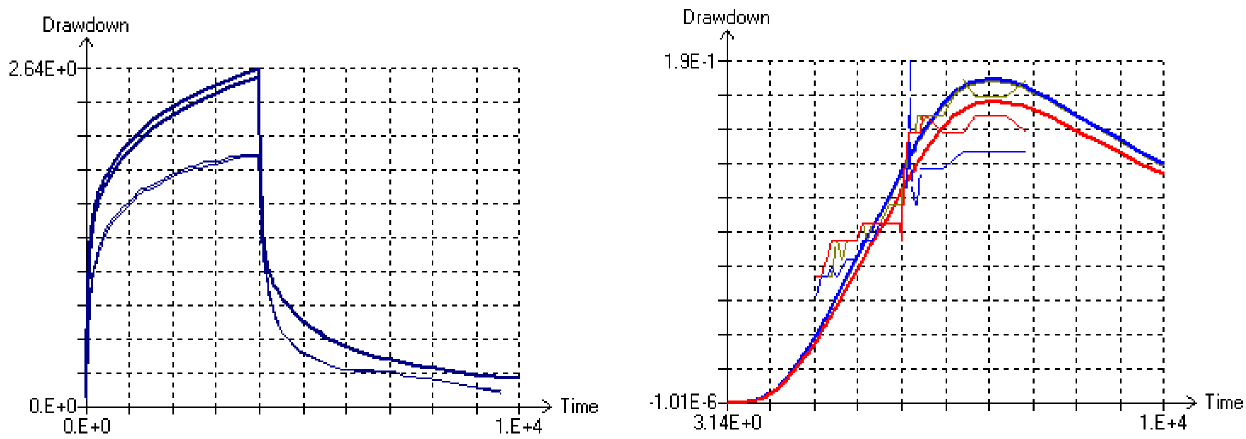


Fig. 4.1.4: Result of inverse modelling with observation data of matrix only (step 3); a) drawdown in the fracture, b) drawdown in the matrix piezometer above the fracture (estimated values are listed in table 4.1.4)

Table 4.1.4: Estimated parameter values of inverse modelling with observation data of the matrix only (comparison of observed and calculated drawdown shown in fig. 4.1.4)

Parameter (model)	**Value**	**Parameter (aquifer)**	**Value**
Khma = Khmb	4.55E-04 m/min	T matrix (20m)	13.1 m^2/day
Khf	2.15E+00 m/min	T fracture	619 m^2/day
Ssma	3.92E-04 /m	S matrix total (20m)	9.07E-03
Ssmb	4.85E-04 /m		
Ssf	1.38E-04 /m	S fracture	2.76E-05
La	1.21E-07 /min	K vertical matrix a	1.74E-04 m/day
Lb	5.20E-07 /min	K vertical matrix b	7.48E-04 m/day
Laf	2.24E-07 /min		
Lbf	4.57E-07 /min		

Step 4a: Inverse modelling with estimated initial values and all observation data

When using the parameter values from Table 4.1.4 as initial values and observation data from both fracture and matrix piezometer, the inverse modelling will give different results (see Table 4.1.5), which do not fit the drawdown behaviour in the matrix well (run 9a, see fig. 4.1.5b).

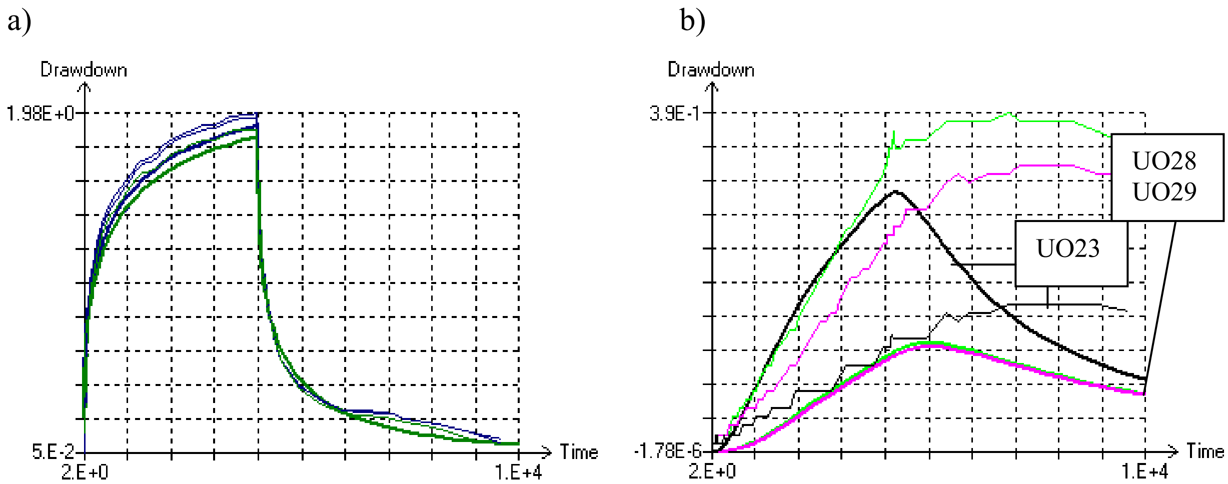


Fig. 4.1.5: Result of inverse modelling with observation data of fracture and matrix; a) drawdown in the fracture, b) drawdown in the matrix piezometer below the fracture (estimated values are listed in table 4.1.5)

Table 4.1.5: Estimated parameter values of inverse modelling with observation data of the fracture and matrix (comparison of observed and calculated drawdown shown in fig. 4.1.5)

Parameter (model)	**Value**	**Parameter (aquifer)**	**Value**
Khma = Khmb	1.63E-03 m/min	T matrix (20m)	46.9 m^2/day
Khf	3.7E+00 m/min	T fracture	1066 m^2/day
Ssma = Ssmb	2.87E-04 /m	S matrix total (20m)	5.74E-03
Ssf	1.07E-04 /m	S fracture	2.14E-05
La = Lb	1.24E-07 /min	K vertical matrix	1.78E-04 m/day
Laf = Lbf	4.95E-07 /min		

Step 4b: Inverse modelling with estimated initial values and specific observation data

From fig. 4.1.5b) it becomes apparent that the behaviour of the drawdown in the UO23-piezometer is completely different to the behaviour in the UO28 and UO29-piezometers and can't be simulated with the same model. Therefore for the next calibration runs only the observation data in the matrix-piezometers UO27a, UO28a, UO29a, UO28b and UO29b were used.

By using these specific observation data for the matrix above and below the fracture, the inverse modelling gives results, which fit the drawdown in both the fracture and the matrix in a better way (run 23, see fig. 4.1.6). But the delay of the drawdown in the matrix piezometers is still not fitted well (see fig. 4.1.6b).

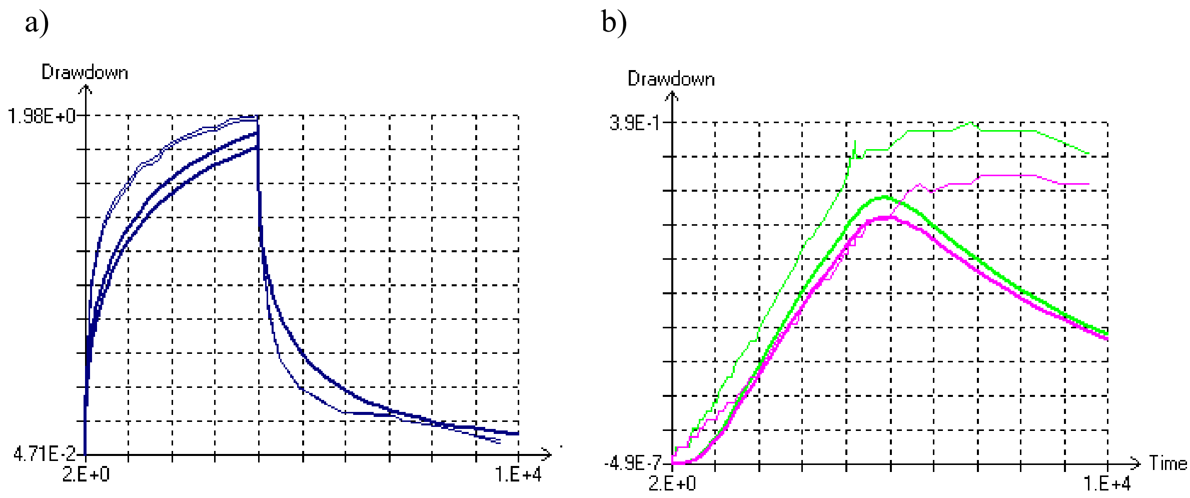


Fig. 4.1.6: Result of inverse modelling with observation data of fracture and matrix and change of initial values, bounds and relation between matrix above and below;
a) drawdown in the fracture, b) drawdown in the matrix piezometer below the fracture
(estimated values are listed in table 4.1.6)

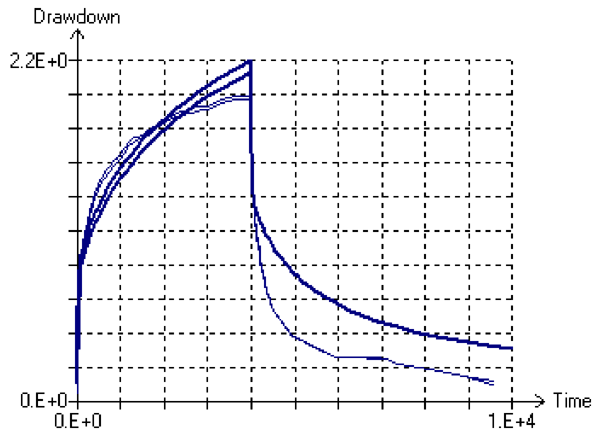
Table 4.1.6: Estimated parameter values of inverse modelling with observation data of the fracture and matrix after releasing the relation between matrix above and below the fracture (comparison of observed and calculated drawdown shown in fig. 4.1.6)

Parameter (model)	Value	Parameter (aquifer)	Value
Khma = Khmb	4.42E-04 m/min	T matrix (20m)	12.7 m^2/day
Khf	2.10E+00 m/min	T fracture	606 m^2/day
Ssma	4.98E-04 /m	S matrix total (20m)	1.05E-02
Ssmb	5.47E-04 /m		
Ssf	1.29E-04 /m	S fracture	2.58E-05
La	1.69E-07 /min	K vertical matrix a	2.44E-04 m/day
Lb	3.45E-07 /min	K vertical matrix b	4.97E-04 m/day
Laf	6.77E-07 /min		
Lbf	1.38E-07 /min		

Step 5: Improve the estimated parameter values manually

Because the delay of the drawdown in the matrix piezometers is still not fitted well with the inverse modelling technique, it was necessary to improve the fit manually. By changing one parameter at a time the impact of parameter changes on the drawdown behaviour was verified, as described in chapter 4.1.4. To fit the delay of the drawdown in matrix piezometer the values for Sma and Smb must be increased. The results of the improvement are shown in figure 4.1.7 and table 4.1.7.

a)



b)

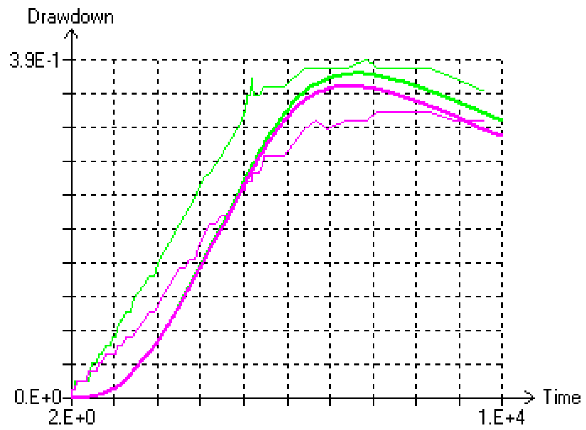


Fig. 4.1.7: Result of improvement the parameter values manually;
a) drawdown in the fracture, b) drawdown in the matrix piezometer below the fracture

Table 4.1.7: Parameter values of improvement (comparison of observed and calculated drawdown shown in fig. 4.1.7)

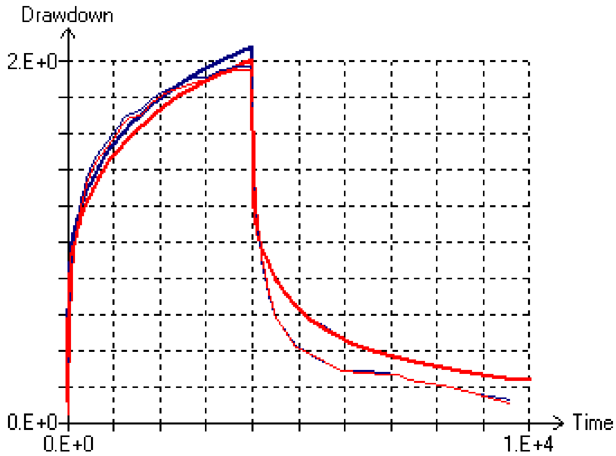
Parameter (model)	**Value**	**Parameter (aquifer)**	**Value**
Khma = Khmb	2.00E-04 m/min	T matrix (20m)	5.8 m^2/day
Khf	1.96E+00 m/min	T fracture	563 m^2/day
Ssma	4.00E-04 /m	S matrix total (20m)	1.40E-02
Ssmb	1.00E-03 /m		
Ssf	8.25E-05 /m	S fracture	1.65E-05
La	1.00E-07 /min	K vertical matrix a	1.44E-04 m/day
Lb	6.00E-07 /min	K vertical matrix b	8.64E-04 m/day
Laf	4.00E-07 /min		
Lbf	6.71E-07 /min		

Step 6: Inverse modelling with initial values obtained from Step 5

To fit the delay of the drawdown in the matrix-piezometer in a better way, the sensitivities of the parameters were tested as described in the section 4.1.4. There are mainly 2 parameters which are responsible for the delay of the drawdown; the storage coefficient of the matrix and the transmissivity of the matrix. While the impact of the storage coefficient on the drawdown-curve of the fracture is small, any change of the transmissivity value will result in a visible change in the drawdown-curve of the fracture.

Therefore the S-value of the matrix was forced to be high for the next calibration runs. By using parameter values obtained from step 5 as initial values, the inverse modelling yields a good fit for both the fracture and the matrix piezometer (run 28, see fig. 4.1.8 and table 4.1.8).

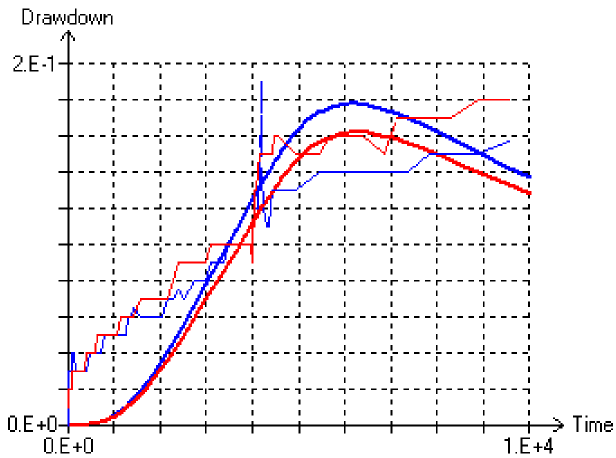
a)



Fracture Piezometer
UO5 and UO23

Bold = calculated
Fine = observed

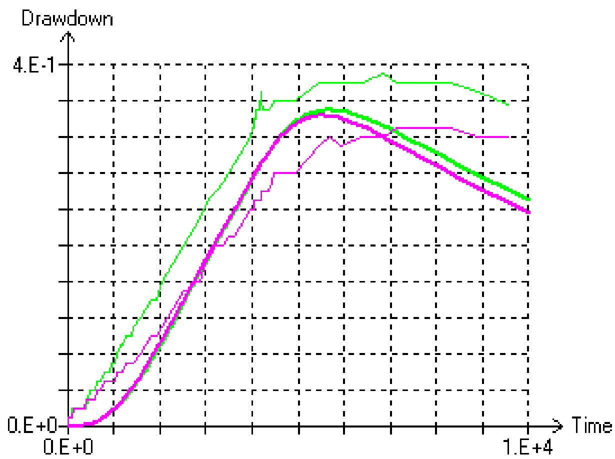
b)



Piezometer Matrix above

UO29a, observed
UO28a, observed
UO28a, calculated
UO29a, calculated

c)



Piezometer Matrix below
UO28b, observed
UO29b, observed

UO28b, calculated
UO29b, calculated

Fig. 4.1.8: Best result of inverse modelling with observation data of fracture and matrix; initial values obtained from step 5 (estimated values are listed in table 4.1.8)

Table 4.1.8: Estimated parameter values of the best fit of inverse modelling with observation data of the fracture and matrix (comparison of observed and calculated drawdown shown in fig. 4.1.8)

Parameter (model)	Value	Parameter (aquifer)	Value
Khma = Khmb	3.13E-04 m/min	T matrix (20m)	9.0 m^2/day
Khf	2.14E+00 m/min	T fracture	616 m^2/day
Ssma	3.19E-04 /m	S matrix total (20m)	1.25E-02
Ssmb	9.27E-02 /m		
Ssf	8.55E-05 /m	S fracture	1.71E-05
La	1.07E-07 /min	K vertical matrix a	1.54E-04 m/day
Lb	8.24E-07 /min	K vertical matrix b	1.19E-03 m/day
Laf	4.27E-07 /min		
Lbf	4.78E-07 /min	Fracture Skin	

The estimated parameter values and their relation to each other are reasonable and the statistical data, listed in table 4.1.9, validate the good fit. The maximum difference between observed and calculated drawdown is 0.058m, the mean value of all residuals is 2.95E-02, which is close to zero, and the correlation coefficient is with 0.9504 close to 1.

Table 4.1.9: Statistical data for the best fit of inverse modelling

Phi (sum of squared weighted residuals)	34.66
Correlation coefficient	0.9504
Mean value of weighted residuals	2.95E-02
Maximum weighted residual	0.5850
Minimum weighted residual	-0.3871
Standard variance of weighted residuals	4.38E-02
Standard error of weighted residuals	0.2092

(obtained with 800 observations and a maximum weighting factor of 10)

A comparison of all reasonable results from the different calibration runs shows that the ranges of the parameter values are relatively small (between 2 and 7) and the results of the best fit are inside this range and mostly close to the mean value (see table 4.1.10).

Table 4.1.10: Minimum, maximum and mean values of the estimated parameters, obtained from all reasonable calibration runs compared with the results of the best fit

Parameter	Unit	Best Fit	Min	Max	Mean
T matrix (aquifer)	m^2/day	9.0	7.8	24.8	13.3
T fracture	m^2/day	616	310	876	594
K horizontal matrix	m/day	0.45	0.39	1.24	0.66
K vertical matrix above	m/day	1.54E-4	1.01E-4	3.88E-4	1.86E-4
K vertical matrix below	m/day	1.19E-3	3.83E-4	1.19E-3	6.21E-4
K horizontal fracture	m/day	3080	1550	4381	2969
S matrix (aquifer)		1.25E-2	5.25E-3	1.50E-2	1.03E-2
S fracture		1.71E-5	3.99E-6	2.76E-5	2.21E-5

4.1.4 Uncertainty of the Parameter Estimation

To check the influence of parameter changes, different runs with both forward and inverse modeling were performed. Several forward runs with MODFLOW were conducted by changing one parameter value at a time. Inverse models with PEST were performed with different aquifer thickness or with different extent of the fracture.

Uncertainty due to non-uniqueness of inverse modeling

The forward runs are documented in the Appendix E.1 as runs 25b ff. and 27ff. The influence of the different parameters on the drawdown curves can be summarized as follows:

- The drawdowns in two different fracture piezometers become closer together, when the T fracture increases or the leakage to the fracture decreases. The influence of the transmissivity is stronger.
- The shape of the drawdown curve in fracture piezometer is controlled by the T matrix and the leakage to the fracture, while an increase of the transmissivity of the matrix and the leakage to the fracture results in a decrease of the drawdown in fracture piezometers at late time. An increase of the S matrix or a decrease of the S fracture shows a similar result.
- The delay in the drawdown behaviour of the matrix is mainly controlled by a high S matrix, but even a decrease of the T matrix or the vertical K matrix can result in a longer delay.
- The absolute drawdown in the matrix piezometers increases when the T matrix or the S matrix decreases or the vertical K matrix increases.

If for instance the T matrix increases, the influence will be seen in the drawdown curves of both the fracture piezometer (i.e. drawdown decreases at late time and the shape of the curve is changed) and the matrix piezometer (i.e. drawdown increases and delay becomes less). An increase of the S matrix results in a decrease of the drawdown in the fracture at late time, a decrease of the drawdown in the matrix, and in a longer delay of the drawdown in the matrix piezometer.

A change of the vertical K matrix will be seen in all drawdown curves, as long as the leakage in the matrix and the leakage to the fracture are linked. To simplify the procedure of the calibration, the vertical K fracture was assumed to be much higher than the vertical K matrix, so that it can be neglected when calculating the leakage to the fracture. This assumption is valid until there is no fracture skin, which reduces the leakage to the fracture. For some calibration runs the link between leakage in the matrix and leakage to the fracture was released (i.e. fracture skin is evident) and the best fit of the hydraulic test data was obtained with a fracture skin (see section 4.1.4 and table 4.1.6). From this model it is not possible to calculate the vertical K fracture and the parameters of the fracture skin, but the evidence of a fracture skin can be proved.

It is apparent that there is no unique solution in a mathematical, numerical way. It is possible to get a good fit with a parameter combination, which is not reasonable (e.g. in run 7c the vertical K matrix is higher than the horizontal K matrix).

Uncertainty due to unknown geometry

The influence of the chosen geometry was estimated with several inverse models using PEST and the same initial conditions as for the best fit. The runs are documented in Appendix E.1 and called run 31, 32 and 33. In run 31 the thickness of the aquifer was reduced, while in run 32 and 33 the extent of the fracture was changed (halved and doubled respectively). The results are listed in table 4.1.9.

One reason for the higher drawdown, observed in the matrix piezometers below the fracture, can be a smaller thickness of this part of the aquifer. To evaluate this the parameters of the layers 19 to 23 were changed to simulate an aquiclude. The change of the parameter values, obtained from the inverse model (i.e. T matrix for 1m thickness, S matrix for 1m thickness, leakage between layers of 1m thickness), between the best fit and this calibration run is not evident, but a calculation of the aquifer parameter shows a decrease of the S matrix for the whole aquifer from 1.25E-2 to 6.84E-3 (see table 4.1.8) due to the change of the aquifer thickness.

Because the real extent of the fracture is unknown, it is important to know the impact of the extent on the estimated parameters. As described in section 4.1.2 the area of the fracture was chosen at 150m x 200m. For run 32 this area was halved to 100m x 150m and for run 33 the area was doubled to 200m x 300m. The estimated parameters for the matrix differ from the values of the best fit (see table 4.1.9) and the relationship can be described clearly:

- When the area of the fracture is **halved**, the S matrix **doubles** and the K vertical matrix increases.
- When the area of the fracture is **doubled**, the S matrix **halves** and the K vertical matrix decreases.

Table 4.1.11: Influence of the geometry of the model (Run 31: Thickness below fracture is halved, Run 32: Area of the fracture is halved, Run 33: Area of the fracture is doubled)

Parameter	**Unit**	**Run 28**	**Run 31**	**Run 32**	**Run 33**
		Best Fit	**Thickness**	**Area x 0.5**	**Area x 2**
T matrix (aquifer)	m^2/day	9.0	9.1	10.6	6.1
T fracture	m^2/day	616	778	519	526.3
K horizontal matrix	m/day	0.45	0.61	0.53	0.31
K vertical matrix above	m/day	1.54E-4	1.64E-4	**2.61E-4**	**9.27E-5**
K vertical matrix below	m/day	1.19E-3	1.10E-3	**1.83E-3**	1.15E-3
K horizontal fracture	m/day	3080	3890	2596	2632
S matrix (aquifer)		1.25E-2	**6.84E-3**	**2.41E-2**	**7.63E-3**
S fracture		1.71E-5	2.11E-5	1.11E-5	2.37E-5

Uncertainty due to non-linear relationship between drawdown and discharge rate

The UO5 test from July 2000, which was used for the parameter estimation in section 4.1.4, was repeated in September 2000 with an abstracting rate of 2 l/s (see section 3.4.2). Using the parameter values, obtained from the inverse modeling of the UO5 test July 2000, the observation data in both the fracture and matrix piezometers don't fit well (see fig. 4.1.7).

a) b)

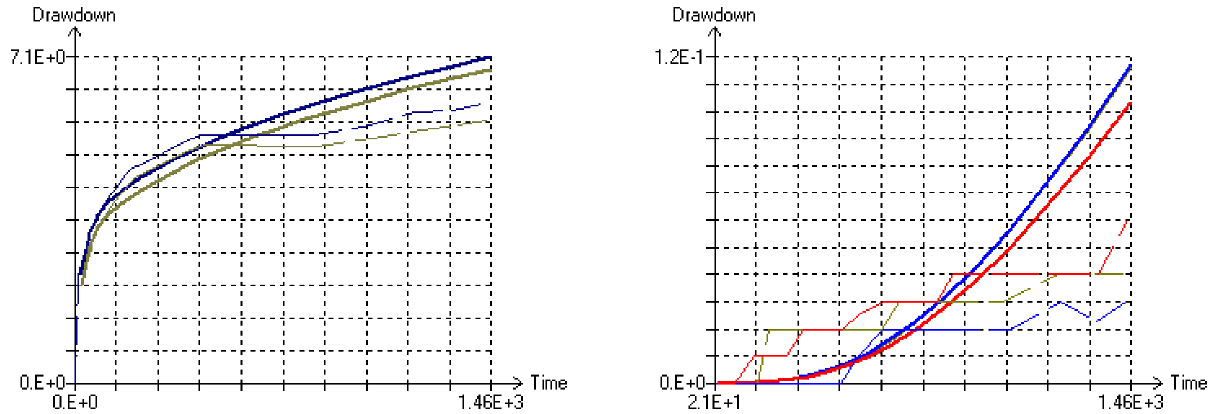


Fig. 4.1.9: Comparison observed and calculated data for the UO5 test September 2000. Forward run with estimated values from UO5 test July 2000 (values are listed in table 4.1.6) a) Fracture piezometers, b) matrix piezometers above (bold = calibrated, fine = observed)

After calibrating the data with inverse modeling, as described in section 4.1.2, the fit of the observation data in the matrix piezometers is better, and the estimated parameter values differ from the values, obtained as the best fit from the UO5 test in July 2000, but they are still between the minimum and maximum values from the UO5 test in July 2000.

Table 4.1.12: Comparison of the estimated parameter values for the UO5 tests, July and September 2000, obtained from the best fit of inverse modelling (July 2000) and the geometric mean of reasonable runs of inverse modelling (September 2000)

Parameter	**Unit**	**UO5 Test July 2000 Best Fit**	**UO5 Test Sept. 2000 Geometric Mean**
Discharge Rate	l/s	0.5	2.0
T matrix (aquifer)	m^2/day	9.0	**28**
T fracture	m^2/day	616	530
K horizontal matrix	m/day	0.45	**1.4**
K vertical matrix	m/day	1.54E-4	1.8E-4
K horizontal fracture	m/day	3080	2650
S matrix (aquifer)		1.25E-2	**8E-3**
S fracture		1.71E-5	1.6E-5

Possible reasons for the non-linear relationship between drawdown and discharge rate are turbulence, dewatering of discrete fractures (as happened in this case after about 500 minutes), elasticity, change from confined to semi-confined or unconfined conditions and the heterogeneity of the aquifer.

4.1.5 Discussion

From the different calibration runs and the above-mentioned results and parameter relations it becomes apparent that it is not possible to fit the drawdown curves in both the fracture piezometers and the matrix piezometers properly with one run. Using only the observation data of the fracture piezometers, the fit for the drawdown curves of the fracture becomes excellent (e.g. see run 6a). When using only the observation data of the matrix piezometer the inverse model results in a good fit for the drawdown curves of the matrix, but with different parameter values (e.g. see run 6b – 6f). There are some reasons for this phenomenon:

- The geometry of the aquifer is not well known and is simplified in the model (e.g., constant thickness over the whole model) and the real extent of the fracture is unknown.
- Secondary horizontal and vertical fractures, which intersect the main fracture, and the resulted semi-confined or unconfined conditions are not considered.
- Heterogeneity in both matrix and fracture systems is unknown and not considered. The unknown heterogeneity could even affect the hydraulic test data.

The heterogeneity of the aquifer and the influence of discrete fractures beneath the single bedding-plane fracture can be seen from the drawdown behavior in the piezometers of the boreholes UO23 (UO23a and b) and UO6 (UO6a and b) and in the piezometer UO27b.

- Compared with the drawdown in UO29a and b (2.5m above and below the fracture) the observed drawdown in UO23a and b (1.5m above and below the fracture) is much too small (see fig. 4.1.4b).
- While the reaction in UO6a is small but equal to the other piezometers, there was no reaction in UO6b. In all other piezometer groups the drawdown below the fracture was bigger than above the fracture.
- The drawdown measured in UO27b is too high for a matrix piezometer and the curve looks more like a fracture piezometer. There seems to be a hydraulic connection between the main horizontal fracture and a small fracture in UO27b. The piezometer UO27b was installed at a depth of 23m to 24m, where in the borehole UO26, which is nearby, the main fracture was detected (see section 2.2.2 and appendix B.1).

A comparison between the results of analytical models (see section 3.4.1) and the numerical model (see section 4.1.3) shows a possibility to simplify the procedure of parameter estimation from a hydraulic test. The results of the used methods are listed in table 4.1.13, where

- *T aquifer min/max* are the minimum and maximum transmissivity values of the entire aquifer, obtained by using different observation boreholes in analytical methods.
- *T matrix* and *T fracture* are transmissivity values of the matrix (sandstone) and fracture, respectively.
- The arrows in the table indicate the way to obtain to bold-typefaced values, which are comparable to values from a numerical model. Refer to chapter 3 for details of estimating parameters with analytical methods.
- The same rule applies to *S aquifer min/max*, *S matrix* and *S fracture*.
- *K v matrix* is the vertical hydraulic conductivity of the matrix.

Table 4.1.13: Comparison of the results from analytical and numerical models

Parameter	Unit	Numerical Model	CJ / Theis Fracture [1)]	CJ / Theis Matrix [2)]	Cooper-Jacob II	Gringarten
T aquifer min	m^2/day	n.a.	9	4.2	50 [4)]	10
T aquifer max	m^2/day	n.a.	11	88.5	743 [3)]	15
T matrix [5)]	m^2/day	**9.0**	**10**	n.a.	n.a.	**12.5**
T fracture [5)]	m^2/day	**616**	n.a.	n.a.	**743**	n.a.
K v matrix	m/day	**1.54E-4 to 1.19E-3**	n.a.	n.a.	n.a.	**3.0E-3**
S aquifer min		n.a.	1.3E-5	5.4E-3	2.0E-15 [3)]	2.0E-5
S aquifer max		n.a.	8.0E-3	3.3E-1	2.3E-2 [4)]	3.0E-3
S matrix		**1.25E-2**	**8.0E-3**	n.a.	**2.3E-2**	n.a.
S fracture		**1.71E-5**	**1.3E-5**	n.a.	n.a.	**2.0E-5**

[1)] Cooper-Jacob I / Theis method using observed values in fracture, [2)] Cooper-Jacob I / Theis method using observed values in matrix, [3)] Using observation data from fracture piezometer, [4)] Using observation data from matrix piezometer, [5)] Estimated T values are effected by chosen thickness

From the abovementioned comparison it is recommended to use the following suggestions to estimate the aquifer parameters with analytical models:

- To estimate the **transmissivity of the matrix**, the Cooper-Jacob or Theis method can be used, when the assumptions for applying these methods are valid. That means the drawdown curve must show radial acting flow and there are no boundary effects.
- To estimate the **transmissivity of the fracture**, the drawdown-distance method (known as Cooper-Jacob II) can be used. At least 2 observation boreholes are required in addition to the abstraction borehole.
- To estimate the **storage coefficient of the fracture**, the Cooper-Jacob or Theis method can be used. It requires an observation borehole, which is intersecting the fracture far away from the abstraction borehole. The problem is that the definition of ‘far away’ is unclear.
- To estimate the **storage coefficient of the matrix:**
  1. The Cooper-Jacob or Theis method: Both methods require an observation borehole, which is intersecting the fracture close to the abstraction borehole. The problem is that the definition of ‘close’ is unclear. These methods can also be applied by using the effective borehole radius of the abstraction borehole itself.
  2. The Cooper-Jacob II methods: Observation data of at least two matrix piezometers are required.
- For the parameters of the matrix **(T, Kv and S)**, the Gringarten method can be used, but it is non-unique and difficult to fit the data without prior information. If the parameters T matrix, S matrix and half-length of the fracture are estimated with other analytical methods, it is possible to get a unique fit of the drawdown data.

A further discussion and recommendation to estimate the storage coefficient of the matrix with analytical methods is described in section 4.3.

4.2 Meadhurst Test Site

4.2.1 Conceptual model

A conceptual model is used to denote the parameters (such as hydraulic conductivity) and conditions (such as boundary conditions) needed to solve the governing equations in a mathematical model.

The conceptual model for the Meadhurst Test Site bases on the geology and hydrogeology of the site. The main aquifer is situated in a nearly vertical dyke with fractures parallel to the conduct zone (see also chapter 2.3). Other water strikes were found during drilling in the overlaying dolerite, high weathered sandstone. The extent and aperture of the fracture zone is unknown. Comparing to the high hydraulic conductivity of the fracture the hydraulic conductivity of the matrix is small. But the storage of the matrix is much higher than that of the fracture. These conditions must be considered by the numerical model.

In a case of a vertical or nearly vertical fracture parallel to a dyke, at least three aquifer systems have to be taken into account when analysing a hydraulic test:

1) The vertical fracture zone as the main aquifer
2) The matrix of the layer, in which the fracture zone occurs (here: mudstone)
3) The dyke, which can be treated as a barrier

On the Meadhurst Test Site there is additionally the weathered dolerite layer, which overlays the mudstone but is intersected by the dyke and the main fracture. This dolerite layer has water strikes and therefore has to be treated as a hydraulic part of the aquifer.

During the pumping in the fracture, it is assumed that groundwater is released from the matrix, flows horizontally to the fracture or vertically to the weathered dolerite and along the dolerite to the fracture. Finally, groundwater flows along the fracture to the pump. The dyke is simulated as a no-flow boundary. The conceptual model is illustrated in fig. 4.2.1.

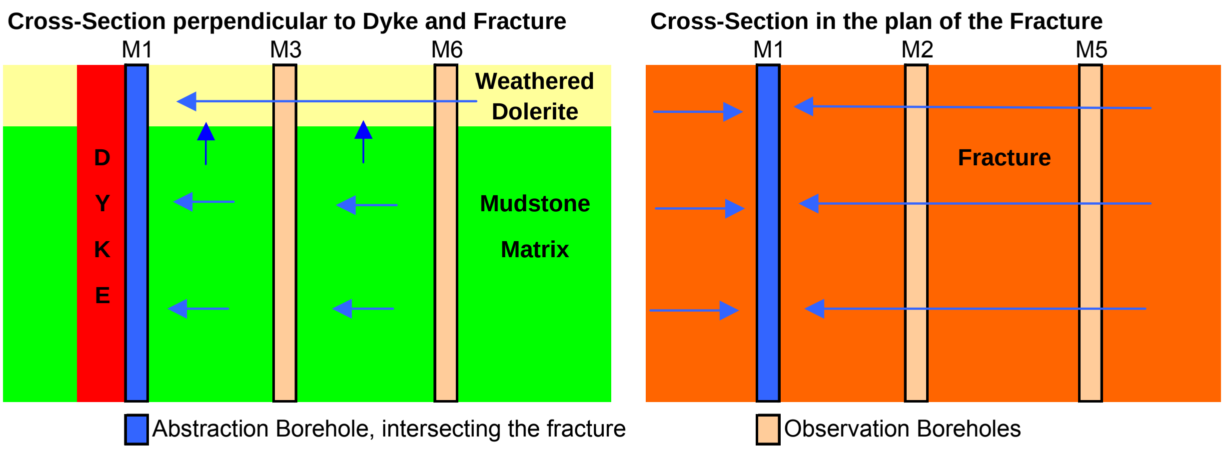


Fig. 4.2.1: Conceptual model of the flow in the mudstone and dolerite aquifer with a vertical fracture parallel to the dyke, at the Meadhurst Test Site

4.2.2 Numerical model

For this study a numerical model is built by using PMWIN (Chiang & Kinzelbach, 2001), which is a user friendly, graphical pre- and postprocessor and includes MODFLOW for the flow modelling and PEST as the inverse modelling technique.

The first step in analysing the groundwater flow in an aquifer with a numerical model is to develop a suitable mesh or grid for the aquifer. The finite difference mesh used in the present model consists of 68 rows, 64 columns of nodes. The horizontal extent of the model chosen was large enough to avoid boundary effects (7000m x 5000m). The grid size varies from 500m at the outer part to 0.5m at the fracture and the abstraction borehole M1.

The 1st layer of the model represents the weathered dolerite. The 2nd layer represents the mudstone matrix. The overlaying red soil can be neglected in the model design, because the water level is normally situated in the dolerite or at the bottom of the soil. As the groundwater level can drop and the model layers can be changed between confined and unconfined, the layer-type 3 are used for all layers.

The column 30, assigned a width of 0.5m, represent the fracture, while the columns 27 to 29, assigned a width of 1m each, represent the vertical dyke. This fine horizontal discretization was necessary to account for the barrier effect of the dyke and the drawdown in the fracture and the mudstone matrix. The horizontal extent of the fracture is unknown, but was assumed as 1500 m, based on the geological profiles of the boreholes. The impact of this size on the estimated parameter values will be discussed in section 4.2.4.

The abstraction borehole M1 and the observation boreholes (M2, M3, M5 and M6) were also placed in the mesh within the fracture and the matrix respectively. Because all boreholes intersect both the dolerite and the mudstone and the boreholes M1, M2 and M5 intersect the fracture at different depth, the vertical position of the observation is not clear. To simplify the procedure the boreholes intersecting the fracture were placed in layer 2, while the other boreholes were placed in layer 1 due to the assumed higher conductivity in the dolerite, compared with the mudstone.

The abstraction rate of 1.4 l/s was put in the cell [30,35,2], while the cell in the layer 1 was assigned a discharge rate of 1E-12 m^3/min. The vertical leakage in the cells representing the abstraction borehole was set to 1 to account for a high vertical conductivity in the borehole. With this method MODFLOW calculates the distribution of the discharge rate inside the borehole for each layer, depending on the transmissivity of the cells. The total discharge rate will be kept constant over the whole stress period, even if a cell falls dry.

To calibrate the model with the pumping test data, the inverse model PEST (Doherty, 2000) is used. The criterion for the automatic parameter estimation with the inverse modelling technique is the sum of squared residuals (called phi), where residuals are the difference between the measured and the calculated data (e.g. hydraulic head or drawdown).

The drawdown observations during the hydraulic test were used as measured data. Because of the big difference of the values in the fracture and in the matrix, the observations were assigned a weighting factor between 4 and 50, which was calculated from the maximum drawdown in the matrix vs. maximum drawdown in the fracture (e.g. maximum drawdown in M1 = 4.2m and maximum drawdown in M3 = 0.22m, weighting factor for the observation data of M3 = 20). Without doing so the higher drawdown values would dominate the inverse modelling process.

The estimated parameters were assigned different parameter numbers. For each parameter initial values, upper and lower bounds were defined. For the first calibration runs the estimated parameter values from the analytical models (see section 3.3) were used as initial values, while the bounds were chosen as big as reasonable while avoiding any effects. Table 4.2.1 shows the parameters to be estimated.

Table 4.2.1: Complete list of parameters for PEST-calibration

Aquifer / Layer	Parameter Description	Abbreviation
Dolerite (d)	Leakage from the dolerite to the mudstone	Ldm
	Hydraulic Conductivity of the dolerite	Khd
	Specific Storage of the dolerite	Ssd
Fracture (f)	Horizontal hydraulic Conductivity of the fracture	Khf
	Vertical hydraulic Conductivity of the fracture	Kvf
	Specific Storage of the fracture	Ssf
Dyke (y)	Horizontal hydraulic Conductivity of the dyke	Khy
	Vertical hydraulic Conductivity of the dyke	Kvy
	Specific Storage of the dyke	Ssy
Mudstone (m)	Hydraulic Conductivity of the mudstone	Khm
	Specific Storage of the mudstone	Ssm

4.2.3 Model results

To estimate the unknown parameters with the inverse model PEST, it is essential to get at first a good guess of the initial values (see steps 1 to 3 in the following procedure). Using initial values, which are not suitable for the aquifer system, will lead to a wrong estimation of the parameters. The following procedure has been used to estimate the unknown parameters:

1. Assume initial values and run the model forward – to make sure that the initial values are in reasonable ranges.
2. Estimate initial values for the parameters horizontal hydraulic conductivity and specific storage by running PEST with the assumed initial values (step 1) and bounds, and using only the observation data in the fracture – to update the initial parameter values

3. Fix the parameter values for the fracture, which are obtained from step 2, and run PEST using the observation data in the dolerite and/or mudstone to update the parameter values for the dolerite and mudstone.
4. Estimate all parameters by running PEST with the parameter values obtained from steps 2 and 3 as initial values and using all reasonable observation data.
5. Eventually improve the fit by changing parameters individually (change one parameter at a time) and running the model forward (see also section 4.2.4).

In the following sections the results of the steps are discussed and finally the estimated parameters are listed.

Step 1: Forward run with assumed initial values

The forward run with the assumed values, obtained from the analytical solutions of the hydraulic test, did not reach an acceptable fit of the drawdown curves. The calculated drawdown values in most boreholes were too low compared to the observed data.

Step 2: Inverse modelling with observation data of the fracture only

Using the observation data of the boreholes M1 and M2, intersecting the fracture and the mudstone, the inverse modelling (run 2) gives parameter values, which look reasonable. The statistic values from PEST indicate a good result (correlation coefficient of 0.9736), but the fit of the drawdown curve is not good at all (see fig. 4.2.2).

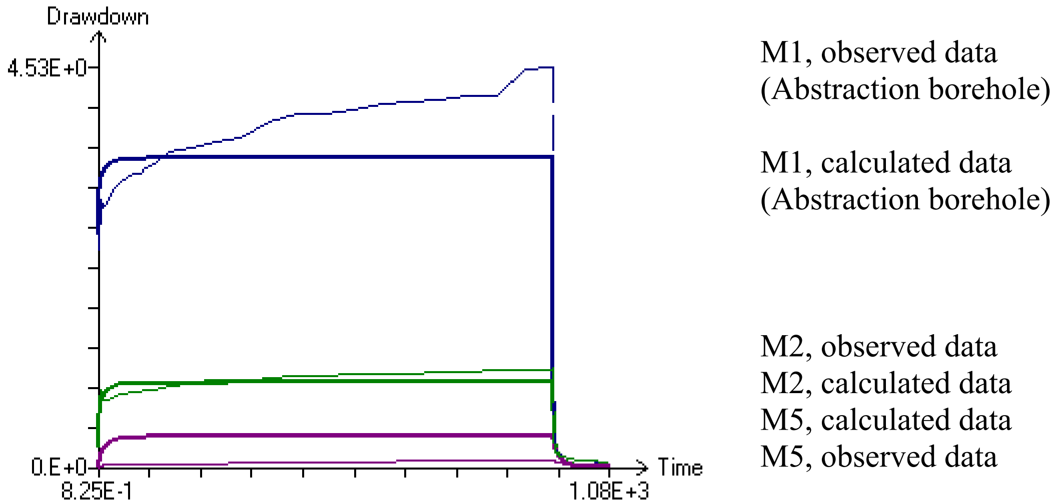


Fig. 4.2.2: Comparison observed (fine line) and calculated drawdown (bold line) of the inverse modelling; using the observation data of the boreholes M1 and M2 (estimated parameter values listed in tab. 4.2.2).

Table 4.2.2: Estimated parameter values of inverse modelling with observation data of the boreholes M1 and M2 (comparison of observed and calculated drawdown shown in fig. 4.2.2)

Parameter (model)	Value	Parameter (aquifer)	Value
Khd (Dolerite)	1.17E-01 m/min	T dolerite (5m)	843 m^2/day
Khf (Fracture)	2.10E-03 m/min	T fracture (30m)	91 m^2/day
Khm (Mudstone)	1.64E-03 m/min	T mudstone (25m)	59 m^2/day
Khy (Dyke)	2.00E-05 m/min	T dyke (30m)	0.86 m^2/day
Ssd (Dolerite)	1.59E-03 /m	S dolerite	7.97E-03
Ssf (Fracture)	4.06E-07 /m	S fracture (30m)	1.22E-05
Ssm (Mudstone)	2.31E-06 /m	S mudstone	5.77E-05

Step 3: Inverse modelling with observation data of the mudstone / dolerite

The above-listed values were used as initial values, while only the observation data of the boreholes, which intersect the mudstone and the dolerite (M3, M6), were used. If the fracture parameter (Khf, Ssf) were fixed, PEST cannot fit the drawdown curves properly. Therefore the fracture parameter had to be released. If using only the observation data of the borehole M6, the fit for this borehole is better but still not acceptable. The estimated parameter values are in a reasonable range.

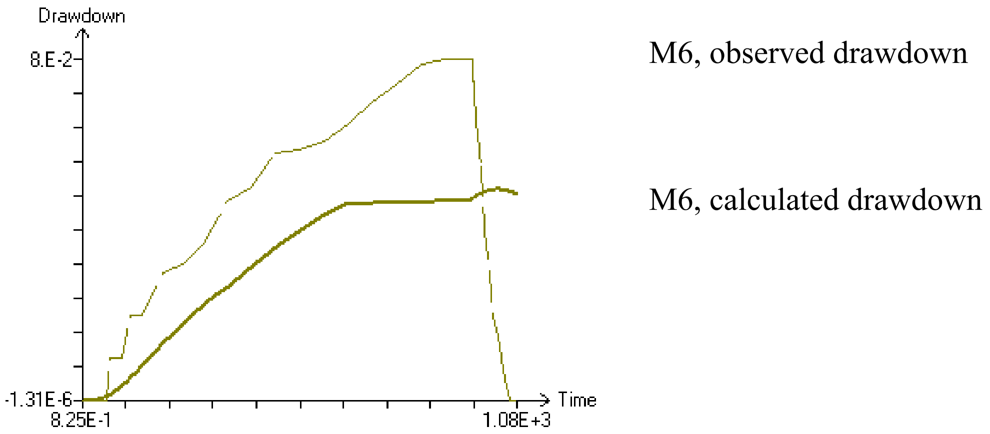


Fig. 4.2.3: Comparison observed and calculated drawdown of the inverse modelling; using the observation data of the borehole M6 (estimated parameter values listed in tab. 4.2.3).

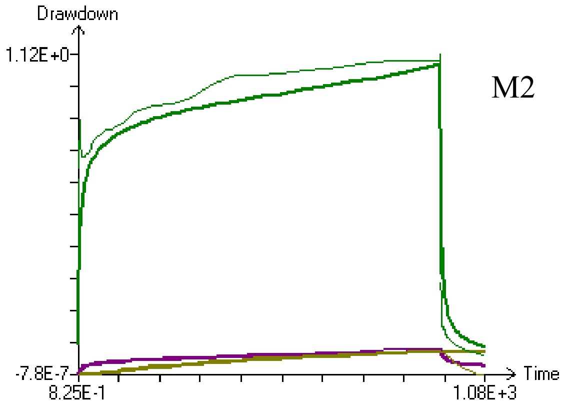
Table 4.2.3: Estimated parameter values of inverse modelling with observation data of the borehole M6 (comparison of observed and calculated drawdown shown in fig. 4.2.3)

Parameter (model)	Value	Parameter (aquifer)	Value
Khd (Dolerite)	5.25E-02 m/min	T dolerite (5m)	378 m^2/day
Khf (Fracture)	4.23E-02 m/min	T fracture (30m)	1827 m^2/day
Khm (Mudstone)	1.56E-04 m/min	T mudstone (25m)	5.6 m^2/day
Khy (Dyke)	1.00E-06 m/min	T dyke (30m)	0.04 m^2/day
Ssd (Dolerite)	6.03E-04 /m	S dolerite	3.01E-03
Ssf (Fracture)	3.55E-08 /m	S fracture (30m)	1.06E-06
Ssm (Mudstone)	3.19E-05 /m	S mudstone	7.96E-04

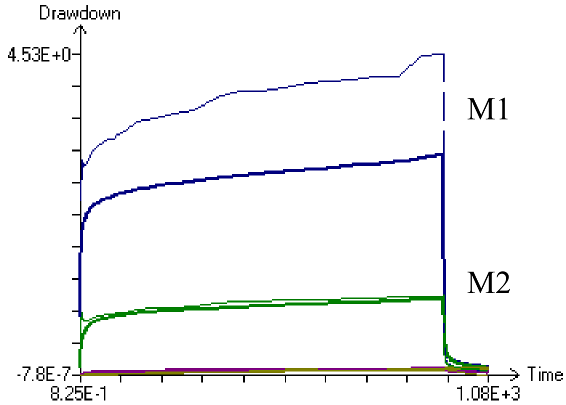
Step 4: Inverse modelling with all observation data

By using all observation data and the parameter values obtained from step 2 and step 3 as initial parameter values, the drawdown curves were obtained after running PEST and compared with observed curves (Fig. 4.2.4). Except the abstraction borehole M1, which undergoes wellscreen lost, the fit is acceptable and the estimated parameter values are shown in table 4.2.4.

a)



b)



c)

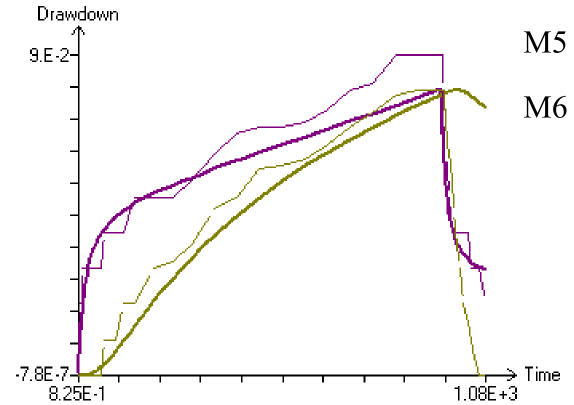


Fig. 4.2.4: Comparison observed (fine line) and calculated drawdown (bold line) of the best fit; using the observation boreholes M2, M5 and M6 (estimated parameter values listed in tab. 4.2.3). a) Observation borehole M2, b) Abstraction borehole M1 (data not used for calibration), c) Observation boreholes M5 and M6

Table 4.2.4: Estimated parameter values of forward modelling (best fit) with observation data of the boreholes M2, M5 and M6 (comparison of observed and calculated drawdown shown in fig. 4.2.4)

Parameter (model)	**Value**	**Parameter (aquifer)**	**Value**
K dolerite	5.3E-02 m/min	T dolerite (5m)	382 m^2/day
K fracture	2.8E-03 m/min	T fracture (30m)	121 m^2/day
K mudstone	8.0E-06 m/min	T mudstone (25m)	0.3 m^2/day
K dyke	1.0E-06 m/min	T dyke (30m)	0.04 m^2/day
Ss dolerite	1.3E-03 /m	S dolerite (5m)	6.5E-03
Ss fracture	5.0E-05 /m	S fracture (30m)	1.5E-03
Ss mudstone	1.2E-04 /m	S mudstone (25m)	3.0E-03

Step 5: Improving of parameter values

The result in step 4 is considered to be acceptable and therefore no further changes of parameter values are made in step 5.

4.2.4 Uncertainty of the Parameter Estimation

To check the influence of parameter changes, different runs were performed. Several forward runs with MODFLOW were conducted, changing the value of only one parameter at time or the geometry of the aquifer (i.e. thickness and extent of the fracture, conductivity of the dyke).

The influence of the different parameters on the drawdown curves can be summarized as follows:

- The drawdown in boreholes, not intersecting the fracture, is controlled by the transmissivity and storage of the dolerite. Changes in other parameter values have only a small impact on the drawdown curve.
- The drawdowns in two different boreholes, intersecting the fracture become closer together, when the T fracture increases.
- The shape of the drawdown curve in boreholes, intersecting the fracture (mainly the abstraction borehole) is controlled by the ratio of the transmissivities of all related aquifer systems (i.e. the mudstone, the dyke, the fracture, the dolerite). An increase of the transmissivity of one of the aquifer systems results in a decrease of the drawdown in the fracture borehole at late time.
- Small changes in the transmissivity of one of the aquifer systems (5% - 10%), calculated from the estimated parameter values, result in a suddenly drop of the drawdown in the abstraction borehole until it falls dry. It doesn't matter, which aquifer system is changed, the reaction is almost the same.
- The S fracture has only a small impact on the drawdown curves, while the influence of the S dolerite (see drawdown curve of M3 and M6) and the S mudstone (see drawdown curve of M1, M2 and M5) is much higher.

A change in the geometry of the aquifer has a similar influence as described above for the change of parameter values. While an increase in the width of the fracture shows a drop in the drawdown curve of the abstraction borehole, a decrease results in less drawdown.

4.2.5 Discussion

From the different calibration runs and the results it is clearly not possible to fit the drawdown curves in all boreholes properly with one parameter set.

There are some reasons for this phenomenon:

- The geometry of the aquifer is not well known and is simplified in the model (e.g., constant thickness over the whole model) and the real extent of the fracture is unknown.
- The drawdown behaviour in the abstraction borehole cannot be simulated correctly with the numerical model due to effects like well bore storage and well bore skin. The radius of the borehole and the cell size in the model are often different, therefore it is only possible to get the same trend of the curve, but not the same values.
- As discussed above the drawdown in the boreholes M3 and M6 represents the hydraulic properties of the weathered dolerite, while the drawdown in the boreholes M2 and M5 represents the hydraulic properties of the fracture.
- Secondary horizontal and vertical fractures, which intersect the main fracture, and the resulted semi-confined or unconfined conditions are not considered.
- Heterogeneity in both matrix and fracture systems is unknown and not considered. The unknown heterogeneity could even affect the hydraulic test data.
- All boreholes intersect more than one reacting aquifer system so that the observed drawdown is a mix of drawdown values in different systems. This makes it difficult to use the data in a numerical model, where the data must be specified to one layer (depth).

The comparison of the results from the numerical model with the analytical methods, as described in section 3.3.2, shows the relationship between the 4 aquifer systems. To use analytical methods for parameter estimation for aquifers with a vertical fracture is more complicated than for aquifers with a horizontal fracture, because more aquifer systems are involved in the former.

As shown in table 4.2.5 the use of analytical solutions will yield a geometric mean value of transmissivity of the involved aquifer systems:

- The abstraction borehole (M1) represents the whole aquifer and therefore applying the analytical method to the drawdown curve will yield a geometric mean of the transmissivity of all aquifer systems.
- The observation borehole M2 intersects the dolerite, mudstone, fracture and dyke. Analytical methods yield values close to the fracture transmissivity, as the groundwater movement occurs dominantly in the fracture.
- The observation boreholes M3, M5 and M6 intersect the mudstone and the dolerite. Analytical methods yield values close to the dolerite transmissivity, as it is higher than the mudstone transmissivity and the groundwater movement occurs dominantly in the dolerite.
- An analytical method for estimating the storage coefficient of the matrix could not be determined.

Tab. 4.2.5: Comparison of estimated transmissivities and their geometric mean values, obtained from the numerical model application and the analytical methods

		Geometric Mean Values					
Run 10	T-value	Fracture	Dolerite	Mudstone	Fr.+ Dyke	Dol.+ Mud	all
Fracture	121.00	121.00				23.98	4.85
Dolerite	380.00	214.43	380.00		12.25		
Mudstone	0.30	6.02	10.68	0.30	1.13		
Dyke	0.04	2.20	3.90	0.11		1.66	

Analytical Methods (Cooper-Jacob I / Theis)		
M1	23.8	represents parameter of all aquifer systems
M2	82.1	represents mainly fracture parameter
M3	167.5	represents mainly dolerite parameter
M5	294.4	represents mainly dolerite parameter
M6	273.7	represents mainly dolerite parameter
all (CJ II)	34.75	represents parameter of all aquifer systems

T-value: Estimated transmissivity values using PEST

Geometric Mean Value: Geometric mean of transmissivity values of involved aquifers, e.g. 214.43 is the geometric mean of the transmissivity values of Fracture and Dolerite.

4.3 Recommendation

A comparison of the results from analytical and numerical models (see section 4.1.5) shows that it is possible to estimate the parameter values for an aquifer system with a horizontal fracture with analytical methods, as described in section 4.1.5. For a vertical fracture parallel to a dyke it is not possible because several aquifer systems have impacts on the drawdwon behaviour, as described in section 4.2.5.

For a system with a horizontal fracture, the estimation of the storage coefficient with analytical methods is still uncertain due to the dependency on the parameter r (see Chapter 3). This parameter can be the distance between abstraction and observation boreholes (Cooper Jacob I / Theis) or the half-length of the fracture (Gringarten). If Cooper Jacob I / Theis is used and an observation borehole is not available, the effective borehole radius is used as the parameter r.

Two Excel-sheets, FC-Method and BPZONE, are often used to estimate the parameter r by using the early data of the drawdown in the abstraction borehole. The FC-method estimates the effective borehole radius. BPZONE estimates the half-length of the fracture. To test the use of these Excel-sheets, a synthetic numerical model with a horizontal fracture and known aquifer parameters has been constructed. The parameters of the model are listed in Table 4.3.1. Drawdown values at the abstraction borehole are calculated by using this model.

Table 4.3.1: Parameter values for forward run and analysing the calculated drawdown data with analytical methods

Transmissivity (T matrix)	28.8	m^2/d
Transmissivity (T fracture)	720	m^2/d
Storage Coefficient (S matrix)	1.0 E-02	
Storage Coefficient (S fracture)	1.0 E-07	
Vertical hydraulic conductivity (Kvm)	1.44 E-03	m/d
Discharge rate	2	l/s
Extent of fracture (150 x 200m) Fracture half length or radius of fracture	100	m

In this example the radial acting flow phase, indicated by a straight line in the semi-log-plot, is reached after approximately 14 days of abstracting. Earlier data cannot be used to estimate the parameter values with analytical methods. Using the late time model-calculated drawdown data and an effective borehole radius of 35 m, the correct value of the storage coefficient will be given by analytical methods. The FC-program estimates an effective borehole radius of 39 m, which is close to 35 m.

In the BPZONE-sheet the fracture extent was calculated to 135m in average (between 109m and 195m with different methods).

A problem related to the use of these two sheets is that they require the early measurement. Depends on the chosen time interval of the “early” data, the estimation can be different. The long the time interval is, the bigger are the estimated values, which result at the end a under-estimation of the storage coefficient.

Another possibility to get a first estimation of the storage coefficient of the matrix is with the program RPTSOLV, which is a 2-dimensional numerical model especially designed for estimating the storage coefficient in fractured aquifers.

The following points for conducting and analysing hydraulic test data in fractured aquifers are given as recommendation:

- The duration of a hydraulic test should be long enough to reach the radial acting flow phase, when analytical methods are intended to be used.
- The discharge rate must be chosen in a way that no fracture will be dewatered during the test. Neither with analytical nor with numerical models it is possible to analyse such a test.
- The discharge rate should be kept constant over the whole period of abstraction. Otherwise no analytical method should be used to estimate the parameter values unless the drawdown is corrected. When using a numerical model, every change in the discharge rate must be considered (in another stress period).
- The measurement of the drawdown must have accuracy of at least 1cm.
- The time intervals of measurement in the beginning of the test should be small, at least less than 1 minute (recommended 10 seconds).
- For estimating vertical hydraulic conductivity, piezometers with short wellscreen should be installed in different depths.
- Parameter r, i.e. the effective borehole radius or half-length of the fracture, must be calculated from early hydraulic test data.
- To estimate the storage coefficient of the aquifer in an accurate way, piezometers in the matrix should be used and the hydraulic test data should be analysed with a numerical model as described in this chapter and in the following chapter.
- Observation boreholes, used for the hydraulic test, should never intersect more than one reacting aquifer system to avoid a mix of observation.

Details of conducting and analysing hydraulic tests in fractured aquifers are given in the “Manual on Pumping Test Analysis in Fractured-Rock Aquifers” (G. van Tonder et.al., 2001) submitted to the WRC in January 2001 as a final report.

CHAPTER 5

Pre-Built Models and their Construction Steps

To simplify the way of estimating the aquifer parameters from hydraulic tests using numerical models pre-built models for typical South African aquifer types are constructed and their use for the estimation is described in the following guidelines. Pre-built models and results have discussed in the previous chapter. It is at more importance to know how to build such kind of model on reader’s own effort, as this knowledge can be applied on more general cases.

5.1 Horizontal bedding-plane Fracture

The Karoo-aquifer is the main aquifer type in South Africa. They consist mainly of horizontal layers of sandstones, mudstones, shales and siltstones. Isostatic upliftment, together with the intrusion of lavas and dolerites, caused intensive fracturing. There is normally at least one horizontal bedding-plane fracture, which is usually found in the sandstone layer.

5.1.1 Description

To analyse a hydraulic test with a numerical model the hydrogeological structure of the aquifer should be represented by the model. In case of an aquifer, consists of a horizontal, bedding-plane fracture in a matrix of sandstone or mudstone, the model should consist of one layer, representing the fracture zone, and above and below this layer some layers, representing the matrix. The whole aquifer is treated as homogeneous and confined. Therefore smaller horizontal fractures and vertical fractures are neglected. The parameters, used in the model and have to be calibrated by inverse modelling, are the T matrix, T fracture, S matrix, S fracture and Leakage in the matrix.

5.1.2 Step-by-step Guideline

The step-by-step guideline will explain the steps needed to build the model, to assign and calibrate the parameters by using PMWIN as the modelling tool. The general procedure is valid for all modelling tools, while some special steps can be different when using another modelling program.

Step 1 Conceptualisation

As base for the numerical model the conceptualisation must be able to represent the aquifer system. The general conceptual model, which is used to build the numerical model for analysing hydraulic tests, is described in section 4.1.1 and 5.1.1. As mentioned a three-dimensional model, consisting of a minimum of three layers, is used in this case. The horizontal size of the model and choose of amount and thickness of layers can’t be fixed a priori, because the hydrogeological structure on each site is different.

In the following some rules and recommendations for the model conceptualisation are given:

- The extent of a model depends mainly on the radius of influence during the hydraulic test. It must be big enough to avoid any boundary effects. In a fractured aquifer the radius of influence depends on the extent of the fracture and the transmissivity of the matrix. Because the hydraulic test should reach the radial acting flow phase, which occurs after the radius of influence is 5 times the half-length of the fracture, the model must be bigger than 10 times the half-length of the fracture. Estimation for the half-length of the fracture can be obtained from the program BPZONE, which is implemented in the FC EXCEL program.

The extent of a model should be at least 30 times, better between 40 and 60 times the half-length of the fracture.

- The number of columns and rows, used in the model, depends on the mesh size and on the required accuracy of the modelling. In the outer region of the model the grid size should be between 5% and 10% of the whole mesh size, while in the area of interest (i.e. the surrounding of the abstraction and observation boreholes) the grid size should be only few meters, depending on the required accuracy.

- There should be at least 5 cells between the positions of the abstraction borehole and the nearest observation borehole to ensure that the model can simulate the drawdown behaviour in a correct way.

- The number of layers depends on the aquifer thickness and the kind of discretization. While the fracture zone can be represented by 1 layer, with a thickness regarding to the assumed or known thickness of the fracture zone, the matrix should be represented by a number of layers. The layers above and below the fracture-layer should have a smaller thickness to account for the development of the cone of depression.

- The thickness of the layers, which represent the matrix, depends then on the positions of the matrix piezometers (i.e. the wellscreens should not be occur in 2 layers or more) and the thickness of the whole aquifer. If the thickness of the aquifer is small enough, it is a good choice to use a thickness of 1m for the layers.

- For a short-time hydraulic test (few days) the influence of the natural gradient on the drawdown can normally be neglected and it can be simplified to use the same initial hydraulic head for the whole model. When calibrating a model with drawdown data, the value of the initial hydraulic head does not necessarily be the real elevation, but must be equal or higher than the elevation of the top of layer 1.

For the procedure of data input, modelling and parameter estimation, it is easier to use the drawdown data, measured during the hydraulic test, than the real hydraulic heads.

Step 2 Create a new model

- To create a new model choose **New Model** form the **File** menu, create a new folder and type the file name for the model without extension, because PMWIN will automatically add the extension **.PM5**.

> **Every model should be saved in its own folder,** because all output files are saved in the same folder as the model. If several models are saved in the same folder, the output files of the last run will overwrite the output files from the other models.

- In MODFLOW an aquifer system is replaced by a discretized domain consisting of an array of nodes and associated finite difference blocks (cells). To generate the model grid choose **Mesh Size** from the **Grid** menu and enter the appropriate numbers of layers, columns and rows as well as the size of the columns and rows, as it was chosen in the conceptualisation (step 1).

- To refine the grid size in the surrounding of the abstraction and observation boreholes choose again **Mesh Size** from the **Grid** menu and refine the size.

> **The difference in the size between neighbouring cells should not be bigger than 1:5, maximum 1:10.**

- The type of the layers should be set as confined as mentioned in the description (section 5.1.1). Therefore choose **Layer Type** from the **Grid** menu and set for all layers the type [*0: Confined*]. The Transmissivity, Leakance and Storage Coefficient should be set as [*User Specified*], because these parameters are estimated during the inverse modelling. Setting as [*Calculated*] means that PMWIN calculates the values from the given values of the parameters horizontal hydraulic conductivity, vertical hydraulic conductivity and specific storage.

- As far as the extent of a model is big enough, the cone of depression during a pumping test should not reach the model boundary and it can be set as impervious boundaries or fixed-head boundaries. The fixed-head boundary condition is set by choosing **Boundary Condition, IBOUND (Modflow)** from the **Grid** menu and assign the value of –1 to the boundary cells. The impervious boundary condition is set by assigning the value of 1 to the boundary cells.

> Note that it is necessary to assign fixed-head boundary condition, if a steady-state flow simulation is intended and if there are no other boundary conditions (i.e. river, drain,…) involved in the model.

- To specify the thickness of the layers the elevations of the top and bottom of all layers have to be given. This is done by choosing **Top of Layer** and **Bottom of Layer** from the **Grid** menu.

> To simplify the procedure use the aquifer thickness as elevation for the top of layer 1 and zero as elevation for the bottom of the last layer.

Step 3 Assign the model data and parameters

- To analyse a hydraulic test with the numerical model, different abstraction rates during the test must be simulated. Therefore choose **Time Parameters** from the **Parameters** menu and enter the different stress periods of the hydraulic test (i.e. stress period 1 = abstraction time, stress period 2 = recovery time).

- The length of each stress period is given from the hydraulic test and must be entered in the same unit used for the observation data (seconds, minutes, hours or days). The number of time steps should be equal as or bigger than the number of observations during the hydraulic test. Click [*transient*] as the type of the flow simulation.

> **PMWIN requires the use of consistent units throughout the modelling process.**
> If for example the time unit, specified in the Time Parameter dialog box and used for the observation data, is minutes and the length, used in the grid size and elevations, is meters, the transmissivity has to be entered in m^2/min and the abstraction rate of the well has to be entered in m^3/min.

- The initial hydraulic head should represent the water level before starting the hydraulic test. Choose **Initial Hydraulic Head** from the **Parameter** menu to specify the water level.

- For confined layers (layer type =0), the inverse model PEST estimates the parameters transmissivity (T), Vertical leakance (VCONT) and confined storage coefficient (S). It is required to assign reasonable guess values prior to running PEST. Refer to section 4.1.5 for how to estimate T and S values and see below for the explanation of VCONT.

- To specify T-values, choose **Transmissivity** from the **Parameter** menu. Note that the T-values obtained in section 4.1.5 refer to the entire thickness of an aquifer and the T-values required by MODFLOW refer to the thickness of each layer. It is recommended to calculate hydraulic conductivity (K) values from the T-values obtained in section 4.1.5, and then use these K-values to obtain the T-values for each model.

> **To assign the values of the fracture use the Zonal Input mode and save the zone as a specific file for further use.** This will guarantee to have the same extent of the fracture for all parameters.

- MODFLOW requires the vertical leakance (VCONT) between two model layers for the simulation. Choose **Vertical Leakance** from the **Parameter** menu and assign reasonable values for each layer. The vertical leakance between layer k and k+1 is given as data of the layer k. The vertical leakance is not required for the last layer (bottom of the model). Due to the definition of the vertical leakance (see equation 5.1 below) the value changes, if the thickness of a layer changes (for examples see table 5.1.1). In the case, where the vertical hydraulic conductivity (Kz) of the fracture is far larger than Kz of the matrix, the former can be neglected in eq. 5.1, and the vertical leakance from the matrix to the fracture depends only on the Kz-value and the thickness of the matrix layer.

$$VCONT = 2 \Big/ \left(\frac{\Delta Vk}{Kz|i,j,k|} + \frac{\Delta Vk+1}{Kz|i,j,k+1|} \right) \qquad \textbf{eq. 5.1.}$$

with ΔVk and $\Delta Vk+1$ Thickness of layer k and k + 1

$Kz|i,j,k|, Kz|i,j,k+1|$ Vertical hydraulic conductivity of layer k and k + 1

- Assuming a high vertical hydraulic conductivity in the fracture compared to the matrix the conductivity in the fracture can be neglected in the equation above. Then the vertical leakance from the matrix to the fracture depends only on the vertical hydraulic conductivity of the matrix and the thickness of the two layers (matrix and fracture).

- To specify S-values, choose **Storage Coefficient** from the **Parameter** menu. Note that the S-values obtained in section 4.1.5 refer to the entire thickness of an aquifer and the S-values required by MODFLOW refer to the thickness of each layer. It is recommended to calculate specific storage (Ss; Ss = S / layer thickness) values from the S-values obtained in section 4.1.5, and then use these Ss-values to obtain the S-values for each model layer.

- Each parameter, which should be estimated with inverse modelling, must be assigned a specific parameter number. When the value of the parameter changes due to different thickness of the layers, the parameter number must be changed too (see table 5.1.1).

- For the flow simulation the effective porosity is not necessary, but if the use of a transport model like PMPATH is intended, reasonable values for the effective porosity must be assigned. During a short-term hydraulic test (few days) the influence of recharge or evapotranspiration is normally neglectable.

- While the positions of the observation boreholes are given in real-world coordinates, the position and discharge rate of the abstraction borehole are assigned in a cell-by-cell basis. Choose **MODFLOW, Well** from the **Model** menu and enter the discharge rate of the hydraulic test in the cell, which should represent the abstraction borehole. Note that the discharge rate must be given in the consistent units, used in the whole model, and as a negative value to indicate an abstraction well.

In most cases an abstraction borehole intersects the matrix and the fracture. However due to the much higher conductivity of the fracture **the position of the well should be in the layer of the fracture.** The flow direct from the matrix to the well can be neglected.

- If the discharge rate is not constant during the test, more stress periods should be specified (see above), each with different discharge rate. The last stress period is the recovery with a discharge rate of zero.

Step 4 Assign the observation data

- The coordinates of the abstraction and observation boreholes, used during the hydraulic test, have to be specified. Therefore choose **Boreholes and Observations** from the **Parameter** menu and enter the coordinates into the **Borehole** table. The real-world coordinates (eastings [x], northings [y]) and the layer number are used to locate a borehole. Observation boreholes, which are included in the calibration process, must be activated by checking the **Active** box.

If a piezometer with a short wellscreen is used, the depth of the wellscreen specifies the layer number. For a borehole intersecting both the matrix and the fracture the layer of the fracture should be used.

- The observed data have to be entered in the **Observation** table with the borehole-name, the observation time, the measurement (as drawdown or hydraulic head) and a weighting factor, which is used for the inverse modelling. The borehole-name must be written in the same way as in the **Borehole** table (see above). The observation time is measured from the beginning of the model simulation and must be specified in ascending order for each borehole and given in the same units as specified in the **Time** menu.

If the observation data already exist in an ASCII-file (or compatible format), create an observation file, as described in the Appendix of the manual and load it into the observation table.

- If using drawdown measurements during the hydraulic test, set the flag to [*Use observed drawdowns for the calibration*].

- The weighting factor of an observation gives normally a relative confidence level of the observed value. The higher the value, the *better* the measurement. If the distribution of the measured values differs far between the boreholes, the weighting factor should be used to relate the observations to the same level. If for example the maximum drawdown in the abstraction borehole is 2m and the maximum drawdown in the observation borehole 1 is 0.2m, a weighting factor of 10 should be assigned to the observation data of the observation borehole 1 when both boreholes are used for the calibration process.

Single observations, which are not used in the calibration process, should be assigned a weight of zero. This can be applied to wrong observations due to short changes of the discharge rate or due to dewatering of discrete fractures, wrong measurements or other observations, which are not consistent with the drawdown curve.

Step 5 Perform the flow simulation

- To check, if the chosen parameter values are reasonable and gives a good estimation for the hydraulic test, a forward run of the model should be conducted. Choose **MODFLOW, Run** from the **Models** menu to start the forward run with the given parameter values. PMWIN will check the model data and generate the files for MODFLOW before staring the iterations.

- Prior to running MODFLOW, one can choose **MODFLOW, Output control** and **MODFLOW, Solver** from the **Models** menu to specify the output files (Drawdown, Head, Budget etc.) and the conditions of the forward run like number of iterations and convergence criteria.

- If the run is not finished successfully, the file OUTPUT.DAT should be checked for possible reasons. In most cases the model configuration or the assumed parameter values are not reasonable, so that some cells get dry during the iterations. Another reason might be that the convergence criteria, which are set by choosing **MODFLOW, Solver**, can't be reached during the maximum number of iteration steps.

- After a successful run check the results by using the graphical tools. Choose **Graphs, Drawdown-Time** or **Head-Time** from the **Tools** menu to compare the observed and the calculated data. Click on the Plot flag of the boreholes to specify for the diagram. To check the differences of the values for one borehole choose **Scatter Diagram**.

- To check the radius of influence or the cone of depression choose **Presentation** from the **Tools** menu, load the calculated drawdown with the **Results Extractor** and draw the contour map using a minimum value of 0.01m or 0.001m.

The minimum contour should not reach or be close to the fixed-head-boundaries.

Step 6 Assign data and parameters for inverse modelling

- For the estimation of the parameters the inverse model PEST is used. Therefore choose **PEST, Parameter List** from the **Models** menu and assign the structure of parameters and the options for the inverse modelling.

- Each parameter, which should be estimated with inverse modelling, must be assigned a specific parameter number, which must be the same as given in the **Parameters** menu in **Step 3**. When the value of the parameter changes due to different thickness of the layers, the parameter number must be changed too (see table 5.1.1).

- The value of an estimated parameter will only be adjusted if the **Active flag** is checked. Otherwise the user-specified cell value will be used for the simulation. A specific name for the parameter can be entered as a description.

- For each parameter initial values for the first iterations (PARVAL1) and reasonable upper and lower bounds for the values (PARLBND, PARUBND) must be given in the **Parameters** tab. The initial values should be the same as the values given in **Step 3** and should result from the analysing of the hydraulic test with analytical methods as described above.

- To reduce the number of parameters, parameters should be tied to another, whenever it is possible. If a parameter is tied to another parameter (e.g. T of layer with 0.5m thickness and T of layer with 1m thickness in a homogenous aquifer), the initial values of both must show this ratio. The parameter transformation (PARTRANS) must be set to [*Tied*] and the parameter number of the 'parent' parameter must be given as PARTIED.

- Normally the parameter transformation (PARTRANS) for the parameters Transmissivity, Storativity and Leakance should be set to [*Log-transformed*]. If a parameter should not be changed during the inverse modelling, the parameter transformation (PARTRANS) must be set to [*Fixed*].

Table 5.1.1: Example for assigning parameter numbers and initial values to a 7 layer model, representing an aquifer of 4.7 m thickness with a single fracture of 0.2 m thickness without fracture skin (bold = tied parameters)

Layer		**Transmissivity**		**Vertical Leakance**	
No.	Thickness	P No.	Value	P No.	Value
1	1 m	1	1.0E-04 m^2/sec	5	1.00E-07 /sec
2	1 m	1	1.0E-04 m^2/sec	**6**	1.33E-07 /sec
3	0.5 m	**2**	5.0E-05 m^2/sec	**7**	2.00E-07 /sec
4	0.5 m	**2**	5.0E-05 m^2/sec	**8**	2.86E-07 /sec
4 (to fract.)	0.5 m	**2**	5.0E-05 m^2/sec	**9**	4.00E-07 /sec
5 (matrix)	0.2 m	**3**	2.0E-05 m^2/sec	**8**	2.86E-07 /sec
5 (fracture)	0.2 m	4	5.0E-01 m^2/sec	**9**	4.00E-07 /sec
6	0.5 m	**2**	5.0E-05 m^2/sec	**6**	1.33E-07 /sec
7	1 m	1	1.0E-04 m^2/sec	-	

- The criteria for the optimisation process can be set in the **Control Data** table of **PEST, Parameter List**. NUMLAM, PHIRATSUF and PHIREDLAM are the criteria for moving to the next optimisation iteration, while PHIREDSTP and NPHISTP are the convergence criteria to stop the optimisation process. If these criteria can't be achieved the termination criteria NOPTMAX, NPHINORED, RELPARSTP and NRELPAR will stop the program. The default setting of the values is normally suitable for most problems.

- After setting all parameters for the inverse modelling, choose **PEST, Run** from the **Models** menu. PMWIN will generate the input files for MODFLOW and PEST. If necessary PMWIN or PEST can check the model data for consistency by checking [*Perform PESTCHEK prior to running PEST*] and [*Check the model data*].

Create for every run of the inverse modelling a new folder and copy all files from the last run into the new folder (using Windows Explorer). This helps to prove the input data and results for each run. If it is necessary, particular runs can be repeated or used for another optimisation process.

- After a successful run check the run record file PESTCTL.REC, which is saved in the same folder as the model and will be opened automatically with NOTEPAD when closing the DOS-window of the PEST run. The estimated parameter values are given as **optimisation result**. The quality of the results can be checked with the 95% confidence limits, the objective function and other statistical values.

- A graphical diagram should be used to visualize the comparison between calculated and observed data. Choose **Graphs, Drawdown-Time** or **Head-Time** from the **Tools** menu and click on the **Plot** flag to specify the boreholes for the diagram. To check the differences of the values for one borehole choose **Scatter Diagram**.

After each run check the run record file for results and confidence and produce output diagrams, as described below.

- The inverse modelling is successfully finished, when reasonable parameter values are obtained, which suits the observed data in the best possible way. The criteria are the visualized comparison of observed and calculated data and the lowest possible objective function (called phi) for the used set of observations.

5.2 Vertical Fracture parallel to a Dyke

Besides the aquifer with a horizontal, bedding-plane fracture the Karoo-aquifers have a second type of aquifers with a fracture system connected to a vertical or semi-vertical dyke. Typically the fracture occurs parallel to the dyke on the contact zone between the intrusion of the dyke and the surrounding rocks.

5.2.1 Description

To analyse a hydraulic test numerically the hydrogeological structure of the aquifer should be represented by the model. In a case of a vertical or nearly vertical fracture parallel to a dyke at least three aquifer features have to be taken into account:

- The vertical fracture zone as the main aquifer
- The matrix of the layer, in which the fracture zone occurs
- The dyke, which can be treated as a barrier

Therefore the model should consist of several layers, representing the matrix. The fracture zone is represented by a vertical plane with a specified width according to the thickness of the fracture, while some columns represent the dyke according to the assumed thickness of the dyke. The whole aquifer is treated as homogeneous and confined / unconfined (depending on the drawdown). Therefore smaller vertical and horizontal fractures and the heterogeneity of the aquifer are neglected.

The parameters, used in the model and have to be calibrated by inverse modelling, are the horizontal conductivity of the matrix, the horizontal conductivity of the fracture, the specific storage of the matrix, the specific storage of the fracture and the leakage in the matrix and in the fracture (to calculate the vertical conductivity). The parameters of the dyke can be fixed during the estimation process.

5.2.2 Step by step Guideline

The step-by-step guideline will explain the steps needed to build the model, to assign and calibrate the parameters by using PMWIN as the modelling tool. The general procedure is valid for all modelling tools, while some steps can be different when using another modelling program.

Step 1 Conceptualisation

A three-dimensional model, consisting of a minimum of two layers, is used in this case. The horizontal size of the model and choose of amount and thickness of layers can't be fixed a priori, because the hydrogeological structure on each site is different.

In the following some rules and recommendations for the model conceptualisation are given:

- The extent of the model depends mainly on the radius of influence during the hydraulic test. It must be big enough to avoid any boundary effects. In a fractured aquifer with infinite conductivity of the fracture the radius of influence depends on the extent of the fracture and the transmissivity of the matrix. Because the hydraulic test should reach the radial acting flow phase, which occurs after the radius of influence is 5 times the half-length of the fracture, the model should be bigger than 10 times the half-length of the fracture. Estimation for the half-length of the fracture can be obtained from the program BPZONE, which is implemented in the FC EXCEL program.

The extent of a model should be at least 20 times the half-length of the fracture.

- The number of columns and rows, used in the model, depends on the mesh size and on the required accuracy of the modelling. In the outer region of the model the grid size should be between 5% and 10% of the whole mesh size, while in the area of interest (i.e. the surrounding of the abstraction and observation boreholes, the fracture and the dyke) the grid size should be only few meters or decimetres, depending on the required accuracy.

- The width of the column or row, which represents the fracture or dyke, should be the same as the real size of the fracture or dyke respectively. The size difference between fracture-column (or row) and dyke-column (or row) should be small. If necessary use more than one column (or row) to represent a dyke or fracture.

- There should be at least 5 cells between the positions of the abstraction borehole and the nearest observation borehole to ensure that the model can simulate the drawdown behaviour in a correct way.

- The number of layers depends on the aquifer thickness and the geology.

- The thickness of each layer depends on the positions of the matrix piezometers (i.e. the wellscreens should not be occur in 2 layers or more) and the thickness of the whole aquifer. If the thickness of the aquifer is small enough, it is a good choice to use a thickness for the layers of 1m.

- For a short-time hydraulic test (few days) the influence of the natural gradient on the drawdown can normally be neglected and it can be simplified to use the same initial hydraulic head for the whole model. When calibrating a model with drawdown data, the value of the hydraulic head does not necessarily be the real elevation, but must be equal or higher than the elevation of the top of layer 1.

For the procedure of data input, modelling and parameter estimation, it is easier to use the drawdown data, measured during the hydraulic test, than the real hydraulic heads.

Step 2 Create a new model

- To create a new model choose **New Model** form the **File** menu, create a new folder and type the file name for the model without extension, because PMWIN will automatically add the extension **.PM5**.

> **Every model should be saved in its own folder,** because all output files are saved in the same folder as the model. If more than one model are saved in the same folder, the output files of the last run will overwrite the output files from the other models.

- In MODFLOW an aquifer system is replaced by a discretized domain consisting of an array of nodes and associated finite difference blocks (cells). To generate the model grid choose **Mesh Size** from the **Grid** menu and enter the appropriate numbers of layers, columns and rows as well as the size of the columns and rows, as it was chosen in the conceptualisation (step 1).

- To refine the grid size in the surrounding of the abstraction and observation boreholes choose again **Mesh Size** from the **Grid** menu and refine the size.

> **The difference in the size between neighbouring cells should not be bigger than 1:5, maximum 1:10.**

- The type of the layers should be set as confined / unconfined as mentioned in the description (section 5.2.1). Therefore choose **Layer Type** from the **Grid** menu and set for all layers the type [*3: Confined / unconfined, Transmissivity varies*]. The Transmissivity and Storage Coefficient should be set as [*Calculated*], while the Leakage should be set as [*User Specified*]. During the inverse modelling the parameters horizontal hydraulic conductivity, vertical leakance and specific storage are to be estimated.

- As far as the extent of a model is big enough, the cone of depression during a pumping test should not reach the model boundary and it can be set as impervious boundaries or fixed-head boundaries. The fixed-head boundary condition is set by choosing **Boundary Condition, IBOUND (Modflow)** from the **Grid** menu and assign the value of –1 to the boundary cells. The impervious boundary condition is set by assigning the value of 1 to the boundary cells.

> Note that it is necessary to assign fixed-head boundary condition, if a steady-state flow simulation is intended and if there are no other boundary conditions (i.e. river, drain,…) involved in the model.

- To specify the thickness of the layers the elevations of the top and bottom of all layers have to be given. This is done by choosing **Top of Layer** and **Bottom of Layer** from the **Grid** menu.

> To simplify the procedure use the aquifer thickness as elevation for the top of layer 1 and zero as elevation for the bottom of the last layer.

Step 3 Assign the model data and parameters

- To analyse a hydraulic test with the numerical model, different abstraction rates during the test must be simulated. Therefore choose **Time Parameters** from the **Parameters** menu and enter the different stress periods of the hydraulic test (i.e. stress period 1 = abstraction time, stress period 2 = recovery time).

- The length of each stress period is given from the hydraulic test and must be entered in the same unit used for the observation data (seconds, minutes, hours or days). The number of time steps should be equal as or bigger than the number of observations during the hydraulic test. Click [*transient*] as the type of the flow simulation.

PMWIN requires the use of consistent units throughout the modelling process.
If for example the time unit, specified in the Time Parameter dialog box and used for the observation data, is minutes and the length, used in the grid size and elevations, is meters, the transmissivity has to be entered in m^2/min and the abstraction rate of the well has to be entered in m^3/min.

- The initial hydraulic head should represent the water level before starting the hydraulic test. Choose **Initial Hydraulic Head** from the **Parameter** menu to specify the water level.

- For confined/unconfined layers (layer type =3), the inverse model PEST estimates the parameters horizontal hydraulic conductivity (HK), Vertical leakance (VCONT) and specific storage (Ss). It is required to assign reasonable guess values prior to running PEST. Refer to section 4.2.5 for how to obtain reasonable HK values and see below for the explanation of VCONT. To specify HK-values, choose **Horizontal Hydraulic Conductivity** from the **Parameter** menu. Note that the T-values obtained in section 4.2.5 refer to the entire thickness of an aquifer and need to be converted to HK-values.

To assign the values of the fracture use the Zonal Input mode and save the zone as a specific file for further use. This will guarantee to have the same extent of the fracture for all parameters.

- MODFLOW requires the vertical leakance (VCONT) between two model layers for the simulation. Choose **Vertical Leakance** from the **Parameter** menu and assign reasonable values for each layer. The vertical leakance between layer k and k+1 is given as data of the layer k. The vertical leakance is not required for the last layer (bottom of the model). Due to the definition of the vertical leakance (see equation 5.2 below) the value changes, if the thickness of a layer changes (for examples see table 5.2.1). In the case, where the vertical hydraulic conductivity (Kz) of the fracture is far larger than Kz of the matrix, the former can be neglected in eq. 5.1, and the vertical leakance from the matrix to the fracture depends only on the Kz-value and the thickness of the matrix layer.

$$VCONT = 2 \Big/ \left(\frac{\Delta Vk}{Kz|i,\, j, k|} + \frac{\Delta Vk+1}{Kz|i,\, j, k+1|} \right) \qquad \textbf{eq. 5.2.}$$

with ΔVk and $\Delta Vk+1$ Thickness of layer k and k + 1

$Kz|i,\, j, k|,\, Kz|i,\, j, k+1|$ Vertical hydraulic conductivity of layer k and k + 1

- Choose **Specific Storage** from the **Parameter** menu and assign a reasonable value of the specific storage.

- Each parameter, which should be estimated with inverse modelling, must be assigned a specific parameter number. When the value of the parameter changes due to different thickness of the layers or due to change of hydraulic properties, the parameter number must be changed too (see table 5.2.1).

- For the flow simulation the effective porosity is not necessary, but if the use of a transport model like PMPATH is intended, reasonable values for the effective porosity must be assigned. During a short-term hydraulic test (few days) the influence of recharge or evapotranspiration is normally neglectable.

- While the positions of the observation boreholes are given in real-world coordinates, the position and discharge rate of the abstraction borehole are assigned in a cell-by-cell basis. Choose **MODFLOW, Well** from the **Model** menu and enter the discharge rate of the hydraulic test in the cell, which should represent the abstraction borehole. Note that the discharge rate must be given in the consistent units, used in the whole model, and as a negative value to indicate an abstraction well.

In most cases an abstraction borehole intersects the matrix and the fracture. However if the abstraction borehole is situated in the vertical fracture, **the discharge rate should be put in the last layer, while the other layers should be assigned a very low discharge rate (say 1E-10 or less) to indicate a borehole.**

- The vertical leakage in the cells representing the abstraction borehole should be set to 1 or higher to account for a high vertical conductivity in the borehole. With this method MODFLOW calculates the distribution of the discharge rate inside the borehole for each layer, depending on the transmissivity of the cells. The total discharge rate will be kept constant over the whole stress period, even if a part of the borehole falls dry.

- If the discharge rate is not constant during the test, more stress periods should be specified (see above), each with different discharge rate. The last stress period is the recovery with a discharge rate of zero.

Step 4 Assign the observation data

- The coordinates of the abstraction and observation boreholes, used during the hydraulic test, have to be specified. Therefore choose **Boreholes and Observations** from the **Parameter** menu and enter the coordinates into the **Borehole** table. The real-world coordinates (eastings [x], northings [y]) and the layer number are used to locate a borehole. Observation boreholes, which are included in the calibration process, must be activated by checking the **Active** box.

If a piezometer with a short wellscreen is used, the depth of the wellscreen specifies the layer number. For a borehole intersecting both the matrix and the fracture the layer of the fracture should be used.

- The observed data have to be entered in the **Observation** table with the borehole-name, the observation time, the measurement (as drawdown or hydraulic head) and a weighting factor, which is used for the inverse modelling. The borehole-name must be written in the same way as in the **Borehole** table (see above). The observation time is measured from the beginning of the model simulation and must be specified in ascending order for each borehole and given in the same units as specified in the **Time** menu.

If the observation data already exist in an ASCII-file (or compatible format), create an observation file, as described in the Appendix of the manual and load it into the observation table.

- If using drawdown measurements during the hydraulic test, set the flag to [*Use observed drawdowns for the calibration*].

If the drawdowns in the fracture boreholes are not simultaneously, don't use the observed data of the abstraction borehole for the inverse modelling.

- The weighting factor of an observation gives normally a relative confidence level of the observed value. The higher the value, the *better* the measurement. If the distribution of the measured values differs far between the boreholes, the weighting factor should be used to relate the observations to the same level. If for example the maximum drawdown in the abstraction borehole is 2m and the maximum drawdown in the observation borehole 1 is 0.2m, a weighting factor of 10 should be assigned to the observation data of the observation borehole 1 when both boreholes are used for the calibration process.

Single observations, which are not used in the calibration process, should be assigned a weight of zero. This can be applied to wrong observations due to short changes of the discharge rate or due to dewatering of discrete fractures, wrong measurements or other observations, which are not consistent with the drawdown curve.

Step 5 Perform the flow simulation

- To check, if the chosen parameter values are reasonable and gives a good estimation for the hydraulic test, a forward run of the model should be conducted. Choose **MODFLOW, Run** from the **Models** menu to start the forward run with the given parameter values. PMWIN will check the model data and generate the files for MODFLOW before staring the iterations.

- Prior to running MODFLOW, one can choose **MODFLOW, Output control** and **MODFLOW, Solver** from the **Models** menu to specify the output files (Drawdown, Head, Budget etc.) and the conditions of the forward run like number of iterations and convergence criteria.

- If the run is not finished successfully, the file OUTPUT.DAT should be checked for possible reasons. In most cases the model configuration or the assumed parameter values are not reasonable, so that some cells get dry during the iterations. Another reason might be that the convergence criteria, which are set by choosing **MODFLOW, Solver**, can't be reached during the maximum number of iteration steps.

- After a successful run check the results by using the graphical tools. Choose **Graphs, Drawdown-Time** or **Head-Time** from the **Tools** menu to compare the observed and the calculated data. Click on the Plot flag of the boreholes to specify for the diagram. To check the differences of the values for one borehole choose **Scatter Diagram**.

- To check the radius of influence or the cone of depression choose **Presentation** from the **Tools** menu, load the calculated drawdown with the **Results Extractor** and draw the contour map using a minimum value of 0.01m or 0.001m.

The minimum contour should not reach or be close to the fixed-head-boundaries.

Step 6 Assign data and parameters for inverse modelling

- For the estimation of the parameters the inverse model PEST is used. Therefore choose **PEST, Parameter List** from the **Models** menu and assign the structure of parameters and the options for the inverse modelling.

- Each parameter, which should be estimated with inverse modelling, must be assigned a specific parameter number, which must be the same as given in the **Parameters** menu in **Step 3**. When the value of the parameter changes due to different thickness of the layers, the parameter number must be changed too (see table 5.2.1).

- The value of an estimated parameter will only be adjusted if the **Active flag** is checked. Otherwise the user-specified cell value will be used for the simulation. A specific name for the parameter can be entered as a description.

Table 5.2.1: Example for assigning parameter numbers and initial values to a 2 layer model, representing an aquifer of 10 m thickness (consist of two geological units) with a vertical fracture parallel to a dyke (bold = tied parameters, italic = fixed parameters)

Layer		**Hydraulic Conductivity**		**Vertical Leakance**	
No.	Thickness	P No.	Value	P No.	Value
1	2 m	1	1.0E-04 m/sec	**5**	**2.5E-08 /sec**
2	8 m	2	1.0E-06 m/sec		
1 (fracture)	2 m	3	5.0E-04 m/sec	**6**	**1.0E-04 /sec**
2 (fracture)	8 m	3	5.0E-04 m/sec		
1 (dyke)	2 m	*4*	*1.0E-07 m/sec*	***7***	***2.0E-10 /sec***
2 (dyke)	8 m	*4*	*1.0E-07 m/sec*		

- For each parameter initial values for the first iterations (PARVAL1) and reasonable upper and lower bounds for the values (PARLBND, PARUBND) must be given in the **Parameters** tab. The initial values should be the same as the values given in **Step 3** and should result from the analysing of the hydraulic test with analytical methods as described above.

- To reduce the number of parameters, parameters should be tied to another, whenever it is possible. If a parameter is tied to another parameter (e.g. T of layer with 0.5m thickness and T of layer with 1m thickness in a homogenous aquifer), the initial values of both must show this ratio. The parameter transformation (PARTRANS) must be set to [*Tied*] and the parameter number of the 'parent' parameter must be given as PARTIED.

- Normally the parameter transformation (PARTRANS) for the parameters Transmissivity, Storativity and Leakance should be set to [*Log-transformed*]. If a parameter should not be changed during the inverse modelling as the parameters for the dyke, the parameter transformation (PARTRANS) must be set to [*Fixed*].

- The criteria for the optimisation process can be set in the **Control Data** table of **PEST, Parameter List**. NUMLAM, PHIRATSUF and PHIREDLAM are the criteria for moving to the next optimisation iteration, while PHIREDSTP and NPHISTP are the convergence criteria to stop the optimisation process. If these criteria can't be achieved the termination criteria NOPTMAX, NPHINORED, RELPARSTP and NRELPAR will stop the program. The default setting of the values is normally suitable for most problems.

- After setting all parameters for the inverse modelling, choose **PEST, Run** from the **Models** menu. PMWIN will generate the input files for MODFLOW and PEST. If necessary PMWIN or PEST can check the model data for consistency by checking [*Perform PESTCHEK prior to running PEST*] and [*Check the model data*].

Create for every run of the inverse modelling a new folder and copy all files from the last run into the new folder (using Windows Explorer). This helps to prove the input data and results for each run. If it is necessary, particular runs can be repeated or used for another optimisation process.

- After a successful run check the run record file PESTCTL.REC, which is saved in the same folder as the model and will be opened automatically with NOTEPAD when closing the DOS-window of the PEST run. The estimated parameter values are given as **optimisation result**. The quality of the results can be checked with the 95% confidence limits, the objective function and other statistical values.

- A graphical diagram should be used to visualize the comparison between calculated and observed data. Choose **Graphs, Drawdown-Time** or **Head-Time** from the **Tools** menu and click on the **Plot** flag to specify the boreholes for the diagram. To check the differences of the values for one borehole choose **Scatter Diagram**.

After each run check the run record file for results and confidence and produce output diagrams, as described below.

- The inverse modelling is successfully finished, when reasonable parameter values are obtained, which suits the observed data in the best possible way. The criteria are the visualized comparison of observed and calculated data and the lowest possible objective function (called phi) for the used set of observations.

CHAPTER 6

Conclusions

During the project period, hydraulic tests have been conducted in two sites, which are located at the campus of the University of the Free State and Meadhurst in the surrounding of Bloemfontein, respectively. These sites represent the main aquifer types in the Karoo. The Campus Test Site contains a horizontal bedding-plane fracture system and the Meadhurst Test Site includes a vertical fracture along a dyke.

The hydraulic test data have been analysed with both numerical and analytical methods. The three dimensional groundwater flow model MODFLOW from the U.S. Geological Survey (McDonald et al. 1996) and the simulation system PMWIN (Chiang and Kinzelbach, 2001) as well as the inverse model PEST (Doherty, 2000) have been used to analyse the hydraulic test data numerically. The results from the numerical models are compared with those from analytical methods. Four analytical methods have been used. They are Cooper Jacob I, Cooper Jacob II, Gringarten and Theis.

Estimating Aquifer Parameters with Analytical Models

Although the numerical models better describe the complex aquifer structures, it is obvious that the use of the numerical models require a certain level of training. However, the comparison between the results of analytical models and the numerical model shows a possibility to simplify the procedure of parameter estimation from hydraulic test data.

It is recommended to use the following suggestions to estimate the aquifer parameters with analytical models:

For aquifers with a single horizontal bedding-plane fracture:

- To estimate the **transmissivity of the matrix**, the Cooper-Jacob or Theis method can be used, when the assumptions for applying these methods are valid. That means the drawdown curve must show radial acting flow and there are no boundary effects.
- To estimate the **transmissivity of the fracture**, the drawdown-distance method (known as Cooper-Jacob II) can be used. At least 2 observation boreholes are required in addition to the abstraction borehole.
- To estimate the **storage coefficient of the fracture**, the Cooper-Jacob or Theis method can be used. It requires an observation borehole, which is intersecting the fracture far away from the abstraction borehole. The problem is that the definition of <u>‘far away’</u> is unclear.
- To estimate the **storage coefficient of the matrix:**
  1. The Cooper-Jacob or Theis method: Both methods require an observation borehole, which is intersecting the fracture close to the abstraction borehole. The problem is that the definition of <u>‘close’</u> is unclear. These methods can also be applied by using the effective borehole radius of the abstraction borehole itself.

The effective borehole radius must be calculated from the early data of the hydraulic test.

2. The Cooper-Jacob II methods: Observation data of at least two matrix piezometers are required.

- For the parameters of the matrix **(T, Kv and S)**, the Gringarten method can be used, but it is non-unique and difficult to fit the data without prior information. If the parameters T matrix, S matrix and half-length of the fracture are estimated with other analytical methods, it is possible to get a unique fit of the drawdown data.

In the case of a vertical fracture, situated on a dyke, the comparison of the results from the numerical model with the analytical methods, as described in section 3.3.2, shows the relationship between the different aquifer features. To use analytical methods for parameter estimating in a case of a vertical fracture is more complicated than for a horizontal fracture, because more than one aquifer system are involved.

- Applying the Cooper-Jacob or Theis method on the hydraulic test data from the abstraction borehole yields a geometric mean of the transmissivity of all aquifer systems.
- Applying the Cooper-Jacob or Theis method on the hydraulic test data from observation boreholes in the fracture yields the transmissivity value of the fracture. Due to its distance dependency, the storage coefficient of the fracture cannot be obtained.
- An analytical method for estimating the storage coefficient of the matrix could not be determined.

Limitation of Numerical Models for Estimating Parameters of Fractured Aquifers

The parameter estimation runs described in chapter 4 show that it is not possible to fit the drawdown curves in all piezometers simultaneously. The reasons for this phenomenon are given below. In most cases, these reasons also apply to analytical methods.

- The geometry of the aquifer is not well known and is simplified in the model (e.g., constant thickness over the whole model) and the real extent of the fracture is unknown.
- The drawdown behaviour in the abstraction borehole cannot be simulated correctly with the numerical model due to effects like well bore storage and well bore skin. The radius of the borehole and the cell size in the model are often different, therefore it is only possible to get the same trend of the curve, but not the same values.
- Secondary horizontal and vertical fractures, which intersect the main fracture, and the resulted semi-confined or unconfined conditions are not considered.
- Heterogeneity in both matrix and fracture systems is unknown and not considered. The unknown heterogeneity could even affect the hydraulic test data.

Recommendation for Conducting and Analyzing Hydraulic Test Data

The following points for conducting and analysing hydraulic test data in fractured aquifers are given as recommendation:

- The duration of a hydraulic test should be long enough to reach the radial acting flow phase, when analytical methods are used.
- The discharge rate must be chosen in a way that no fracture will be dewatered during the test. Neither with analytical nor with numerical models it is possible to analyse such a test.
- The discharge rate should be kept constant over the whole period of abstraction. Otherwise no analytical method should be used to estimate the parameter values unless the drawdown is corrected. When using a numerical model, every change in the discharge rate must be considered (in another stress period).
- The measurement of the drawdown must have accuracy of at least 1cm.
- The time intervals of measurement in the beginning of the test should be small, at least less than 1 minute (recommended 10 seconds).
- For estimating vertical hydraulic conductivity, piezometers with short wellscreen should be installed in different depths.
- Parameter r, i.e. the effective borehole radius or half-length of the fracture, must be calculated from early hydraulic test data.
- To estimate the storage coefficient of the aquifer with an analytical method, use the estimated parameter r as distance between abstraction and observation borehole.
- To estimate the storage coefficient of the aquifer in a more accurate way, piezometers in the matrix should be used and the hydraulic test data should be analysed with a numerical model as described in this report.
- Observation boreholes, used for the hydraulic test, should never intersect more than one reacting aquifer system to avoid a mix of observation. If a borehole intersects more than one reacting aquifer system the drawdown data shows a mix of drawdown resulting from different systems and it is difficult to use those data in a numerical or analytical model.

Details of conducting and analysing hydraulic tests in fractured aquifers are given in the "Manual on Pumping Test Analysis in Fractured-Rock Aquifers" (van Tonder et.al., 2001) submitted to the WRC in January 2001 as a final report.

CHAPTER 7

References

[1] Black, J.H. (1993) Hydrogeology of Fractured rocks – A question of uncertainty about geometry. In proceedings: Hydrogeology of Hard Rocks, XXIVth Congress, International Association of Hydrogeologists, Norway.

[2] Botha, J.F., Verwey, J.P., van der Voort, I., Vivier, J.J.P., Buys, J., Colliston, W.P. and Loock, J.C. (1998). Karoo Aquifers – Their Geology, Geometry and Physical Properties. Report to the Water Research Commision by the Institute for Groundwater Studies University of the Free State.- WRC Report No. 487/1/98, Pretoria

[3] Botha, J.F., van Wyk, B., Zhang, J. and van Tonder, G.J. (1999). *Groundwater pollution in the area for which the environmental section of the processing division is responsible*. Institute for Groundwater Studies, UOVS, Bloemfontein.

[4] Braune, E. (1996) Sustainable Water Resource Management – A groundwater perspective. Department of Water Affairs and Forestry, Private Bag X313, Pretoria.

[5] Chiang, W.-H. & Kinzelbach, W. (2001) *3D-Groundwater modelling with PMWIN*. Berlin, Heidelberg, New York: Springer

[6] Doherty J. (2000) *PEST – Model-independent parameter estimation. User's manual*. Watermark Computing. Australia

[7] Hammed, M.M. and Bedient, P.B. (1997) On the Performance of Computational Methods for the Assessment of Risk from Groundwater Contamination. *GROUND WATER*, **35**, 638 - 646.

[8] Midgley, D. C., Pitman, W.V. & Middleton, B. J. (1994) *Surface Water Resources of South Africa* 1990. Water Research Commission, Pretoria.

[9] National Water Act (1998). *Government Gazette*, 19182. Act 38, 26 August 1998. Pretoria, South Africa.

[10] Novakowski, K.S, Lapcevic, P., Bickerton, G., Voralek, J. Zanini, L. and Talbot, C. (1999) *The Development of a Conceptual Model for Contaminant Transport in the Dolostone Underlying Smithville, Ontario*. Department of Earth Sciences, Brook University, St. Catherines, ON, L2S 3A1.

[11] Olsson, O. (1992) Site characterization and validation – final report. Technical report of the Stripa Project No. 92 –22, Published by Swedish Nuclear Fuel and Waste Management Co. SKB, Stockholm.

[12] Reynders, A.G. (1997) *The second technical workshop on the development of groundwater quality management strategy for South Africa*. Midrand Protea Hotel, Midrand.

[13] Rosén, L. and Norberg, T. (1998*). Modelling of geological properties using Markov random fields*. Department of Geology, Chalmers University of Technology, Goeteborg.

[14] Rosen, L., Gustafson, G. (1996). Bayesian Markov Geostatistical Model for Estimation of hydrogeological properties. *GROUND WATER*, **34**.

[15] Rosén, L. (1995). *Estimation of hydrogeological properties in vulnerability and risk assessment.* Dissertation at the Department of Geology, Publ. A79, ISSN 1104-9839, Goeteborg.

[16] Rosenbaum, M.S., Rosen, L. and Gustafson, G. (1996). Probabilistic models for estimating lithology. *Engineering Geology*, **47**, 43 - 55.

[17] Schmelling, S.G. and Ross, R.R. (1989) *Contaminant transport in Fractured Media: Models for Decision Makers*. Reference no. EPA/540/4-89/004. EPA Superfund Ground Water Issue, Superfund Technology Support Centers for Ground Water, Robert S. Kerr Environmental Research Laboratory, Ada.

[18] Skivington, P. (1997) Risk Assessment for Water Quality Management. WRC project no. TT 90/97. Water Research Commission, PO Box 824, Pretoria.

[19] Van der Voort, I.(1995) *An investigation of the geometry of Karoo aquifers and the effect this has on their ability to yield water*. MSc thesis, University of the Orange Free State, Bloemfontein

[20] Van Tonder, G.J., Botha, J.F., Chiang, W.H., Kunstmann, H. and Xu, Y. (2001): *Estimation of the sustainable Yields of Boreholes in fractured Rock Formations*. Journal of Hydrology, 241(1-2)

[21] Van Tonder, G.J., Bardenhagen, I., Riemann, K., van Bosch, J., Dzanga, P. and Xu, Y. (2001). *Manual on Pumping Test Analysis in fractured-Rock Aquifers*. Final Report, WRC Project, Pretoria

[22] Van Wyk, B., Xu, Y., De Lange, F., Van Tonder, G. and Chiang, W.H. (1999) Draft Final Report: *Utilization of Tracer Experiments for the development of rural water supply management strategies for secondary aquifers*. Institute for Groundwater Studies, University of the Free State, Bloemfontein.

[23] Vegter, J.R. (1995) *An explanation of a set of National Groundwater Maps*. WRC report no. TT74/95. Water Research Commission.

Appendix

Appendix A Maps and Figures

- A.1. Locations of the Boreholes at Campus Test Site (after Botha et.al., 1998)
- A.2. Lithology of boreholes on the Campus Site (after Botha et al., 1998)
- A.3. Acoustic scan of borehole UO5 and UO23 at a depth of between 20 and 25 m below surface
- A.4(a) Borehole video of the fracture in borehole UO23 at a depth of between 21.0 – 21.2 m below surface
- A.4(b) Borehole video of the fracture zone in borehole UO5 showing a fracture zone thickness of about 200mm
- A.5. Position of boreholes, pitlatrines and septic tanks at Meadhurst test site

Appendix B Borehole Logs

- B.1 Borehole Logs Campus Test Site
- B.2 Borehole Fluid Logs, EC-Profiles Campus Test Site
- B.3 Borehole Logs Meadhurst Test Site

Appendix C Analysing of Hydraulic Tests

- C.1 Constant Rate Test UO26
- C.2 Multirate Test M1
- C.3 Constant Rate Test M1, at 1.4l/s
- C.4 Constant Rate Test M1, at 2l/s
- C.5 Constant Rate Test UO5, at 0.5l/s
- C.6 Constant Rate Test UO5, at 2l/s

Appendix D Data of Hydraulic Tests

- D.1 Constant Rate Test UO26
- D.2 Multirate Test M1
- D.3 Constant Rate Test M1, at 1.4l/s
- D.4 Constant Rate Test M1, at 2l/s
- D.5 Constant Rate Test UO5, at 0.5l/s
- D.6 Constant Rate Test UO5, at 2l/s

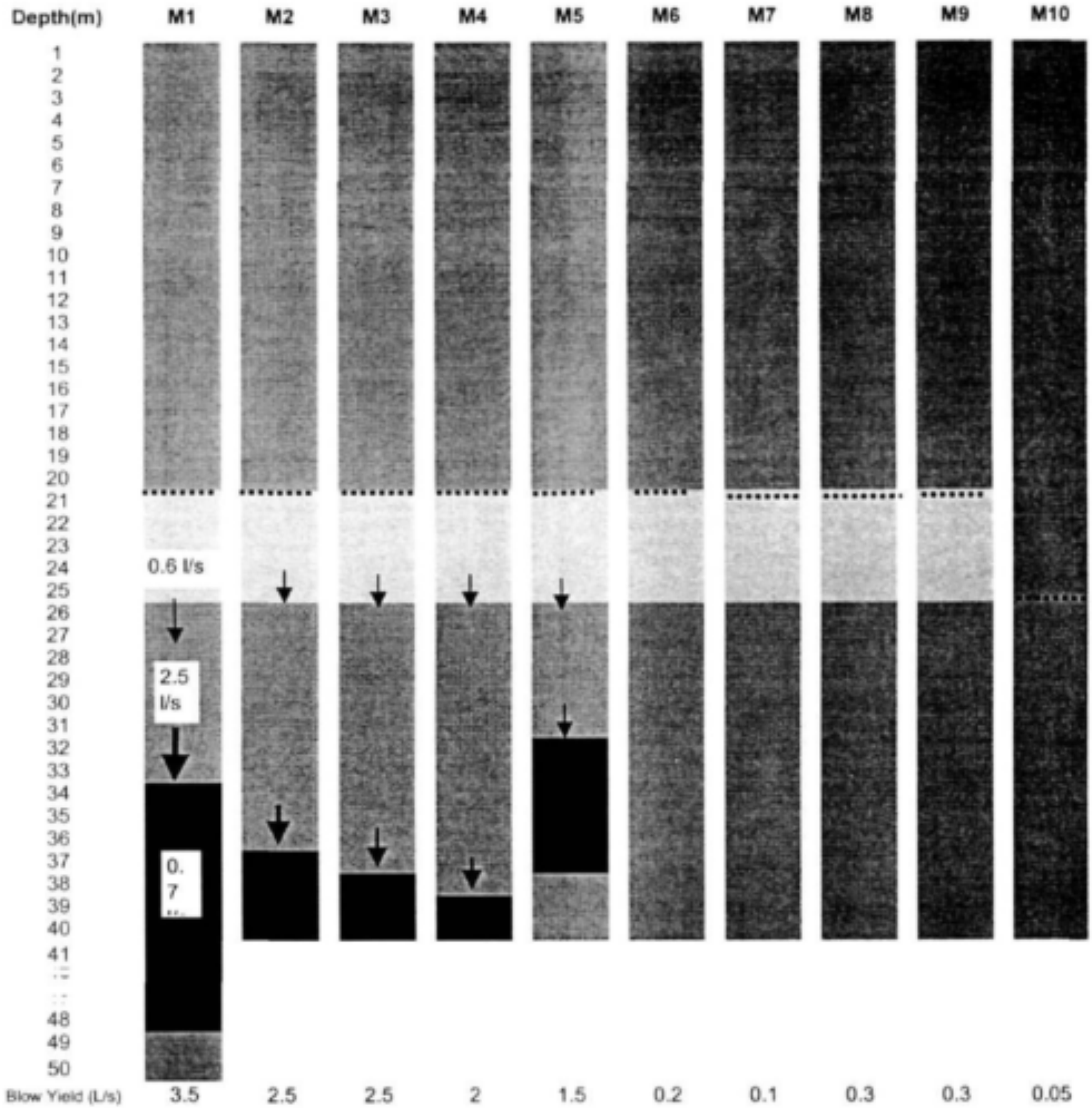
Appendix E Numerical Models

- E.1 Documentation of calibration runs, Campus Test Site
- E.2 Summary of reasonable calibration runs, Campus Test Site
- E.3 Documentation of calibration runs, Meadhurst Test Site
- E.4 Summary of results, Meadhurst Test Site

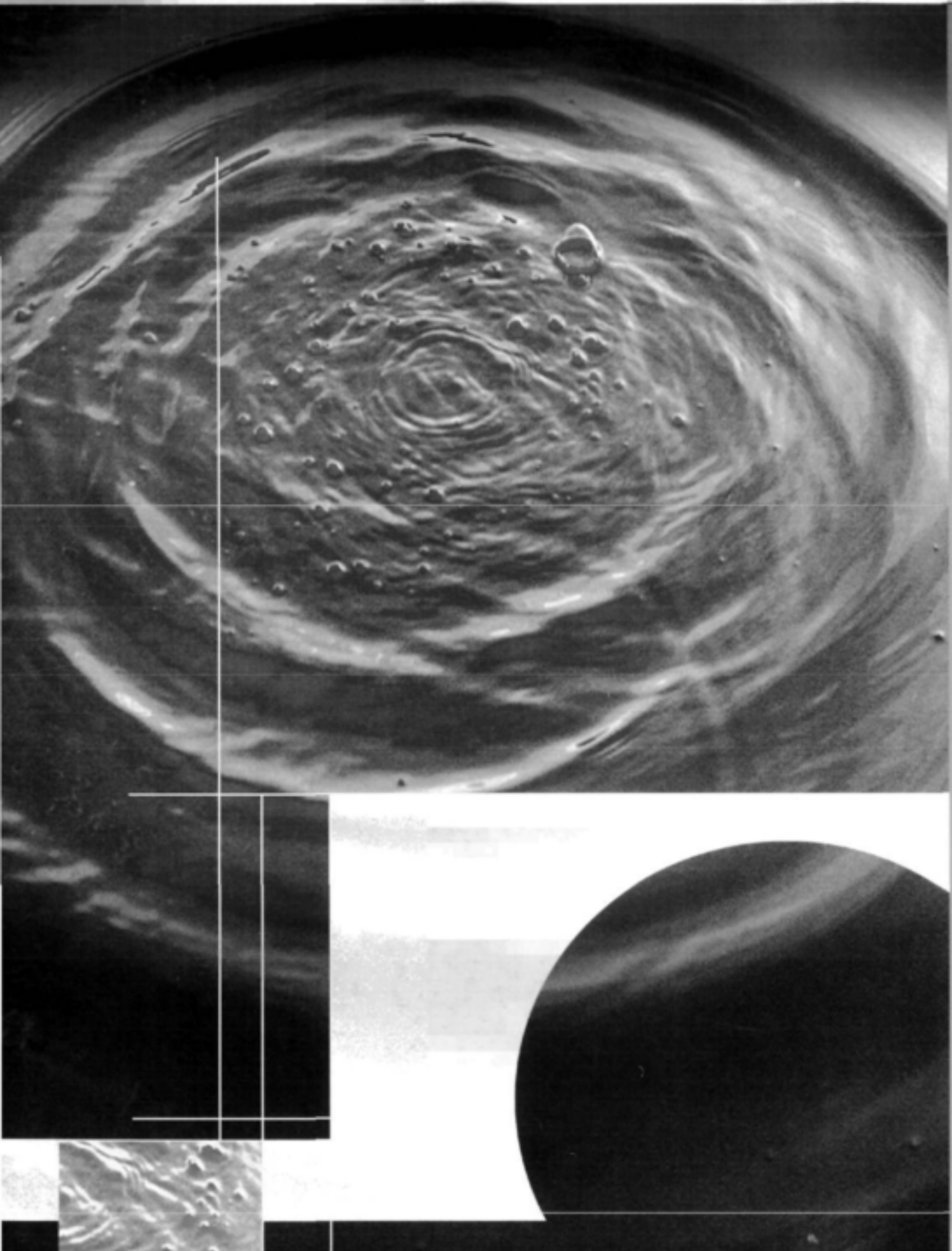
Appendix F Data Disc

- F.1 Data of hydraulic Tests, used for numerical modelling
- F.2 Pre-built model for horizontal bedding-plane fracture
- F.3 Pre-built model for vertical fracture, situated on a dyke

Appendix B.3 Borehole-Logs of Meadhurst Test Site



Solid casing from 0 - 20 m in all boreholes
Perforated casing in all boreholes from 20 - 25 m



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Appendix A: Figures and Maps

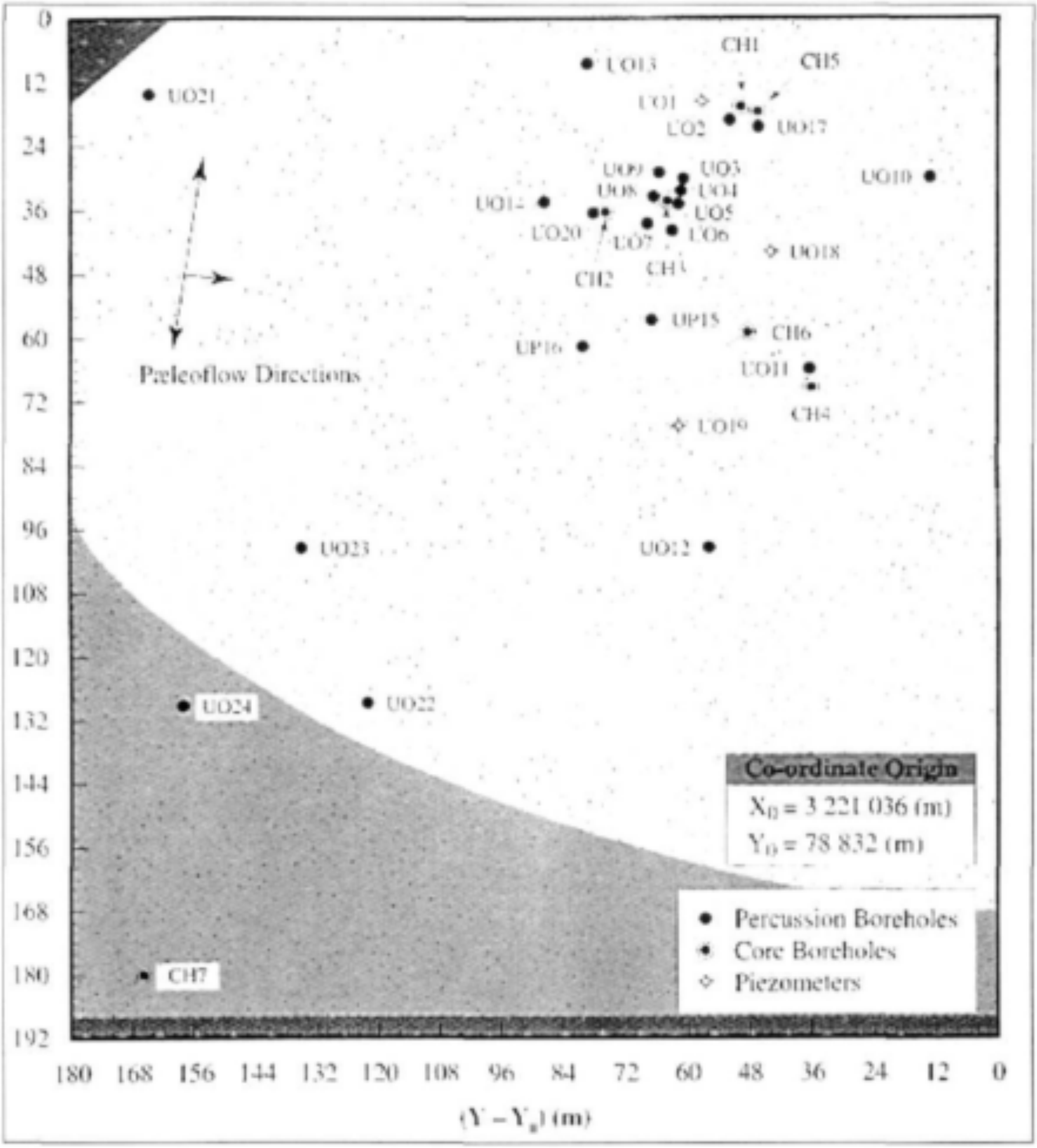


Fig. A.1. Locations of the Boreholes at Campus Test Site (after Botha *et.al.*, 1998)

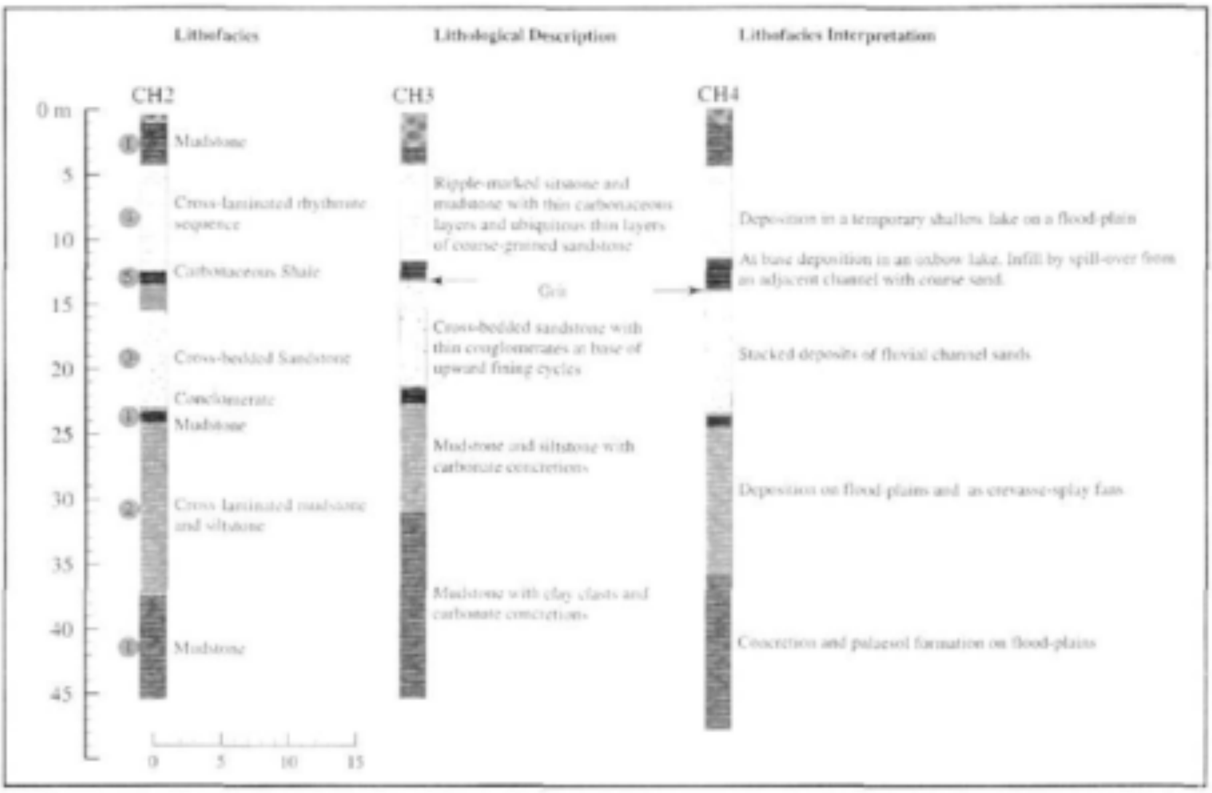


Fig. A.2. Lithology of boreholes on the Campus Site (after Botha *et al.*, 1998)

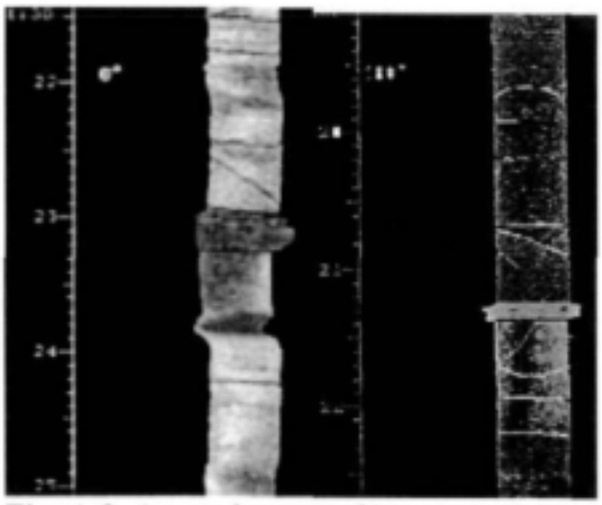


Fig. A.3. Acoustic scan of borehole UO5 and UO23 at a depth of between 20 and 25 m below surface

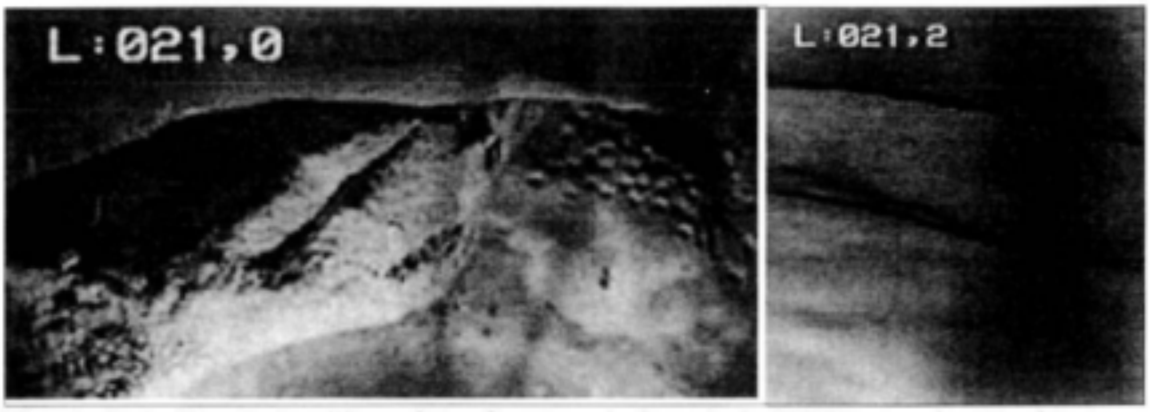


Fig. A.4(a). Borehole video of the fracture in borehole UO23 at a depth of between 21.0 – 21.2 m below surface

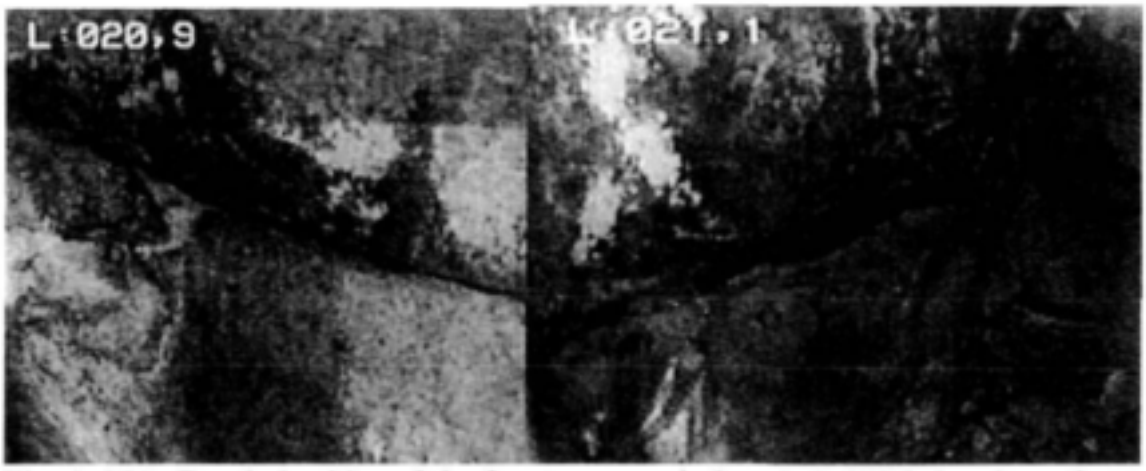


Fig. A.4(b). Borehole video of the fracture zone in borehole UO5 showing a fracture zone thickness of about 200mm.

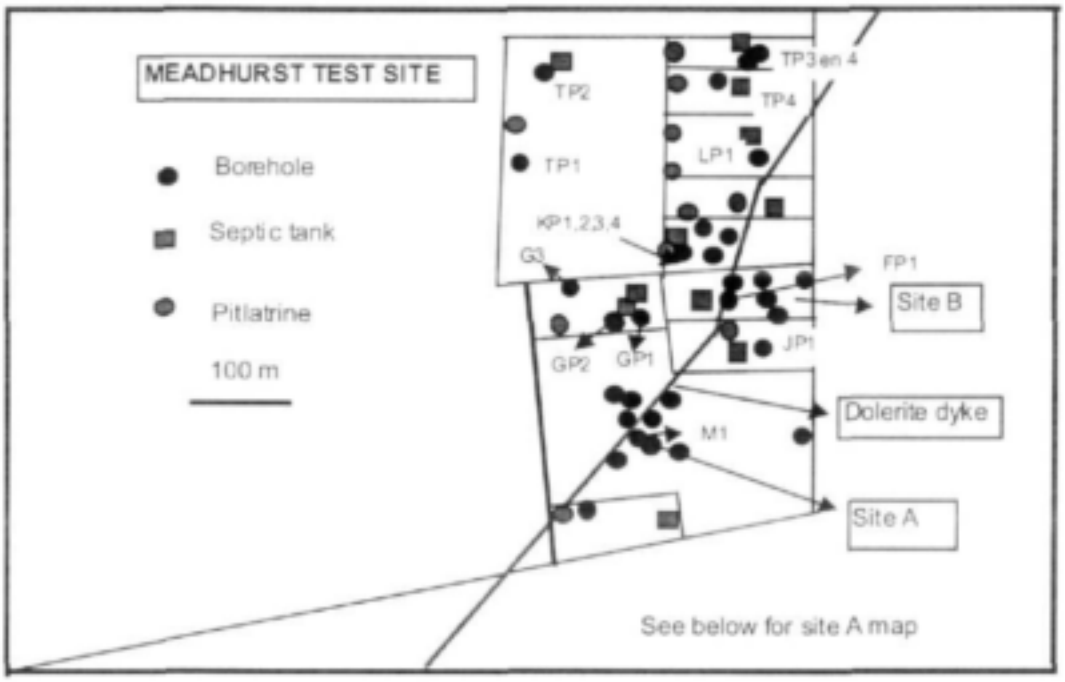


Fig. A.5. Position of boreholes, pitlatrines and septic tanks at Meadhurst test site

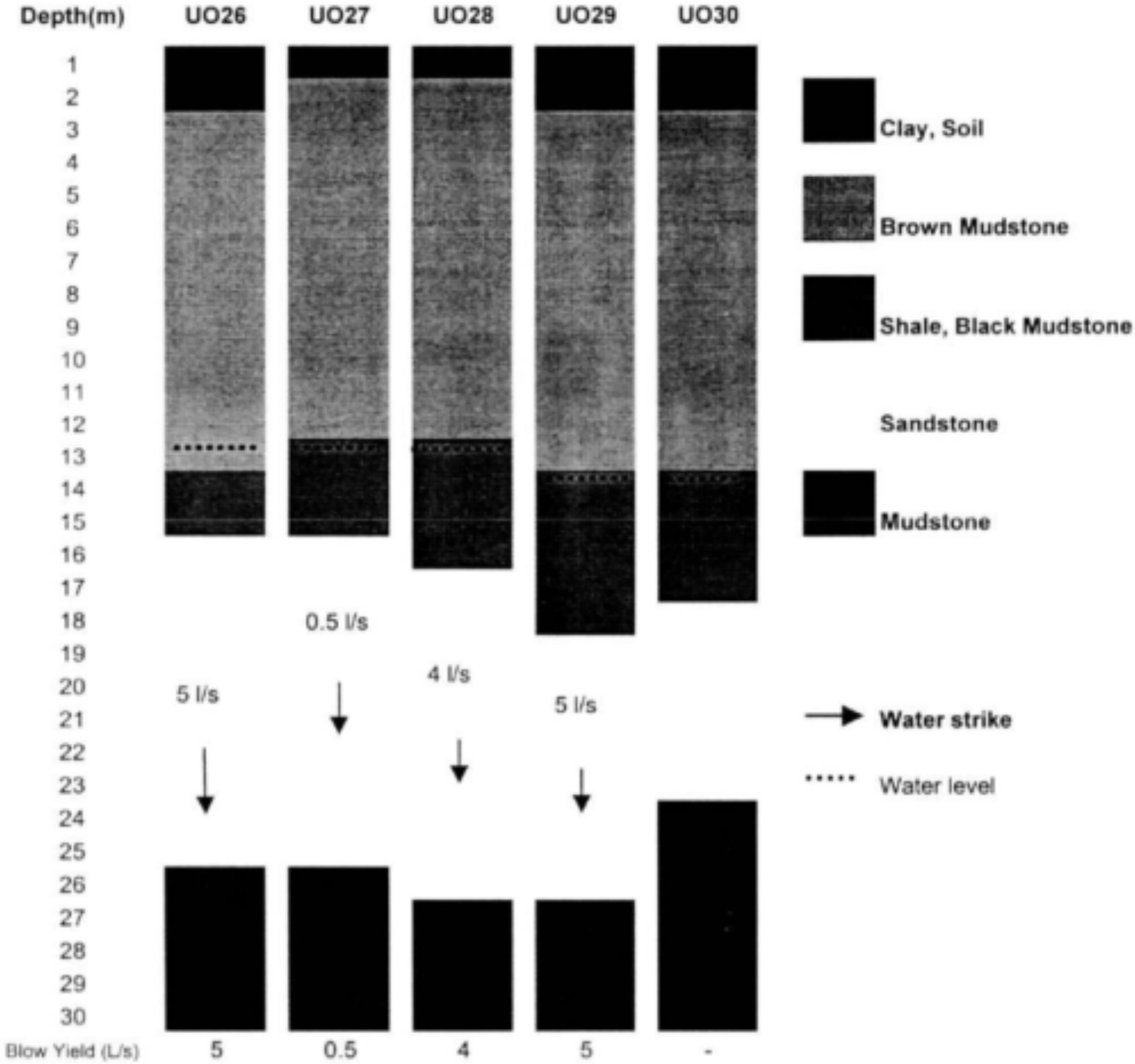
Appendix B: Borehole Logs

B.1 Borehole Logs Campus Test Site

B.2 Borehole Fluid Logs, EC-Profiles Campus Test Site

B.3 Borehole Logs Meadhurst Test Site

Appendix B.1 Borehole Logs Campus Test Site

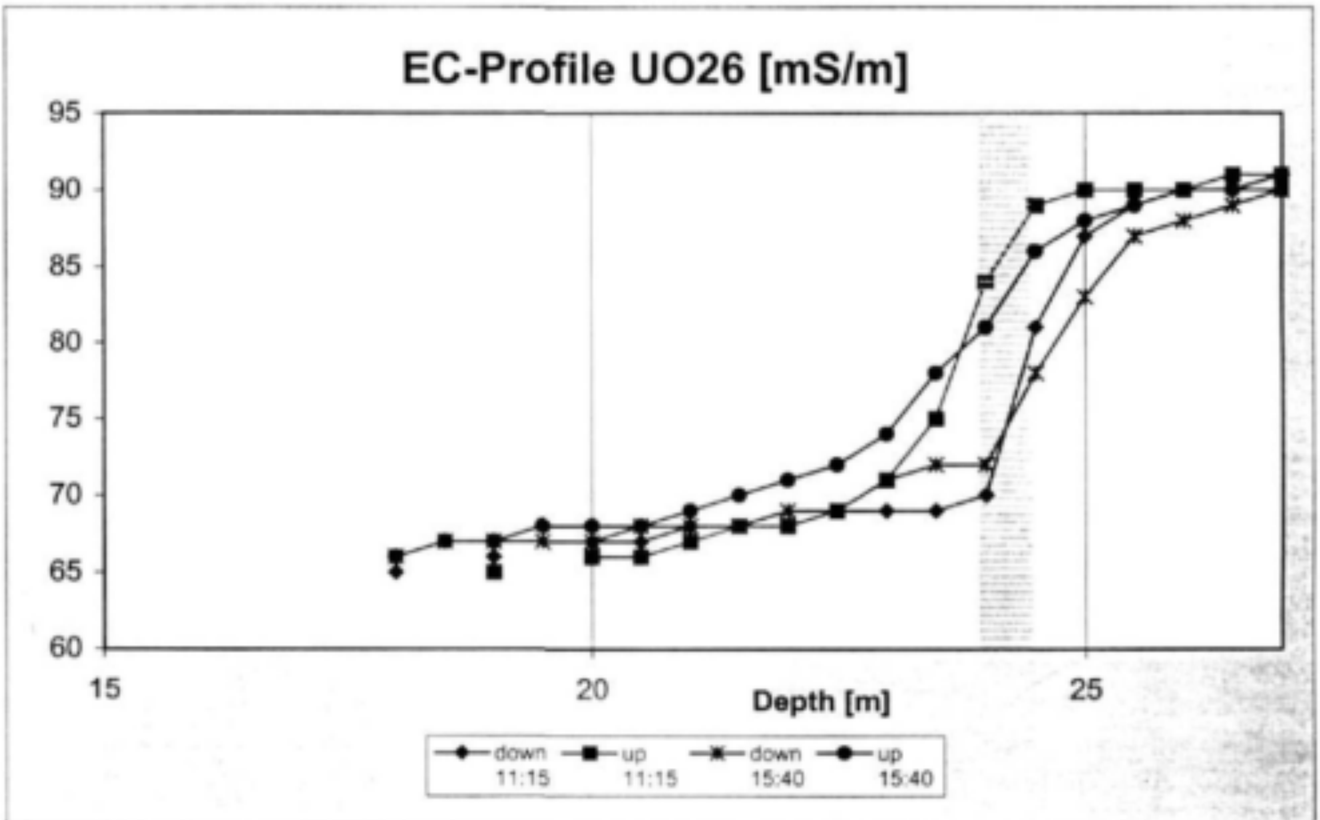


Appendix B.2

EC-Profiles of Borehole UO26 **Date: 22.05.2000**

Abstraction at UP16 with appr. 3 l/s	Start pumping: 10:20		Stop pumping: 14:05
Injection of 300g NaCl in UO7	Start injection: 10:30		Stop mixing: 11:30

Depth [m]	down 11:15	up 11:15	down 15:40	up 15:40	Estimated Position of Fracture
15					
16					
17					
18	65		66	66	
18.5			67	67	
19	66	65	67	67	
19.5			67	68	
20	67	66	67	68	
20.5	67	66	68	68	
21	68	67	68	69	
21.5	68	68	68	70	
22	68	68	69	71	
22.5	69	69	69	72	
23	69	71	71	74	
23.5	69	75	72	78	
24	70	84	72	81	about 24 m below surface
24.5	81	89	78	86	
25	87	90	83	88	
25.5	89	90	87	89	
26	90	90	88	90	
26.5	90	91	89	90	
27	91	91	90	90	



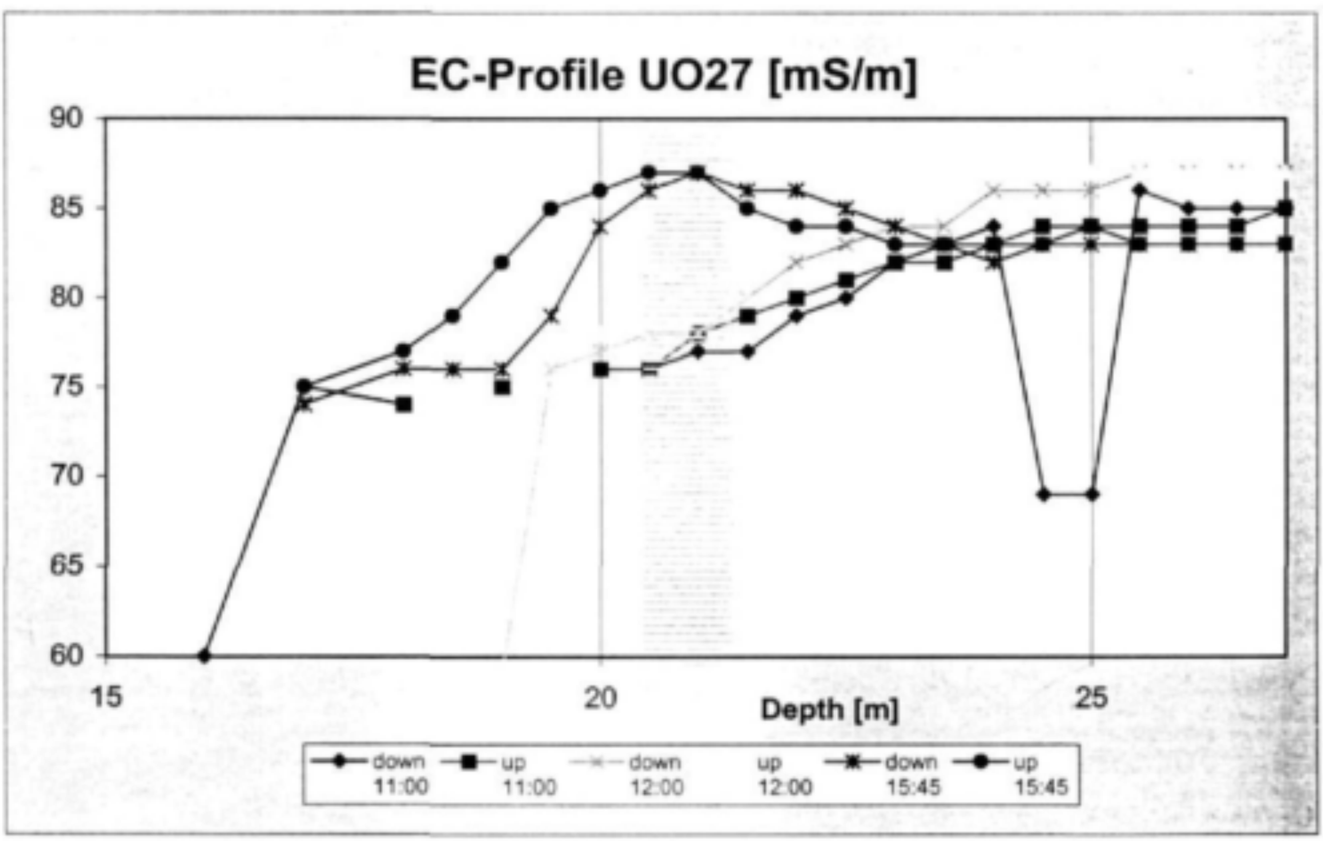
Appendix B.2

EC-Profiles of Borehole UO27

Date: **22.05.2000**

Abstraction at UP16 with appr. 3 l/s	Start pumping:	10:20	Stop pumping:	14:05
Injection of 300g NaCl in UO7	Start injection:	10:30	Stop mixing:	11:30

Depth [m]	down 11:00	up 11:00	down 12:00	up 12:00	down 15:45	up 15:45	Estimated Position of Fracture
15							
16	60						
17	75				74	75	
18	74	74			76	77	
18.5					76	79	
19	75	75	59	76	76	82	
19.5			76	77	79	85	
20	76	76	77	78	84	86	
20.5	76	76	78	79	86	87	
21	77	78	78	81	87	87	about 21 m below surface
21.5	77	79	80	82	86	85	
22	79	80	82	84	86	84	
22.5	80	81	83	85	85	84	
23	82	82	84	86	84	83	
23.5	83	82	84	86	83	83	
24	84	83	86	87	82	83	
24.5	69	84	86	87	83	83	
25	69	84	86	87	83	84	
25.5	86	84	87	87	83	83	
26	85	84	87	87	83	83	
26.5	85	84	87	87	83	83	
27	85	85	87	87	83	83	



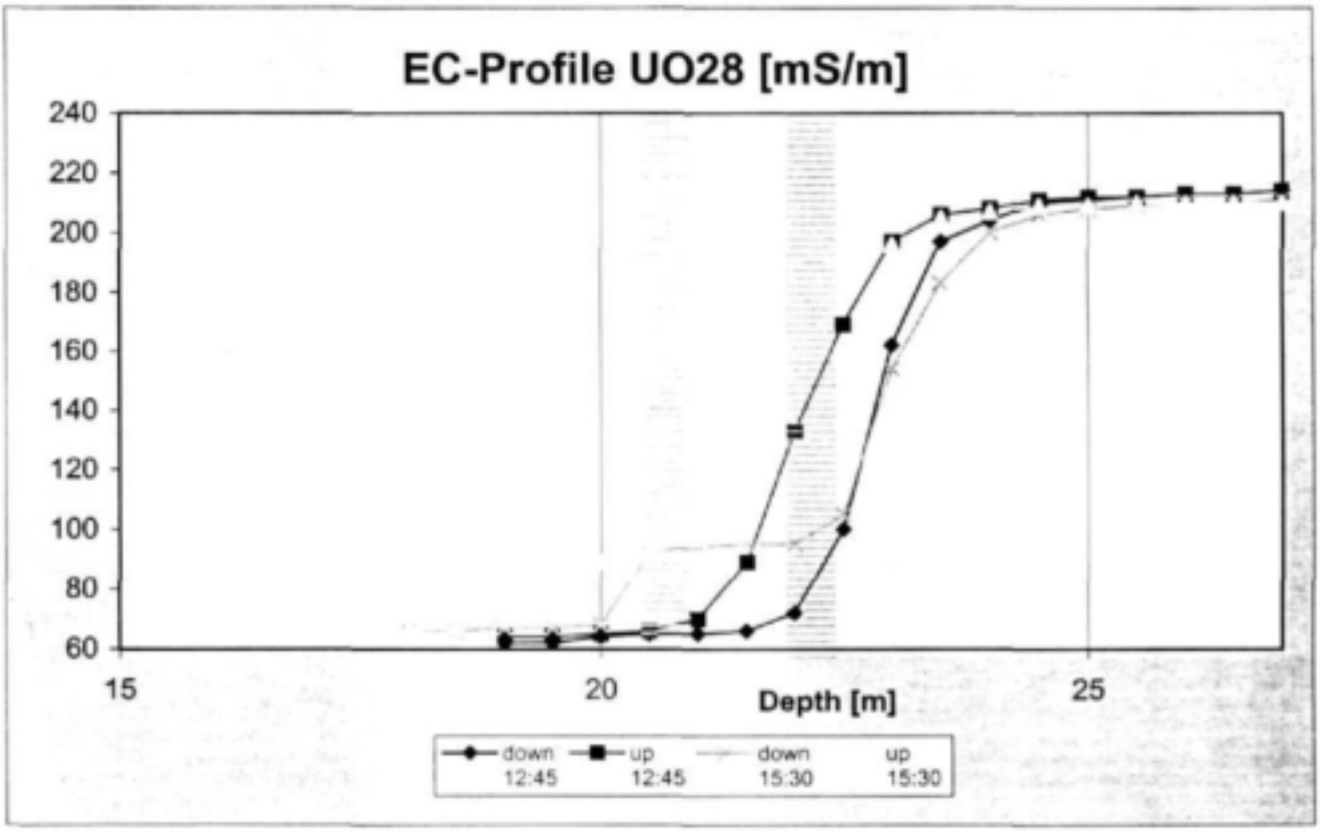
Appendix B.2

EC-Profiles of Borehole UO28

Date: **22.05.2000**

Abstraction at UP16 with appr. 3 l/s	Start pumping: 10:20	Stop pumping:	14:05
Injection of 350g NaCl in UO14	Start injection: 11:55	Stop mixing:	13:00

Depth [m]	down 12:45	up 12:45	down 15:30	up 15:30	Estimated Position of Fracture
15					
16					
17					
18			66	66	
18.5			66	68	
19	62	64	67	70	
19.5	62	64	67	77	
20	64	65	68	89	
20.5	65	66	92	93	about 20.5 m below surface
21	65	70	94	97	
21.5	66	89	95	102	
22	72	133	95	152	about 22 m below surface
22.5	100	169	105	186	
23	162	197	154	196	
23.5	197	206	183	205	
24	204	208	200	207	
24.5	210	211	206	209	
25	211	212	208	209	
25.5	212	212	209	210	
26	213	213	210	210	
26.5	213	213	210	210	
27	214	214	211	210	

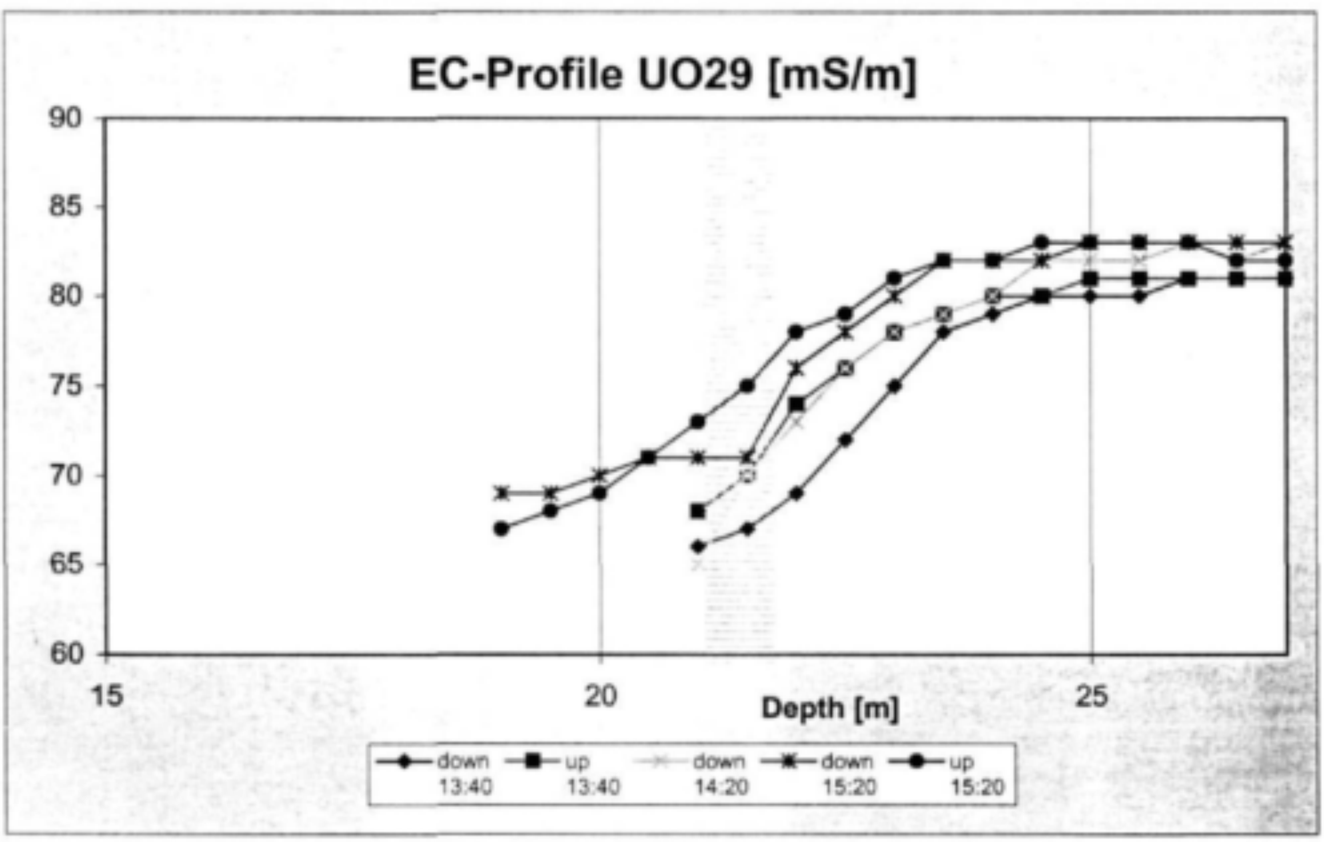


Appendix B.2

EC-Profiles of Borehole UO29 **Date: 22.05.2000**

Abstraction at UP16 with appr. 3 l/s	Start pumping: 10:20	Stop pumping:	14:05
Injection of 350g NaCl in UO23	Start injection: 13:10	Stop mixing:	14:30

Depth [m]	down 13:40	up 13:40	down 14:20	down 15:20	up 15:20	Estimated Position of Fracture
15						
16						
17						
18						
18.5						
19				69	67	
19.5				69	68	
20				70	69	
20.5				71	71	
21	66	68	65	71	73	**about 21 m below surface**
21.5	67	70	70	71	75	
22	69	74	73	76	78	
22.5	72	76	76	78	79	
23	75	78	78	80	81	
23.5	78	79	79	82	82	
24	79	80	80	82	82	
24.5	80	80	82	82	83	
25	80	81	82	83	83	
25.5	80	81	82	83	83	
26	81	81	83	83	83	
26.5	81	81	82	83	82	
27	81	81	83	83	82	

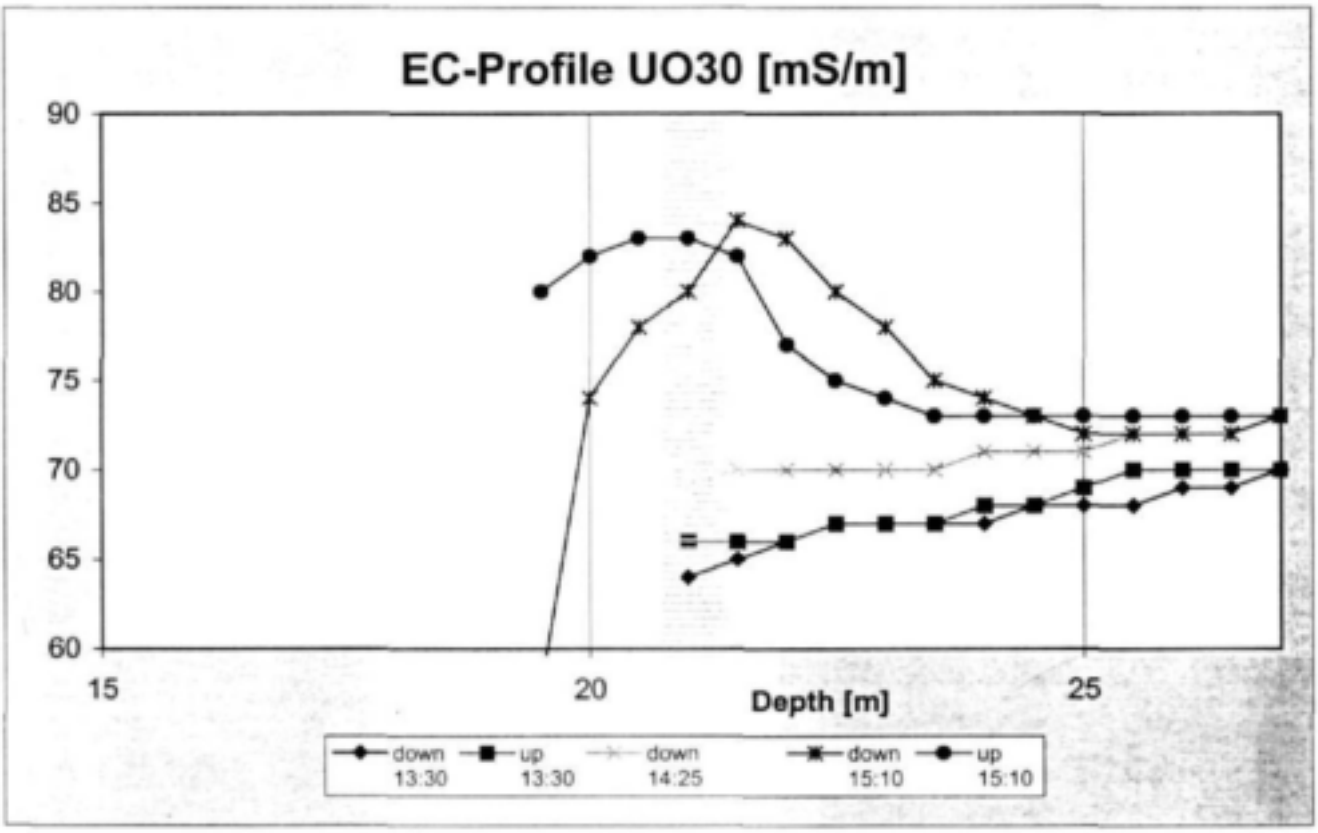


Appendix B.2

EC-Profiles of Borehole UO30 **Date:** **22.05.2000**

Abstraction at UP16 with appr. 3 l/s	Start pumping: 10:20	Stop pumping:	14:05
Injection of 350g NaCl in UO23	Start injection: 13:10	Stop mixing:	14:30

Depth [m]	down 13:30	up 13:30	down 14:25	down 15:10	up 15:10	Estimated Position of Fracture
15						
16						
17						
18						
18.5						
19						
19.5				58	80	
20				74	82	
20.5				78	83	
21	64	66	69	80	83	**about 21 m below surface**
21.5	65	66	70	84	82	
22	66	66	70	83	77	
22.5	67	67	70	80	75	
23	67	67	70	78	74	
23.5	67	67	70	75	73	
24	67	68	71	74	73	
24.5	68	68	71	73	73	
25	68	69	71	72	73	
25.5	68	70	72	72	73	
26	69	70	72	72	73	
26.5	69	70	72	72	73	
27	70	70	73	73	73	



Appendix C: Analyzing of Hydraulic Tests

C.1 Constant Rate Test UO26, Campus Test Site
Aquifer Parameter Estimation with the methods Cooper-Jacob, Theis and Cooper-Jacob II for the Boreholes UO26, UO27, UO28 and UO29

C.2 Multirate Test M1, Meadhurst Test Site

C.3 Constant Rate Test M1, Meadhurst Test Site (at 1.4l/s)
Aquifer Parameter Estimation with the methods Cooper-Jacob, Theis and Cooper-Jacob II for the Boreholes M1, M2, M3, M5 and M6

C.4 Constant Rate Test M1, Meadhurst Test Site (at 2l/s)
Aquifer Parameter Estimation with the methods Cooper-Jacob and Theis for the Borehole M1

C.5 Constant Rate Test UO5 (at 0.5 l/s), Campus Test Site
Aquifer Parameter Estimation with the methods Cooper-Jacob and Theis for the Boreholes UO5, UO23, UO23a, UO23b, UO27, UO27a, UO27b, UO28, UO28a, UO28b, UO29, UO29a and UO29b; and with Cooper-Jacob II for fracture-piezometer, matrix-piezometer above and matrix-piezometer below the fracture

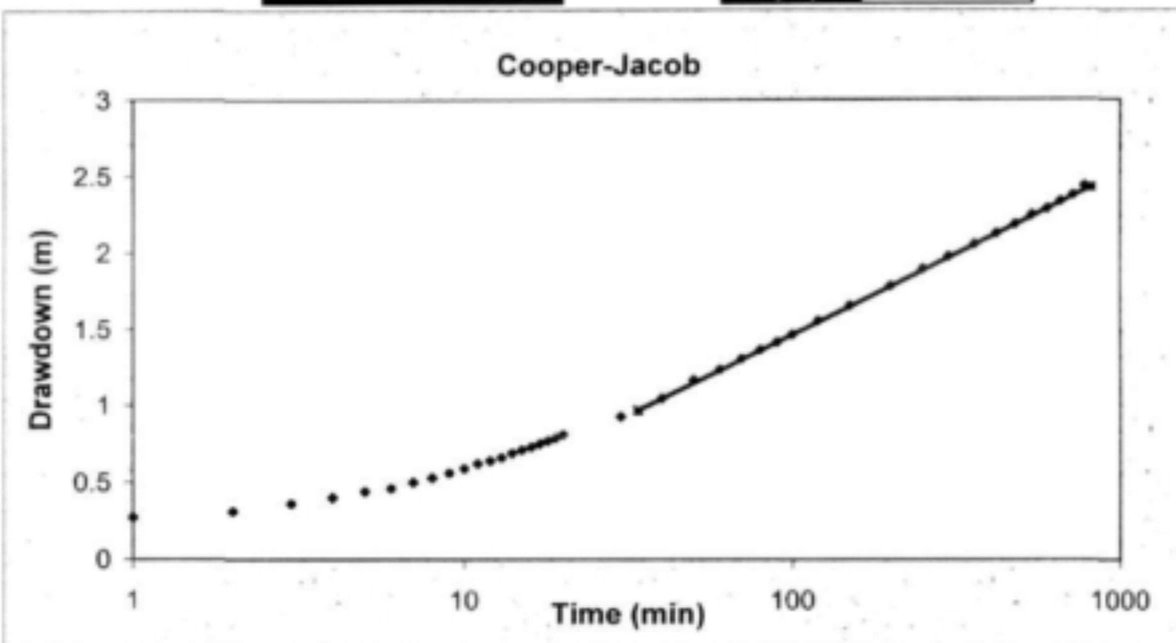
C.6 Constant Rate Test UO5 (at 2.0 l/s), Campus Test Site
Aquifer Parameter Estimation with the methods Cooper-Jacob and Theis for the Boreholes UO5, UO23 and UO27; and with Cooper-Jacob II for fracture-piezometer, matrix-piezometer above and matrix-piezometer below the fracture

Appendix C.1

Cooper-Jacob method

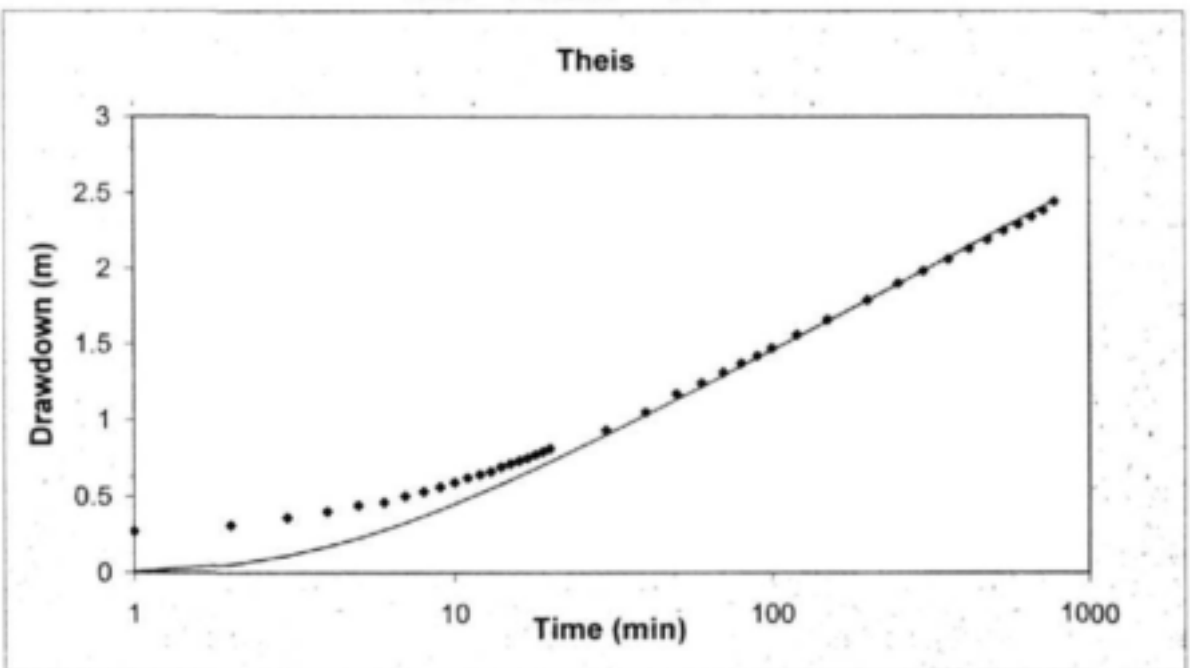
Constant Rate Test UO 26, Abstraction BH

$T (m^2/d)$ =	10.6	r_e (m)=	49.70
S =	2.75E-05	Q (l/s) =	0.71



Theis

T (m2/d)	S	r
10	3.30E-05	49.70

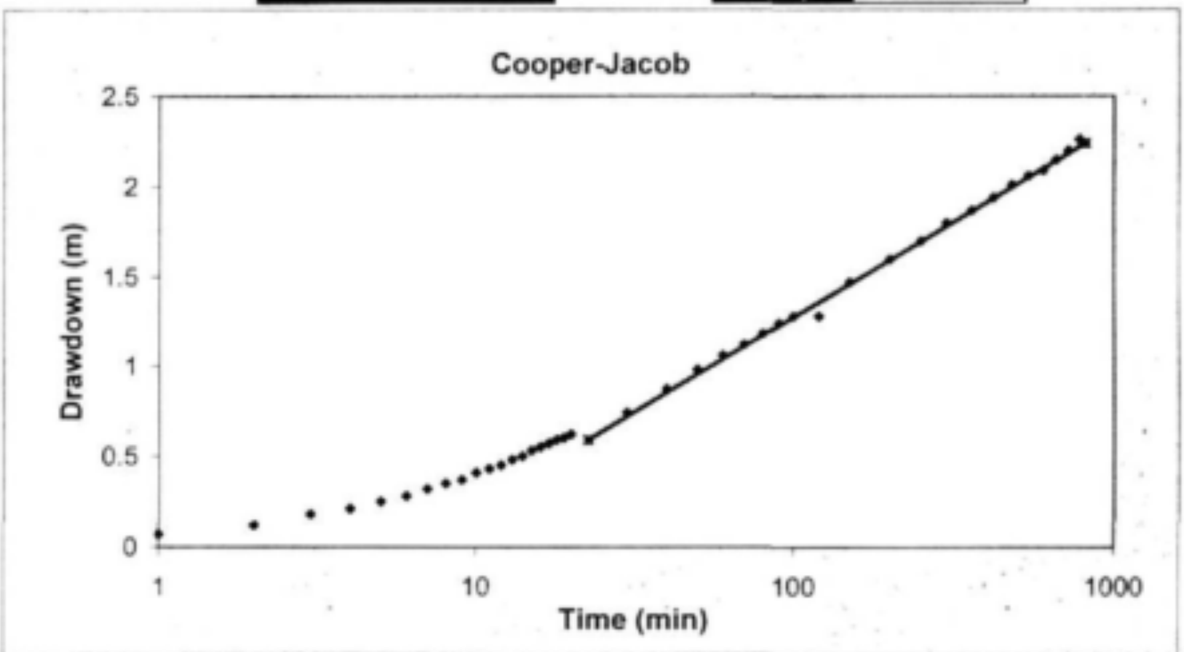


Appendix C.1

Cooper-Jacob method

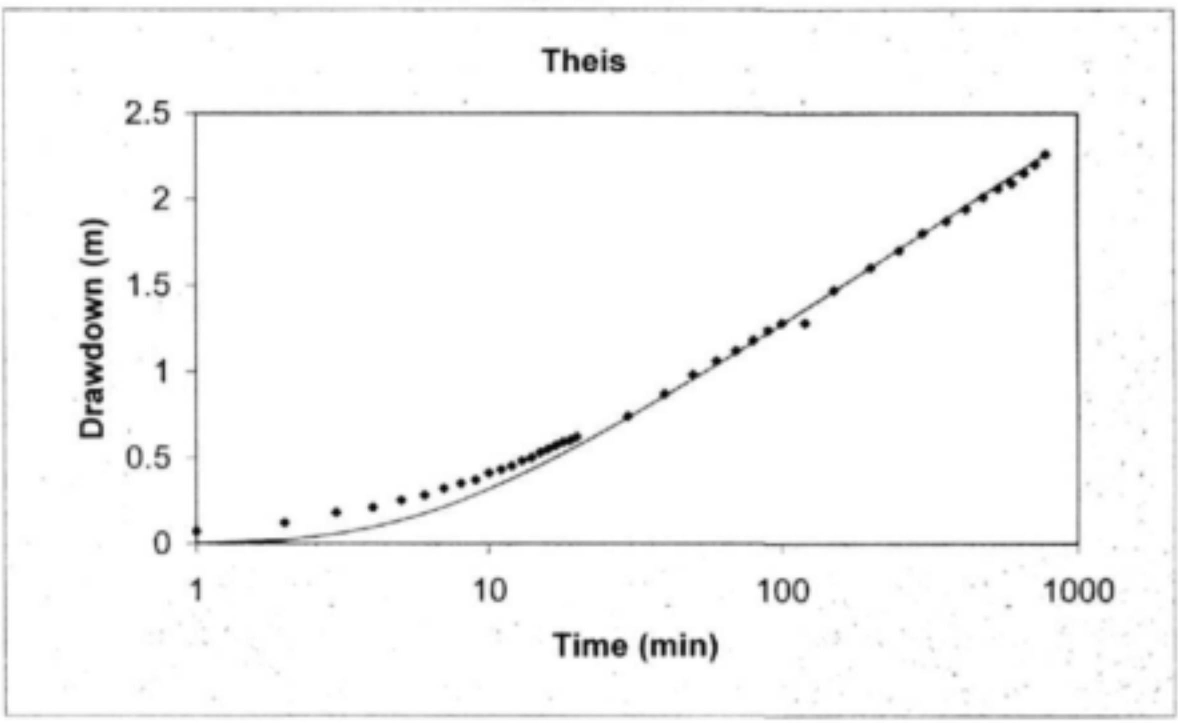
Constant Rate Test UO 26, Observ. BH UO27

$T (m^2/d)$ =	10.6	r_e (m)=	7.00	7
S =	2.13E-03	Q (l/s) =	0.71	



Theis

T (m2/d)	S	r
10	2.45E-03	7.00

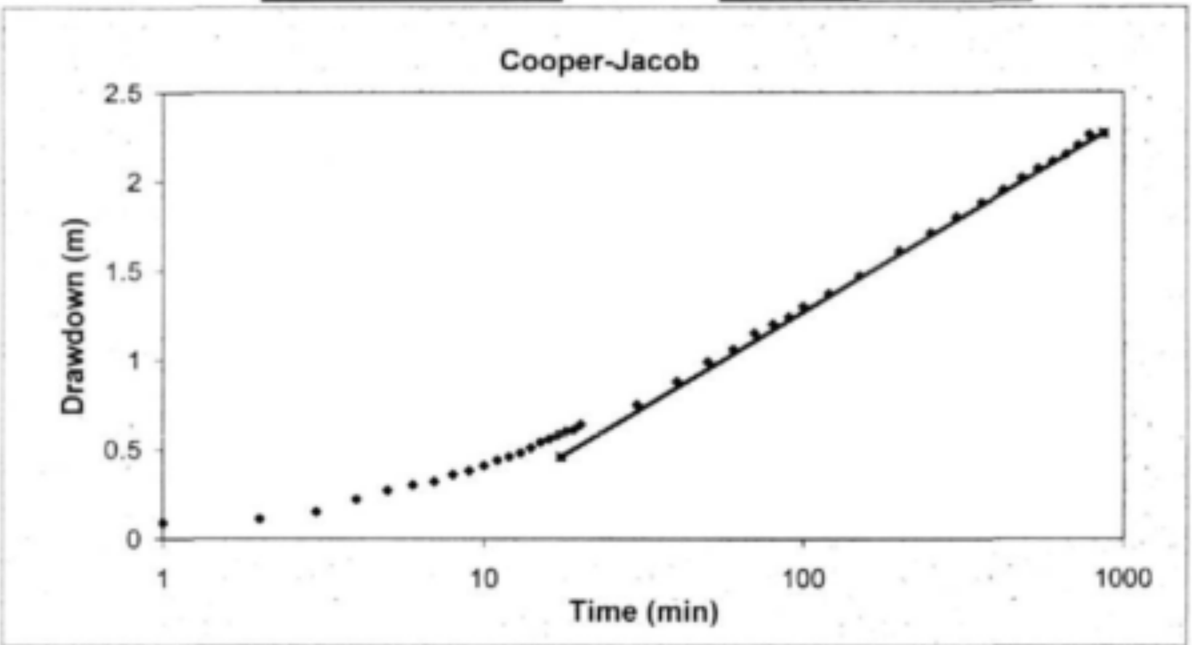


Appendix C.1

Cooper-Jacob method

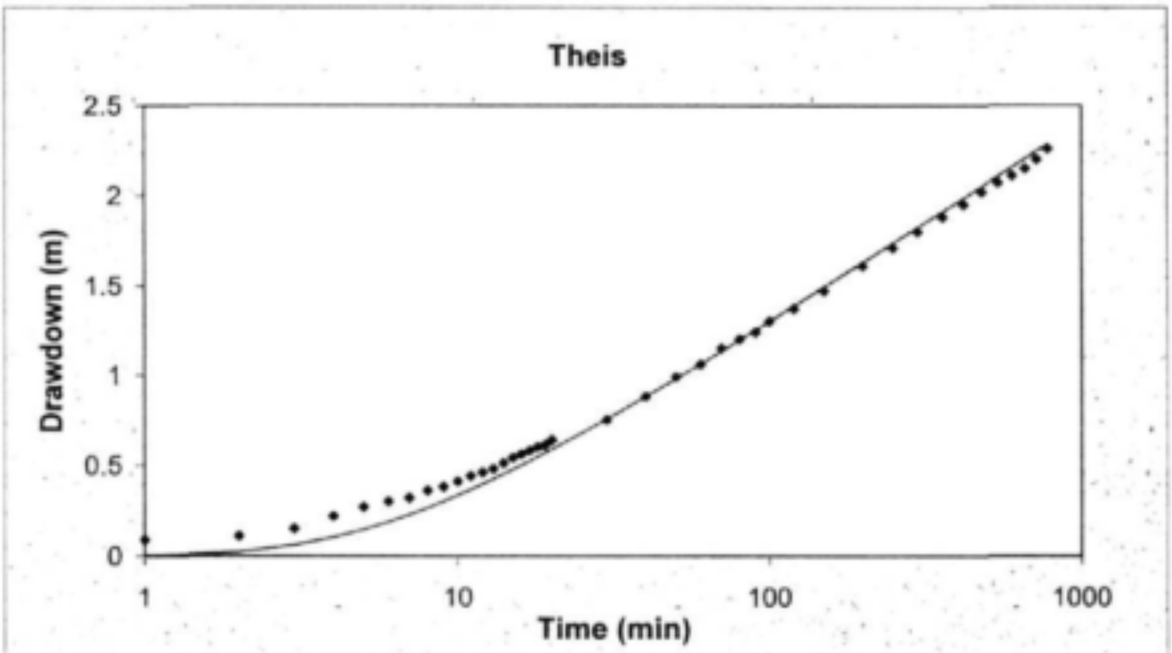
Constant Rate Test UO26, Observ. BH UO 28

$T(m^2/d)$ =	10.5	r_e (m)=	34.95 →	14
S =	5.41E-04	Q (l/s) =	0.71	



Theis

T (m2/d)	S	r
10	5.80E-04	14.00

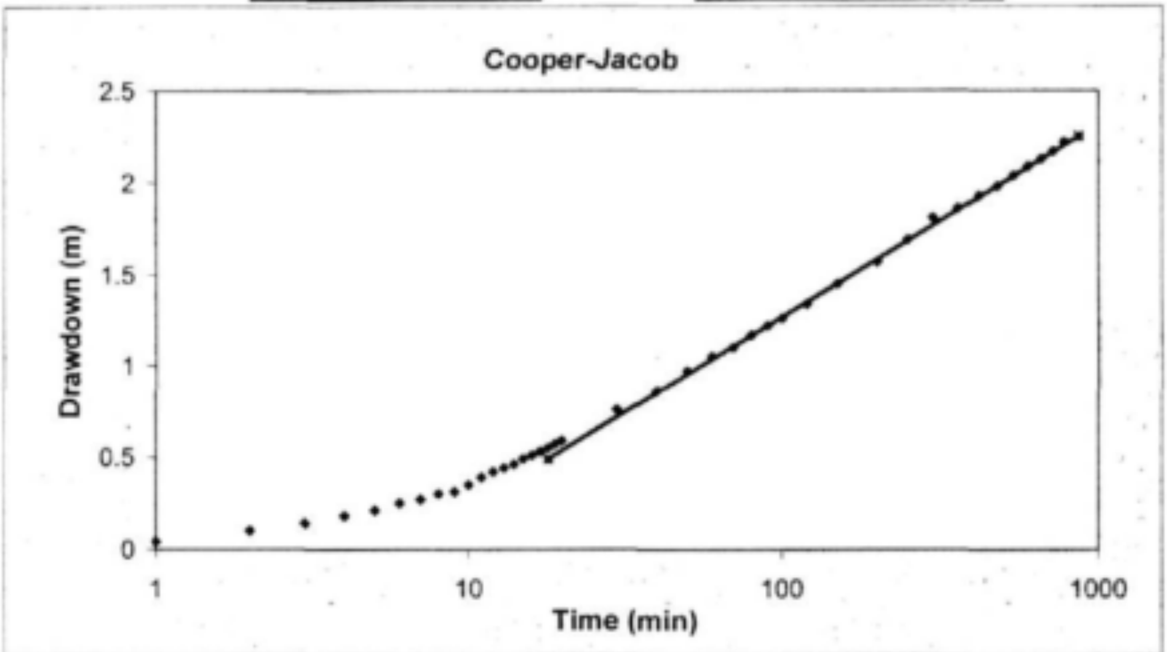


Appendix C.1

Cooper-Jacob method

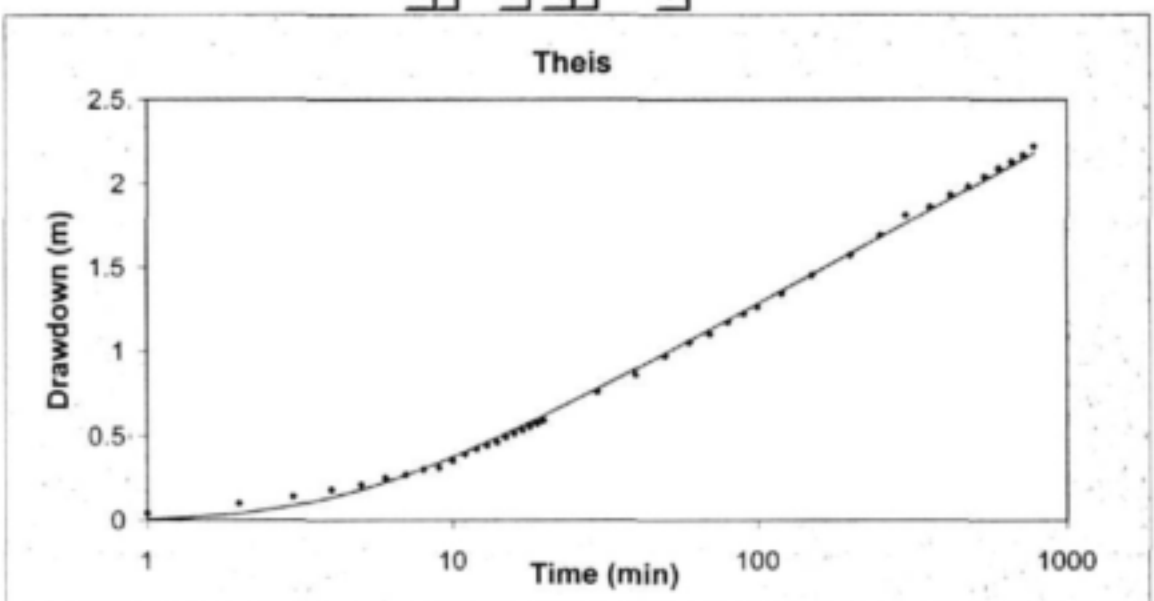
Constant Rate Test UO26, Observ. BH UO 29

$T(m^2/d)$ =	10.7	r_e (m)=	25.26 →	34
S =	8.92E-05	Q (l/s) =	0.71	



Theis

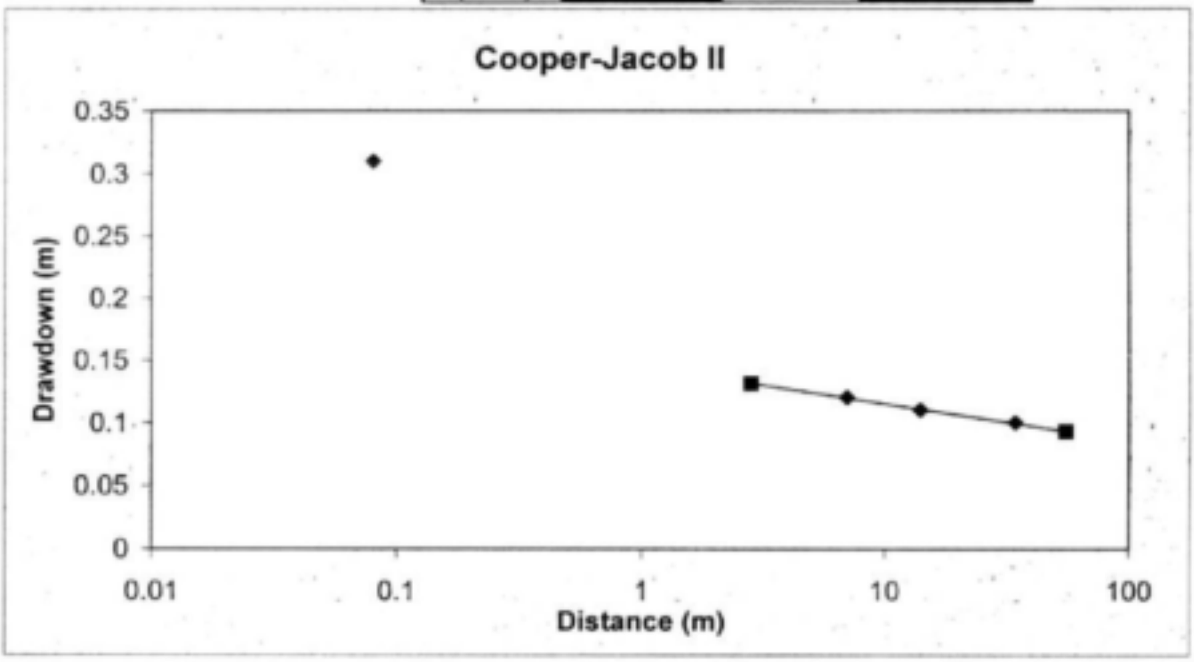
T (m2/d)	S	r
11	8.60E-05	34.00



Appendix C.1

Cooper-Jacob 2: Distance drawdown

	UO26	UO27	UO28	UO29		
Distance r (m)	0.08	7	14	34		
Drawdown (m)	0.31	0.12	0.11	0.1		
Time (minutes)	2					
		T (m^2/d) =	754.74	S	5.87E-07	



Appendix C.2

Multirate Test Meadhurst M1, Abtraction BH

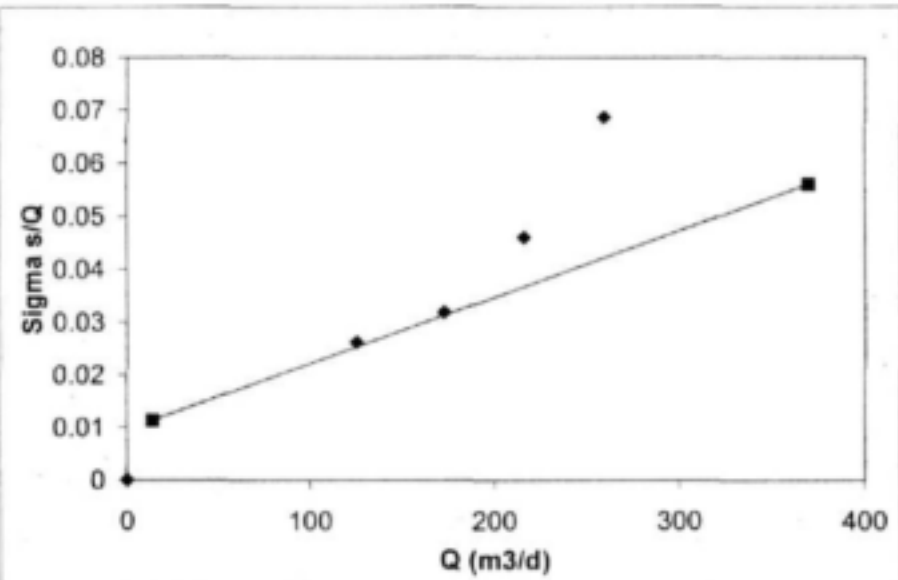
STEP DRAWDOWN AND MULTIRATE ANALYSIS

Enter field step test data at bottom of sheet

☐ Step drawdown ☑ Multirate

	Q (l/s)	Q (m^3/d)	s_i (m)	Sigma s_i	Sigma s_i/Q_i
Step 1	1.45	125.28	3.28	3.28	0.02618135
Step 2	2	172.8	5.5	5.5	0.0318287
Step 3	2.5	216	9.94	9.94	0.04601852
Step 4	3	259.2	17.78	17.78	0.06859568
Step 5		0			0
Step 6		0			0
Step 7		0			0

B =	9.5E-03	d/m^2
C =	1.3E-04	d^2/m^5



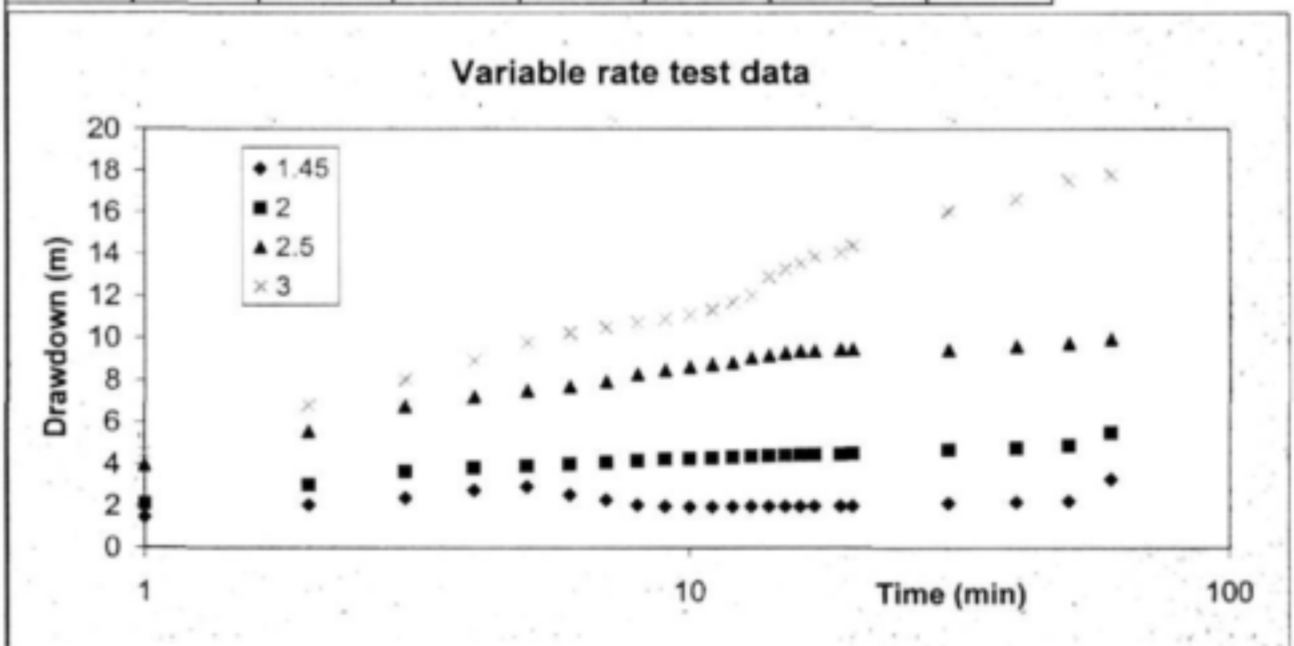
Q (l/s)	Well effiency(%)
1.45	38
2	31
2.5	26
3	23

Appendix C.2

Multirate Test Meadhurst M1, Abtraction BH

Step test data

	Step1	Step1	Step3	Step4	Step5	Step6	Step7
Q (l/s) =	1.45	2	2.5	3			
t(min)	s (m)	s (m)	s (m)	s (m)	s (m)	s (m)	s (m)
1	1.46	2.11	3.96	4.53			
2	2.05	3.02	5.55	6.8			
3	2.37	3.65	6.75	8.03			
4	2.75	3.83	7.2	8.94			
5	2.91	3.91	7.5	9.78			
6	2.53	3.99	7.7	10.23			
7	2.28	4.09	7.93	10.48			
8	2.04	4.17	8.28	10.74			
9	1.98	4.24	8.47	10.87			
10	1.95	4.25	8.62	11.07			
11	1.95	4.29	8.75	11.32			
12	1.96	4.33	8.82	11.68			
13	1.97	4.37	9.05	12			
14	1.98	4.39	9.16	12.88			
15	1.98	4.42	9.28	13.25			
16	1.98	4.44	9.36	13.53			
17	1.99	4.46	9.38	13.85			
19	1.99	4.47	9.44	14.01			
20	1.99	4.5	9.45	14.38			
30	2.15	4.7	9.44	16.03			
40	2.19	4.78	9.61	16.62			
50	2.24	4.9	9.75	17.51			
60	3.28	5.5	9.94	17.78			

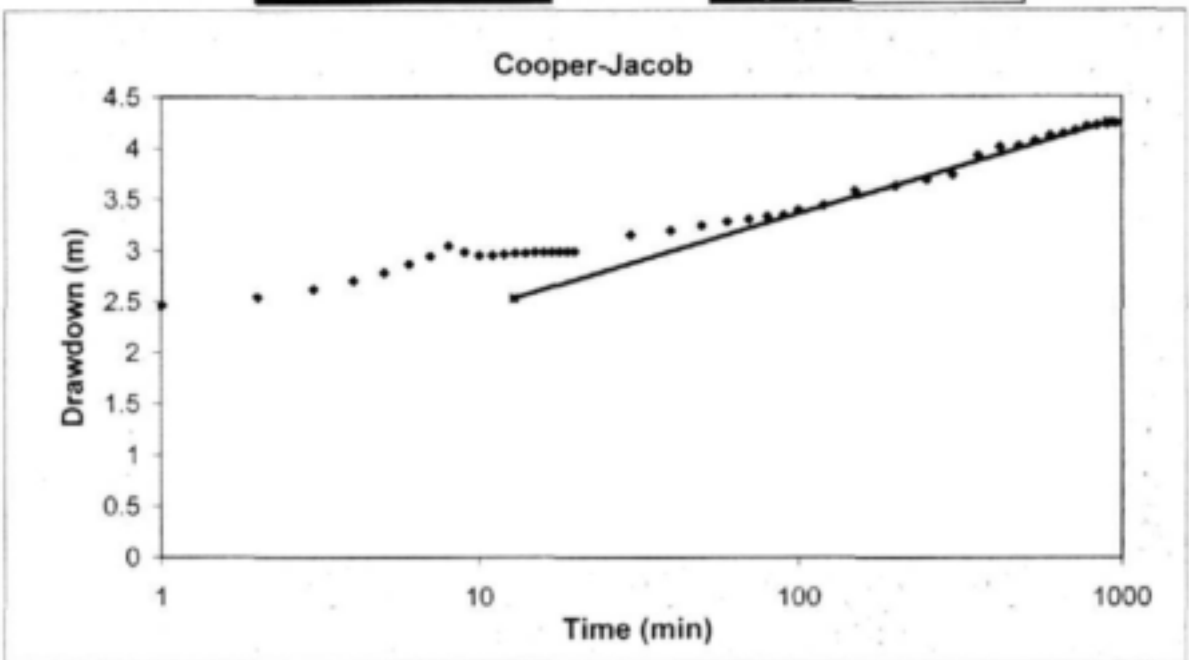


Appendix C.3

Cooper-Jacob method

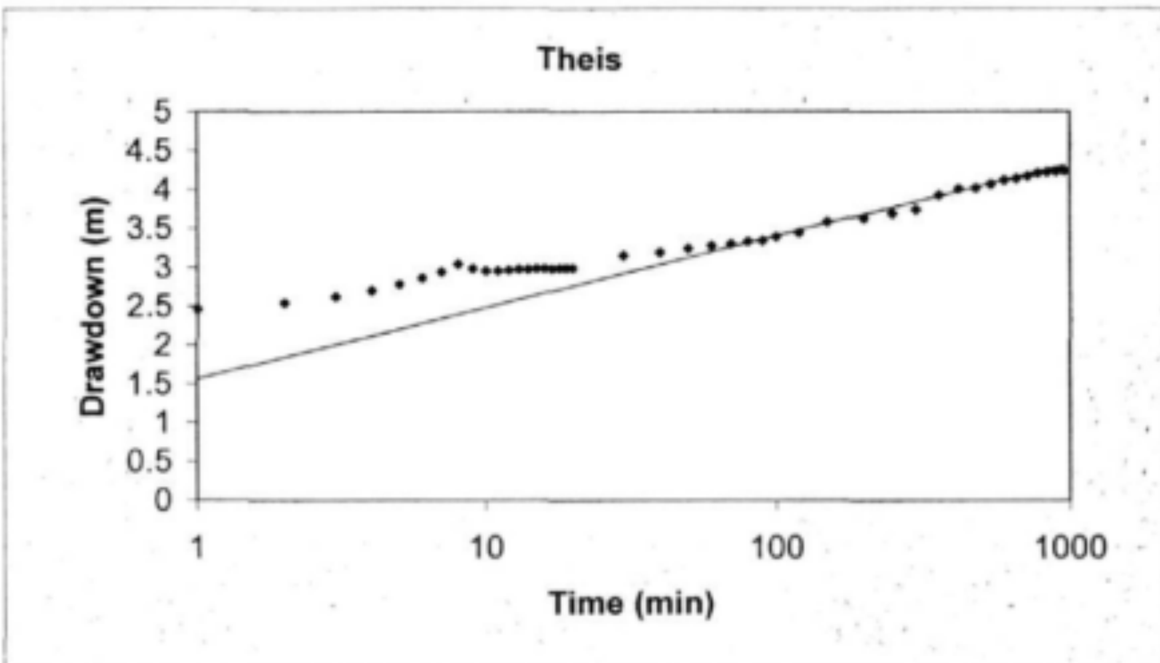
Constant Rate Test Meadhurst M1, Abtraction BH

$T (m^2/d)$ =	23.8	r_e (m)=	6.76
S =	2.00E-05	Q (l/s) =	1.4



Theis

T (m2/d)	S	r
24	1.70E-05	6.76

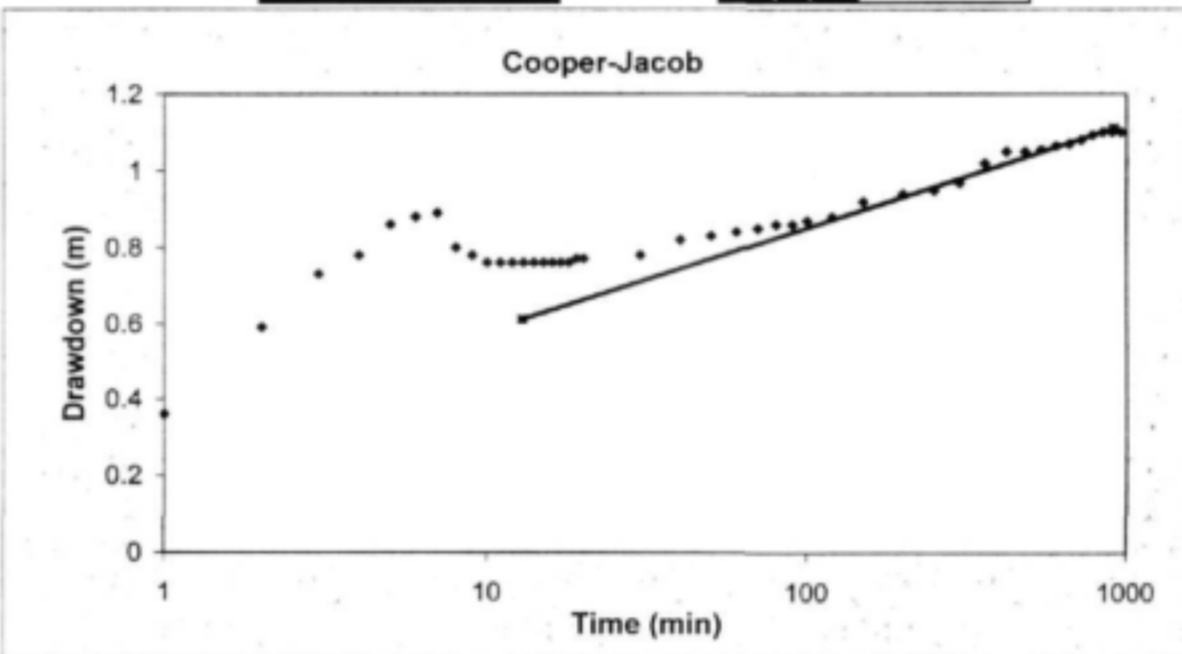


Appendix C.3

Cooper-Jacob method

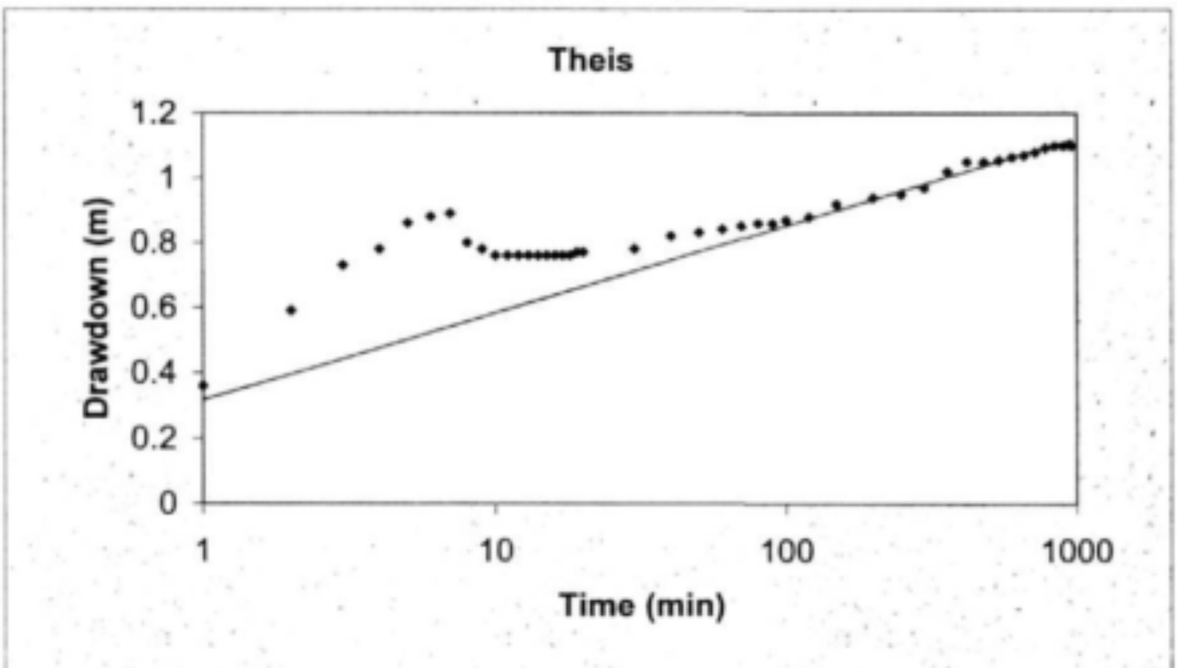
Constant Rate Test Meadhurst M1, Observ. BH M2

$T(m^2/d)$ =	82.1	r_e (m)=	30.30 →	21.75
S =	1.90E-05	Q (l/s) =	1.4	



Theis

T (m2/d)	S	r
82	1.90E-05	21.75

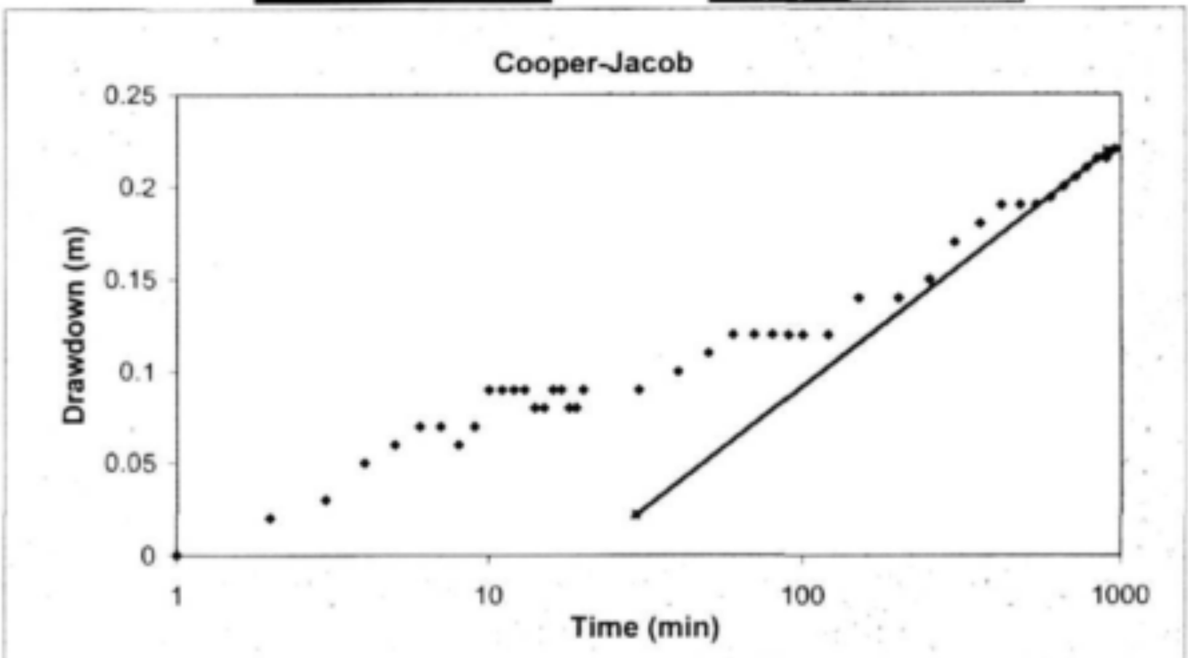


Appendix C.3

Cooper-Jacob method

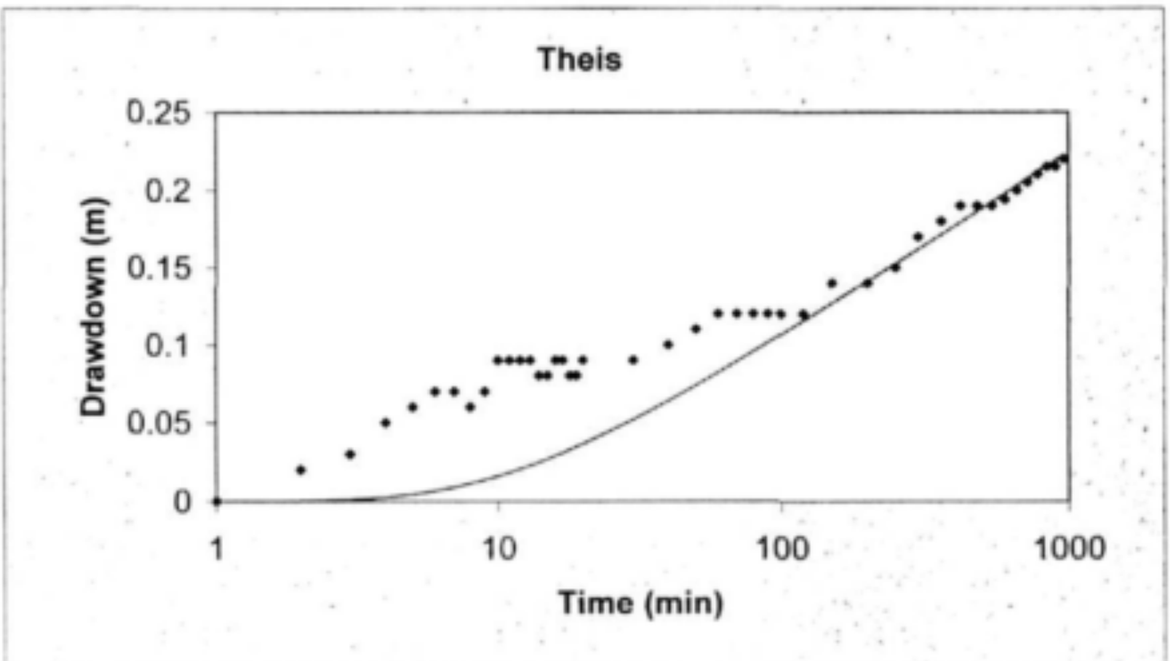
Constant Rate Test Meadhurst M1, Observ. BH M3

$T(m^2/d) =$	167.5	r_e (m)=	#DIV/0! →	21.97
S =	1.09E-02	Q (l/s) =	1.4	



Theis

T (m2/d)	S	r
182	8.50E-03	21.97

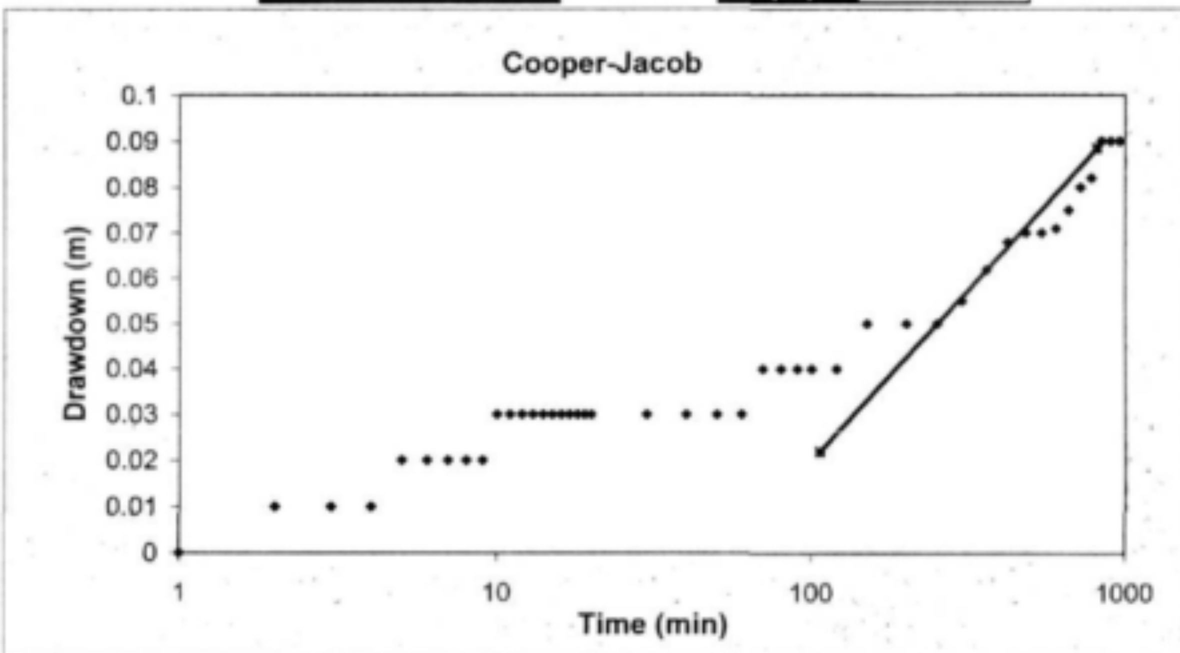


Appendix C.3

Cooper-Jacob method

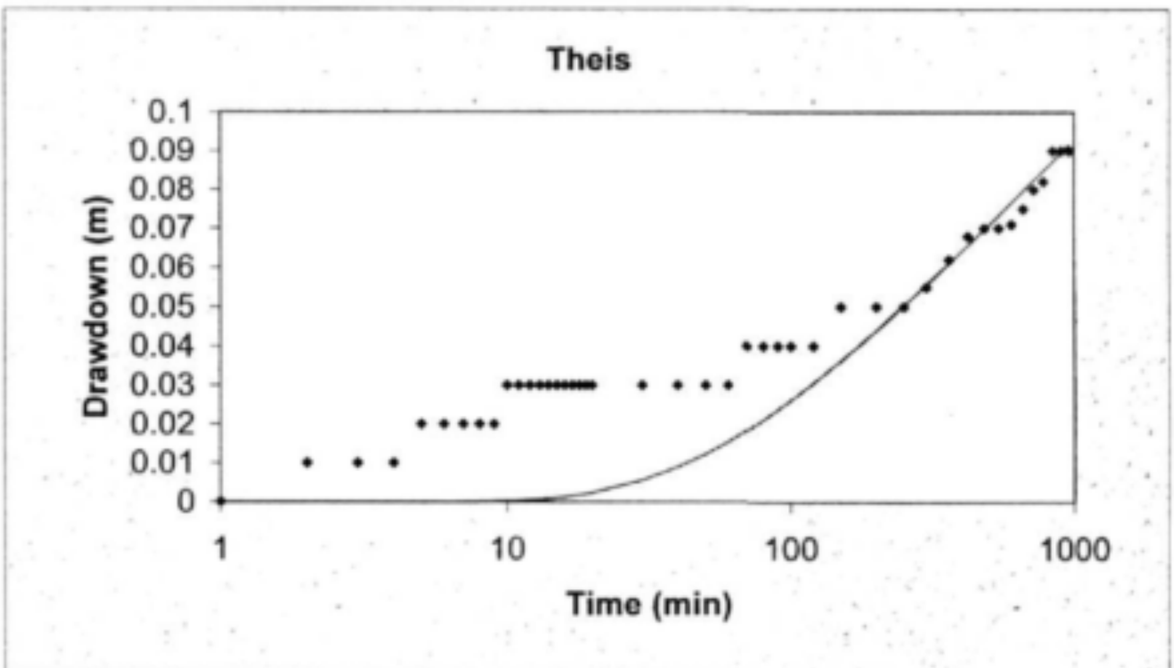
Constant Rate Test Meadhurst M1, Observ. BH M5

$T(m^2/d)$ =	294.4	r_e (m)=	#DIV/0! →	80.2
S =	3.87E-03	Q (l/s) =	1.4	



Theis

T (m2/d)	S	r
292	4.40E-03	80.20

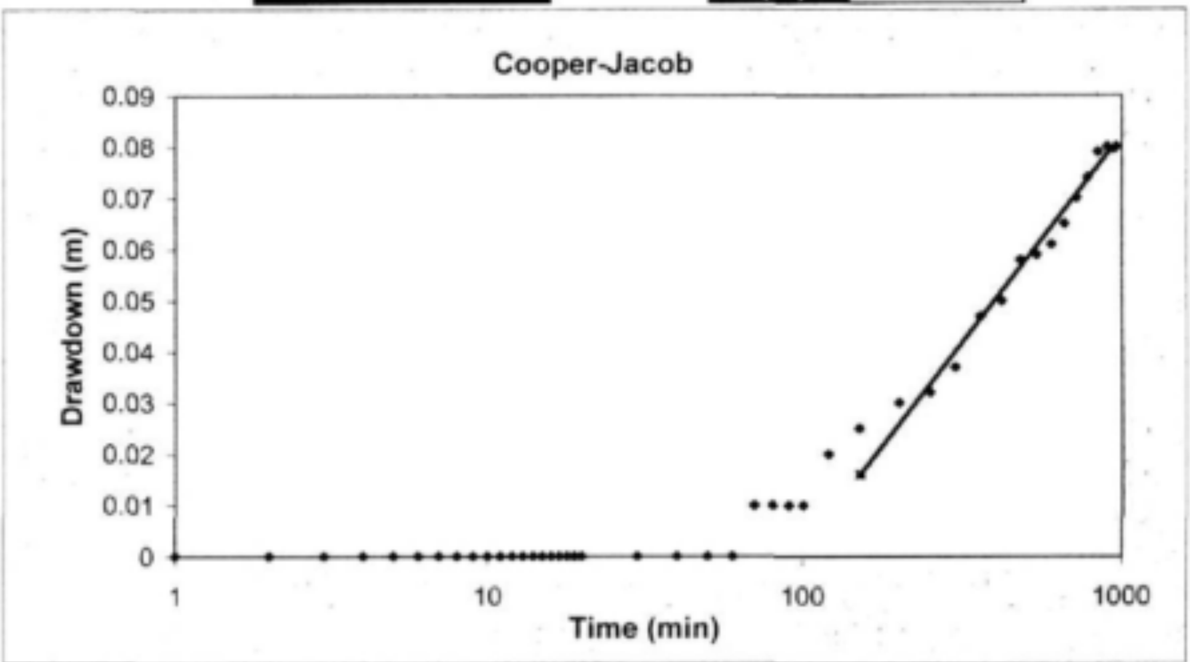


Appendix C.3

Cooper-Jacob method

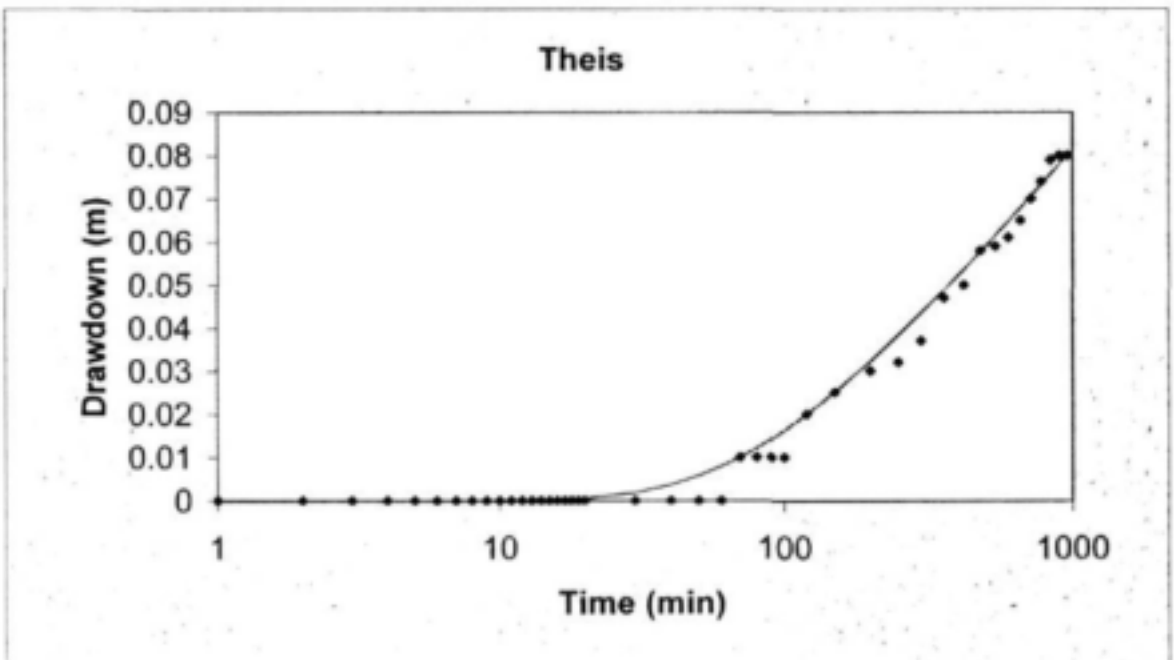
Constant Rate Test Meadhurst M1, Observ. BH M6

T(m²/d) =	273.7	r_e (m)=	#DIV/0! →	35.84
S =	3.19E-02	Q (l/s) =	1.4	



Theis

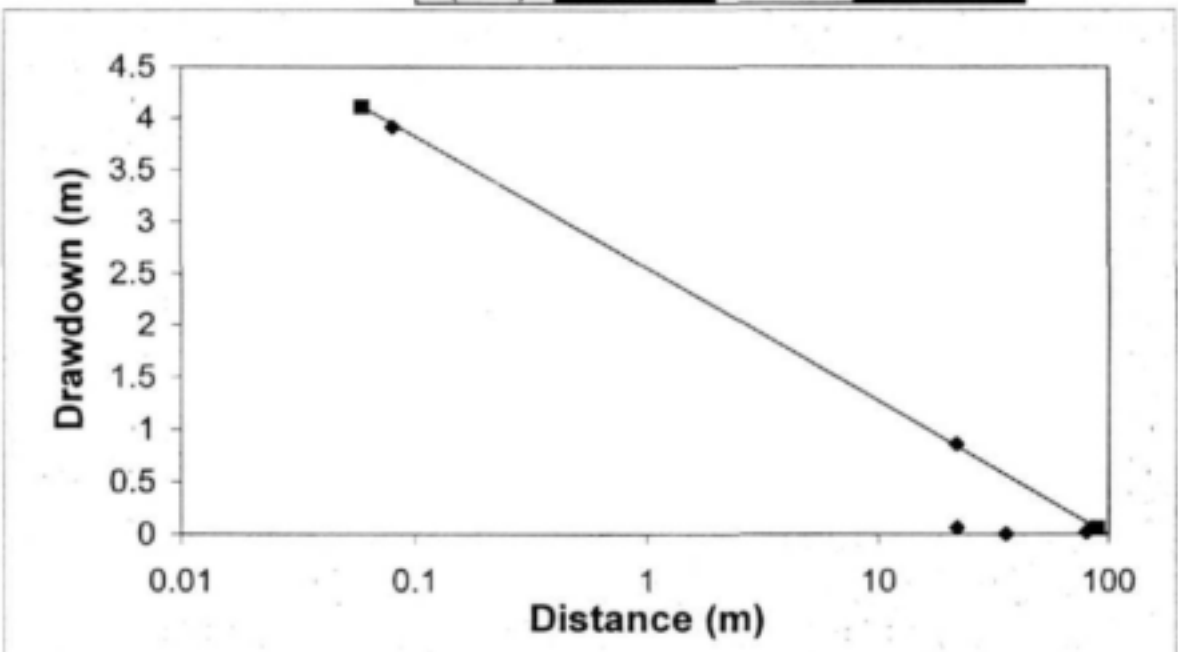
T (m2/d)	S	r
273	3.49E-02	35.84



Appendix C.3

Cooper-Jacob 2: Distance drawdown

	Obs 1	Obs 2	Obs 3	Obs 4	Obs 5	Obs 6
Distance r (m)	0.08	21.75	21.97	35.84	80.2	
Drawdown (m)	3.91	0.86	0.06	0	0.02	
Time (minutes)	5					
		T (m^2/d) =	34.75	S	3.07E-05	

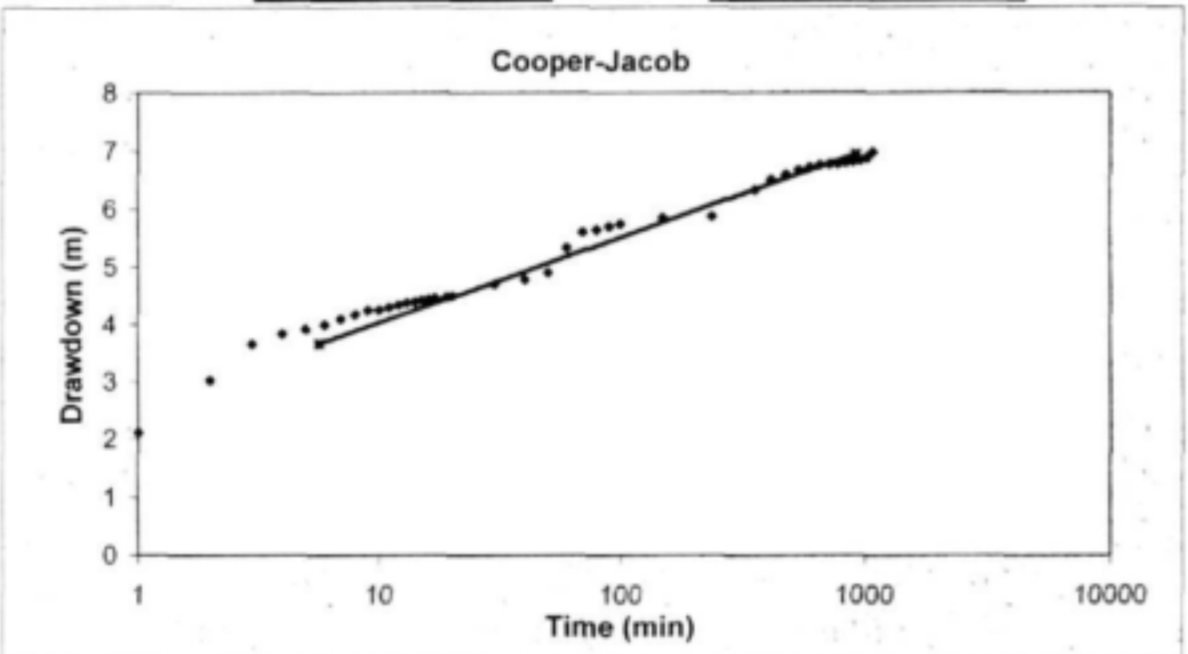


Appendix C.4

Cooper-Jacob method

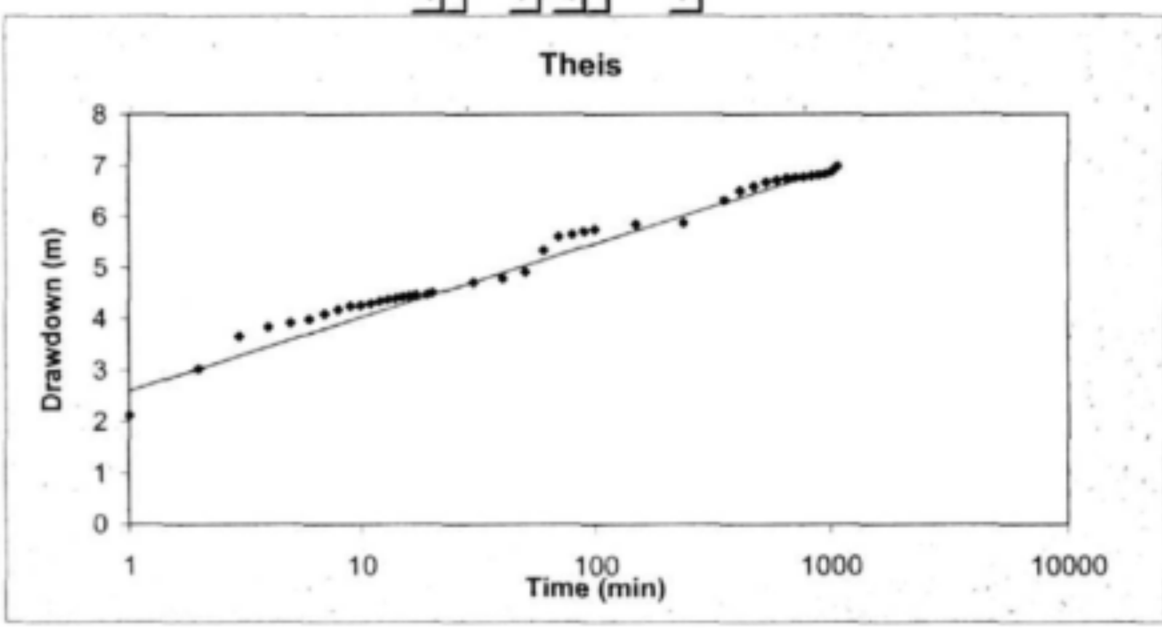
Constant Rate Test Meadhurst M1, at 2l/s

$T(m^2/d)$ =	21.3	r_e (m)=	23.51
S =	1.17E-06	Q (l/s) =	2



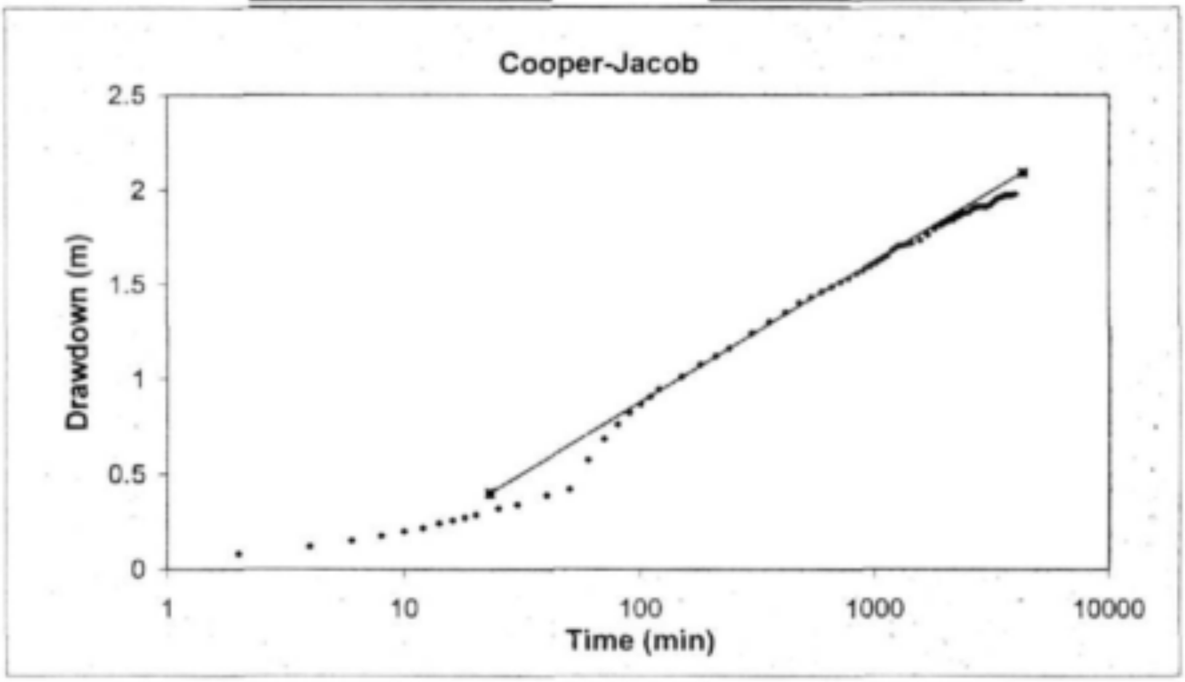
Theis

T (m2/d)	S	r
22	1.00E-06	23.51

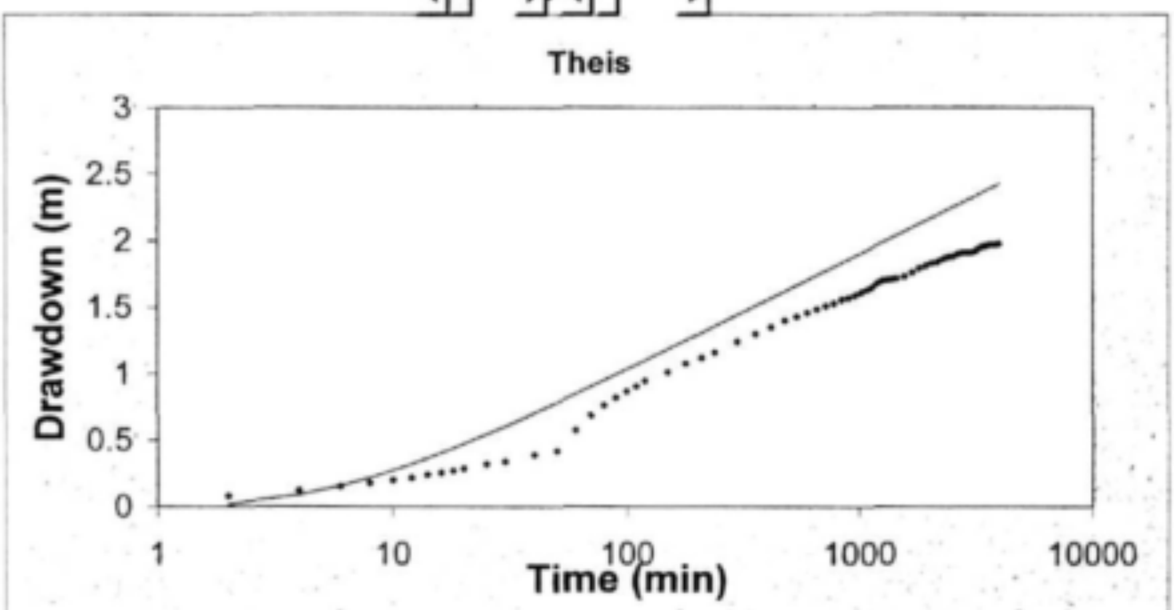


Appendix C.5

Cooper-Jacob method					
UO5					
$T (m^2/d)$ =	10.6	r_e (m)=	25.00	→	3.5
S =	9.01E-03	Q (l/s) =	0.5		



Theis	T (m2/d)	S	r
	9	8.01E-03	3.50

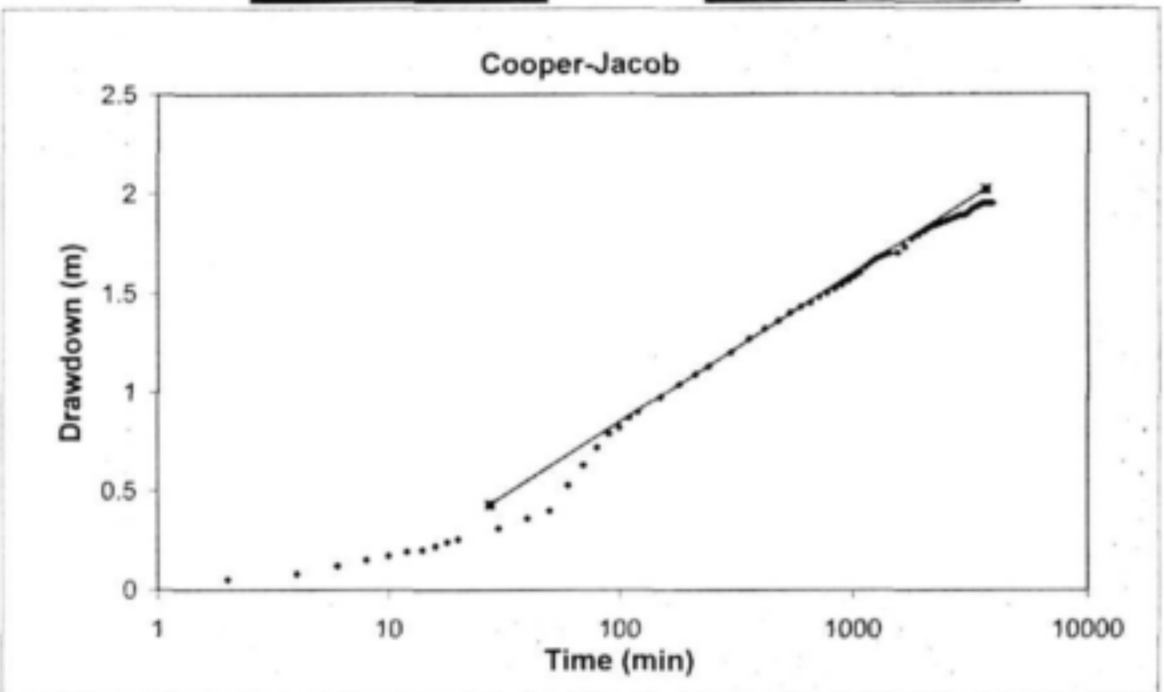


Appendix C.5

Cooper-Jacob method

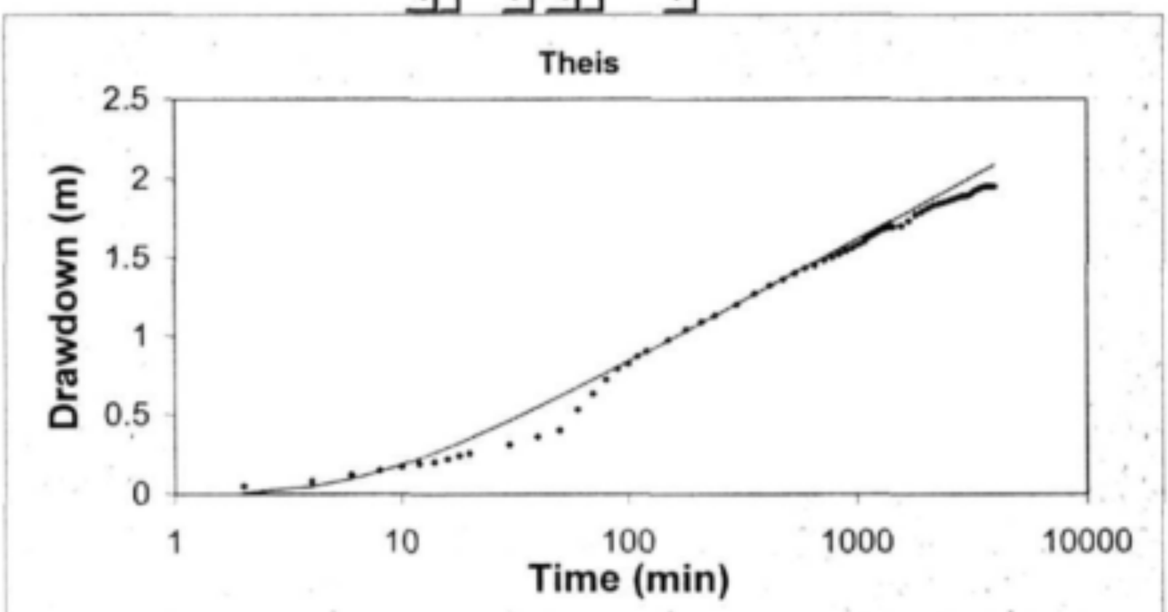
UO5-Test, Obs. BH UO23

$T (m^2/d)$ =	10.6	r_e (m)=	98.00 →	98
S =	1.26E-05	Q (l/s) =	0.5	



Theis

T (m2/d)	S	r
10	1.50E-05	98.00

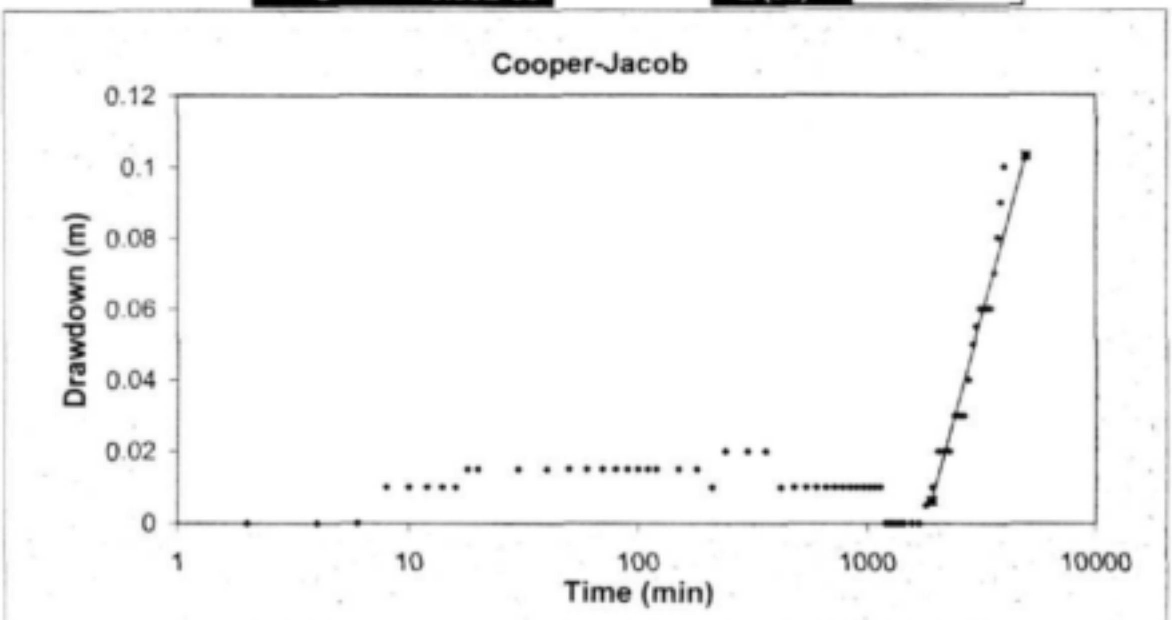


Appendix C.5

Cooper-Jacob method

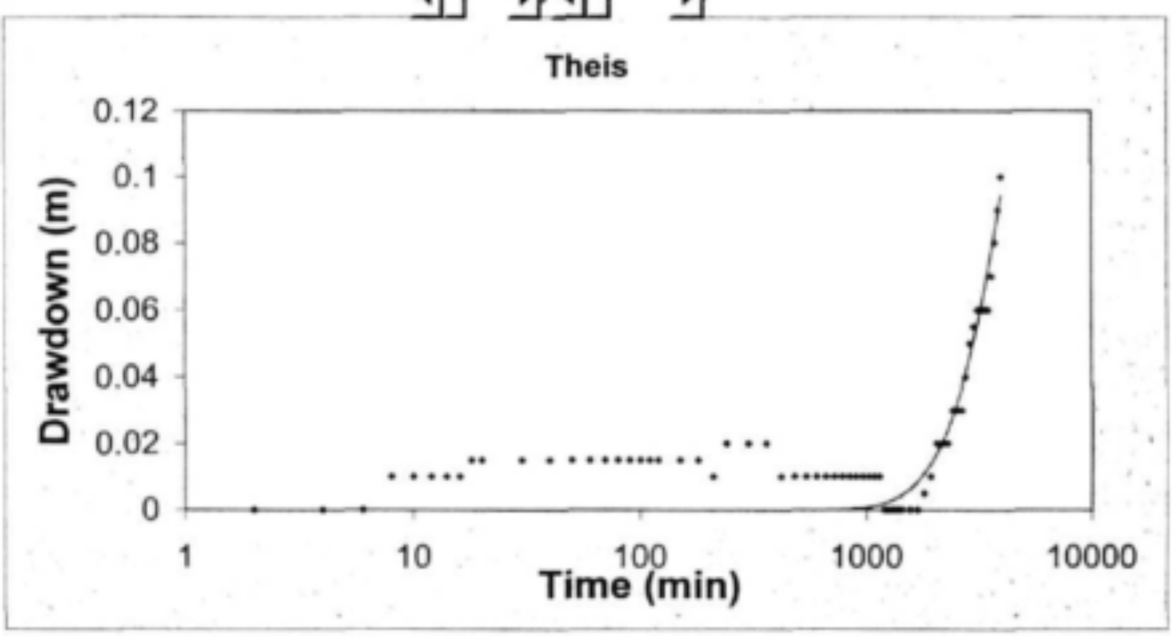
UO5-Test, Obs. BH UO23a (Matrix above)

$T (m^2/d)$ =	33.7	r_e (m)=	98.00	98
S =	9.85E-03	Q (l/s) =	0.5	



Theis

T (m2/d)	S	r
5	7.41E-03	98.00

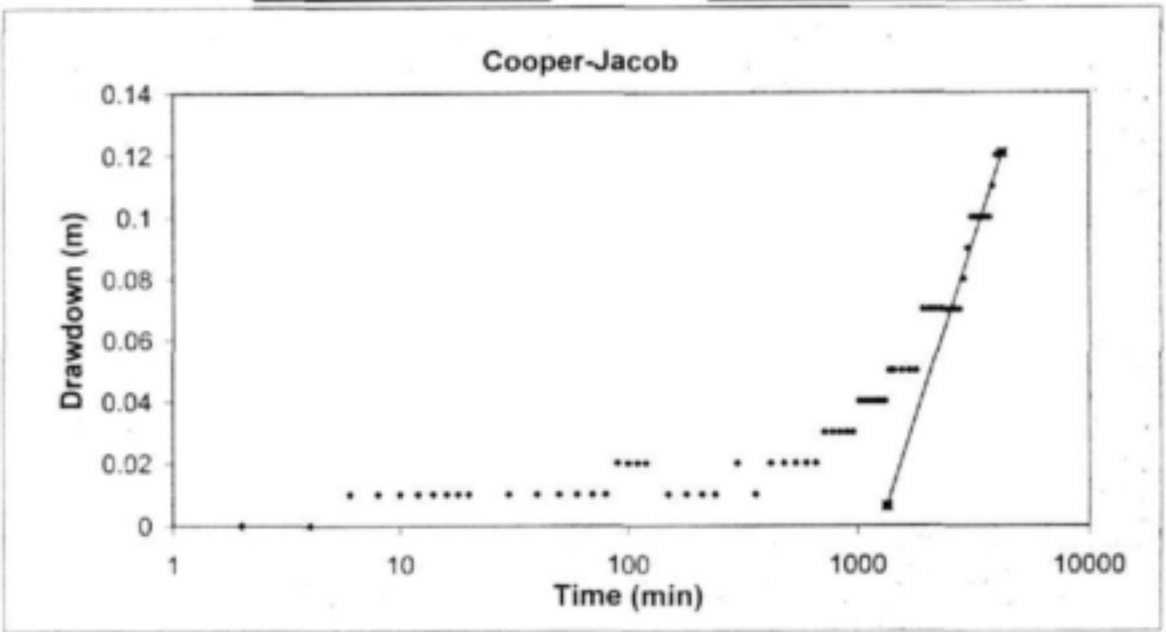


Appendix C.5

Cooper-Jacob method

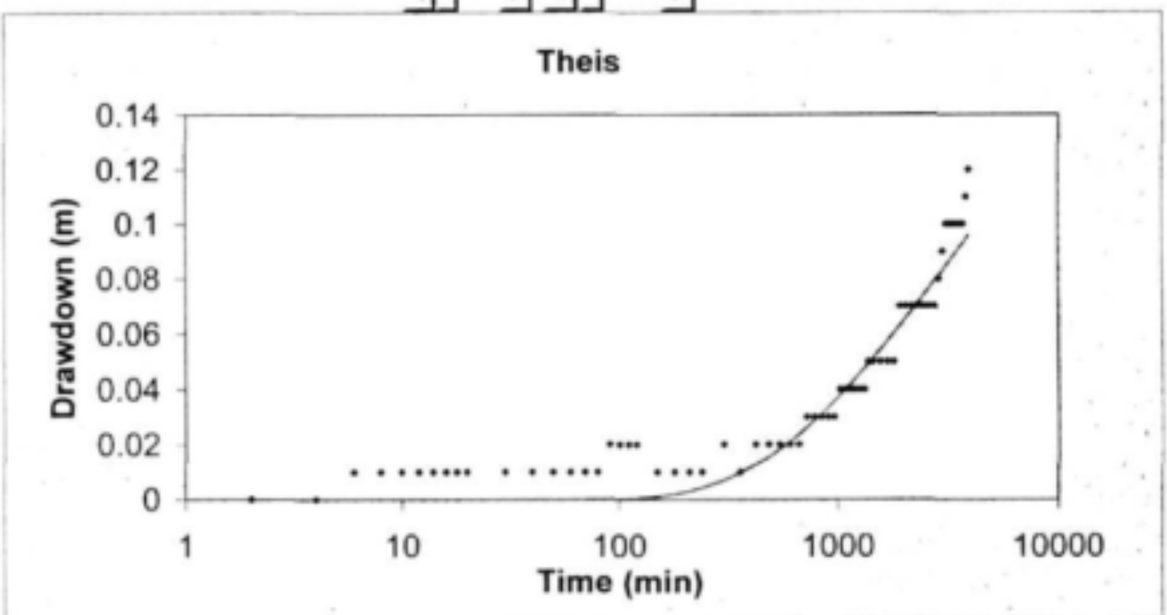
UO5-Test, Obs. BH UO23b (Matrix below)

$T(m^2/d)$ =	34.5	r_e (m)=	98.00	98
S =	7.06E-03	Q (l/s) =	0.5	



Theis

T (m2/d)	S	r
65	7.50E-03	98.00

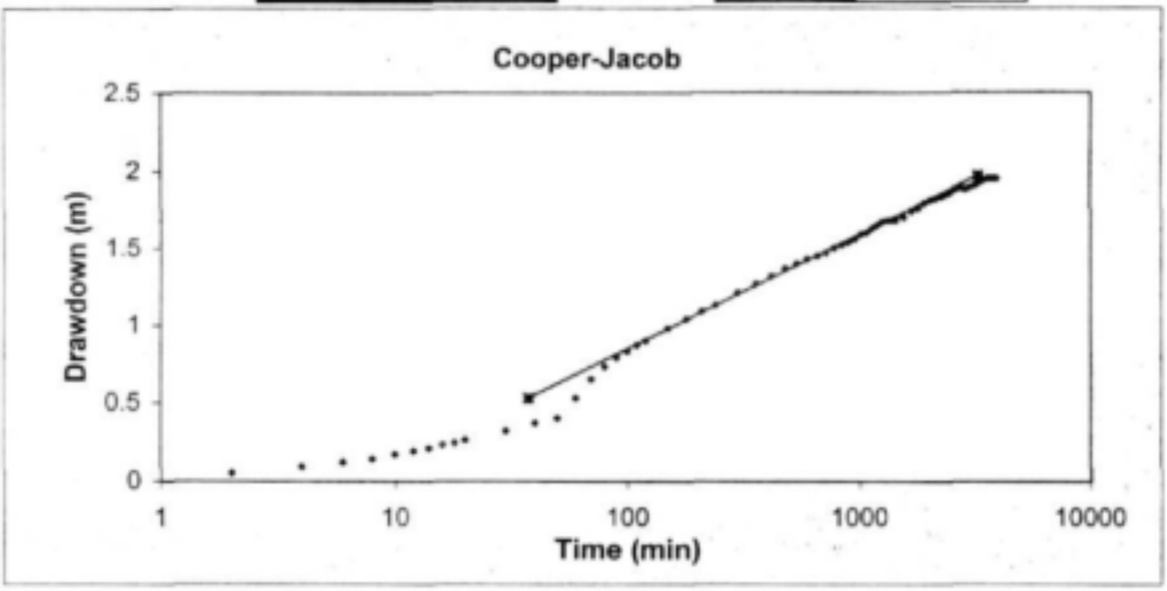


Appendix C.5

Cooper-Jacob method

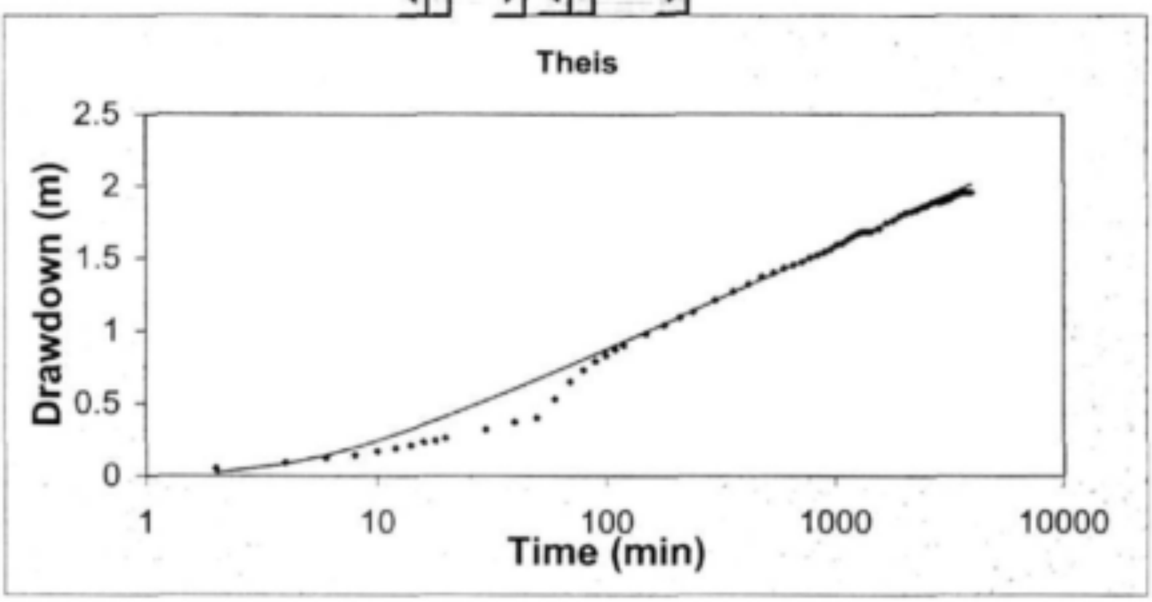
UO5-Test, Obs. BH UO27

$T(m^2/d)$ =	10.7	r_e (m)=	11.50
S =	9.09E-04	Q (l/s) =	0.5



Theis

T (m2/d)	S	r
11	8.30E-04	11.50

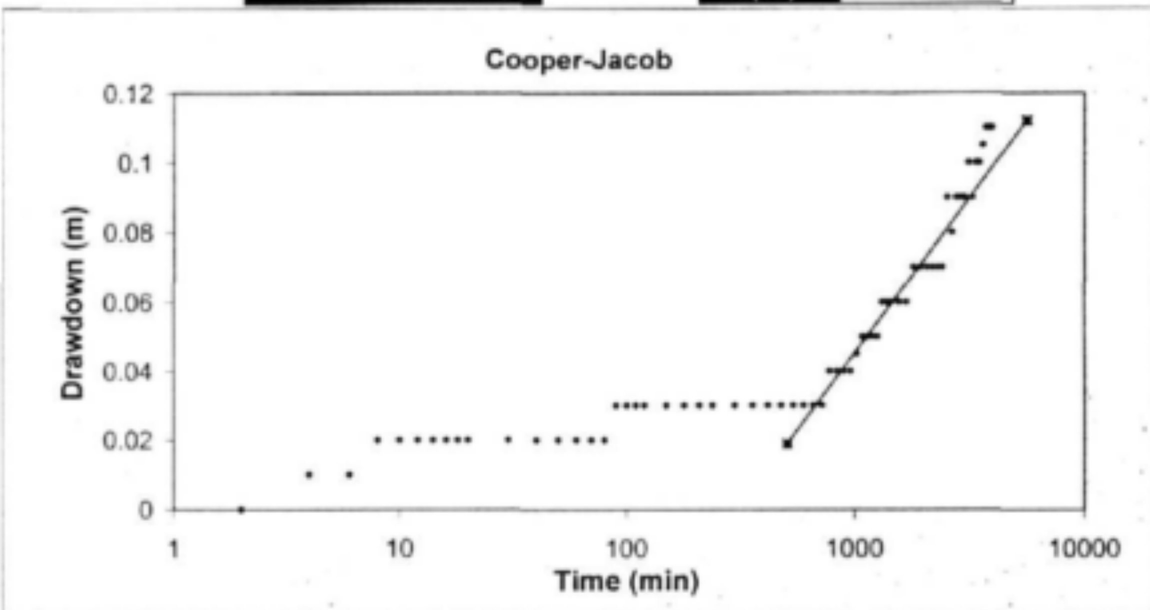


Appendix C.5

Cooper-Jacob method

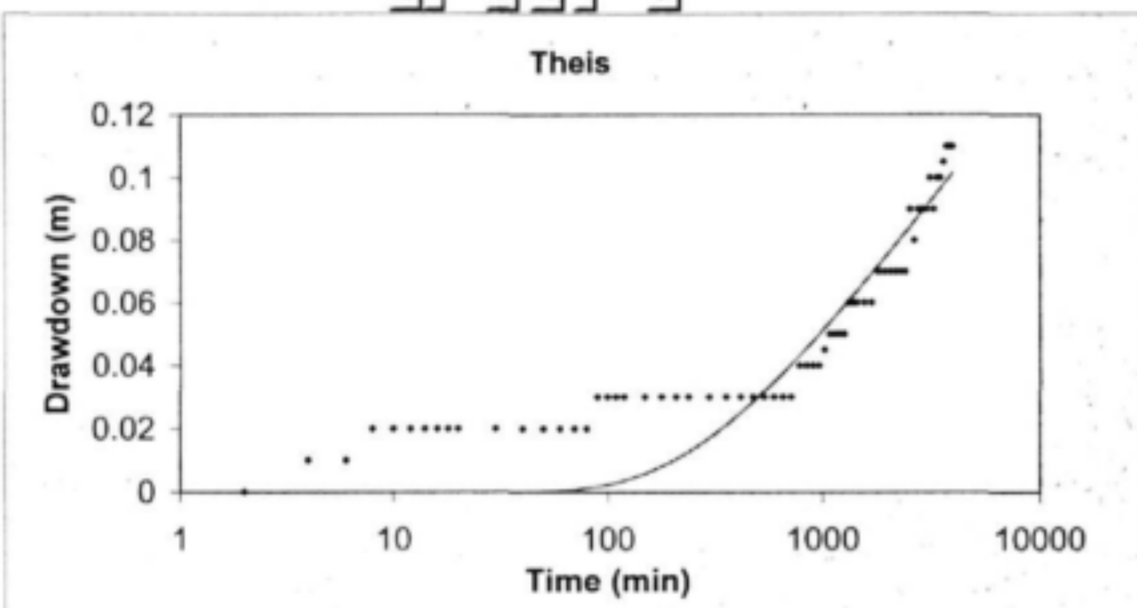
UO5-Test, Obs. BH UO27a (Matrix above)

$T(m^2/d)$ =	88.5	r_e (m)=	11.50
S =	3.28E-01	Q (l/s) =	0.5



Theis

T (m2/d)	S	r
85	3.39E-01	11.50

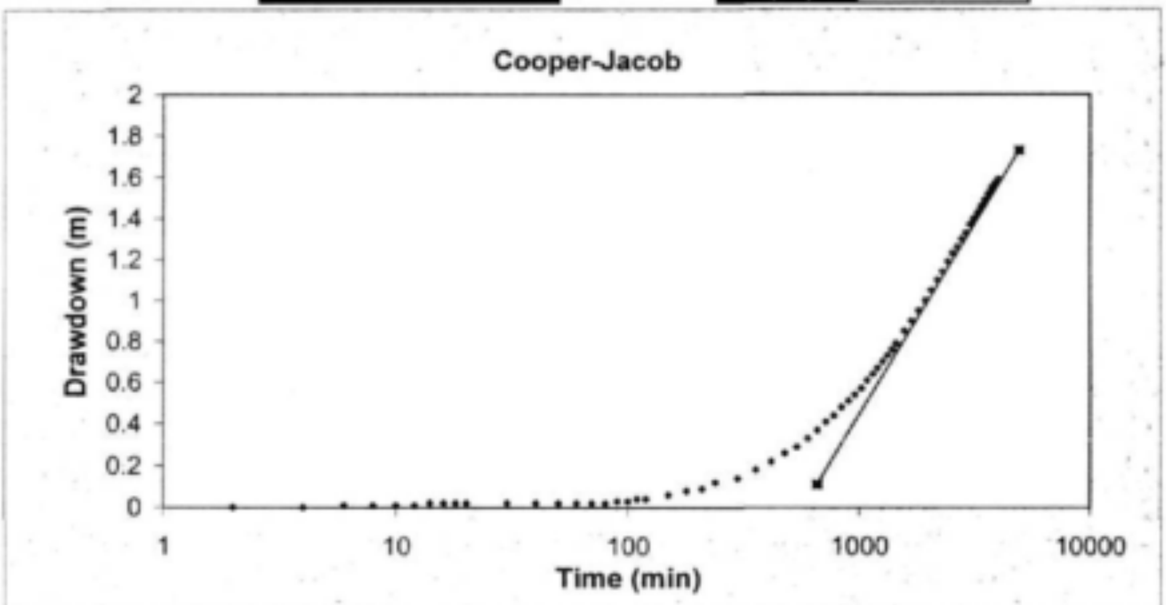


Appendix C.5

Cooper-Jacob method

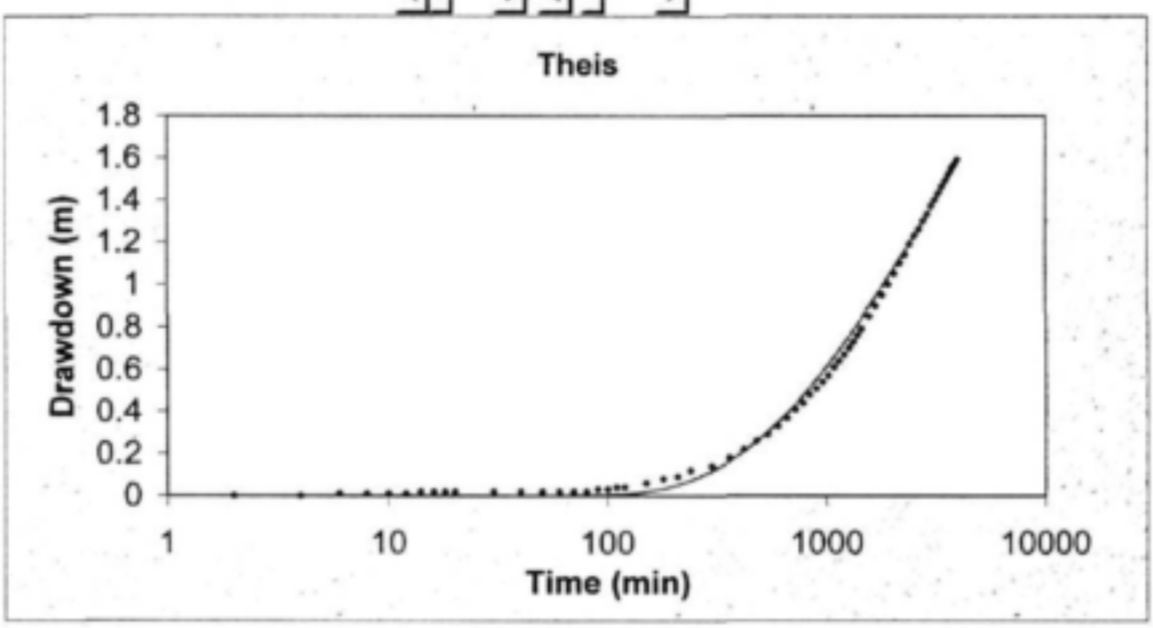
UO5-Test, Obs. BH UO27b (Matrix)

$T(m^2/d)$ =	4.2	r_e (m)=	11.50
S =	2.89E-02	Q (l/s) =	0.5



Theis

T (m2/d)	S	r
4	3.30E-02	11.50

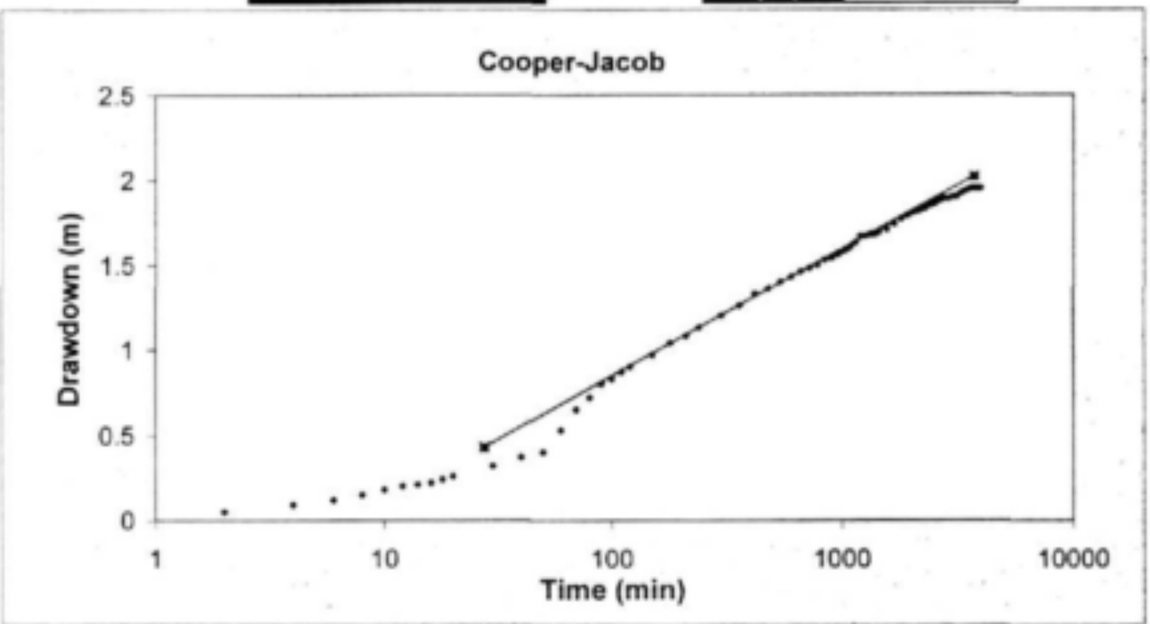


Appendix C.5

Cooper-Jacob method

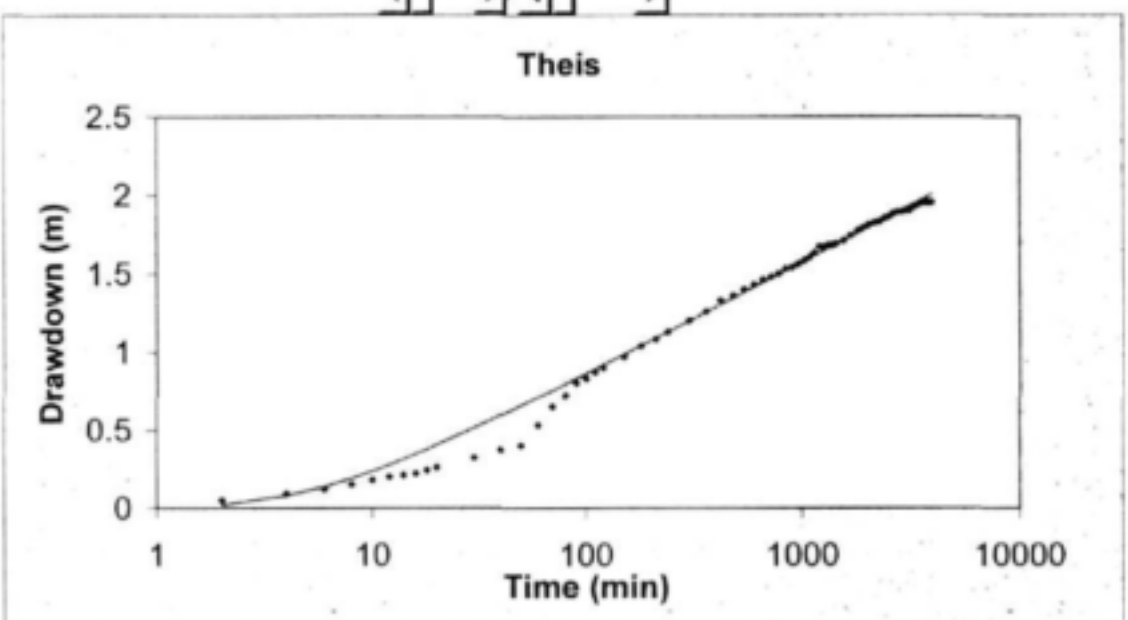
UO5-Test, Obs. BH UO28

$T(m^2/d)$ =	10.6	r_e (m)=	27.25
S =	1.63E-04	Q (l/s) =	0.5



Theis

T (m2/d)	S	r
11	1.52E-04	27.25

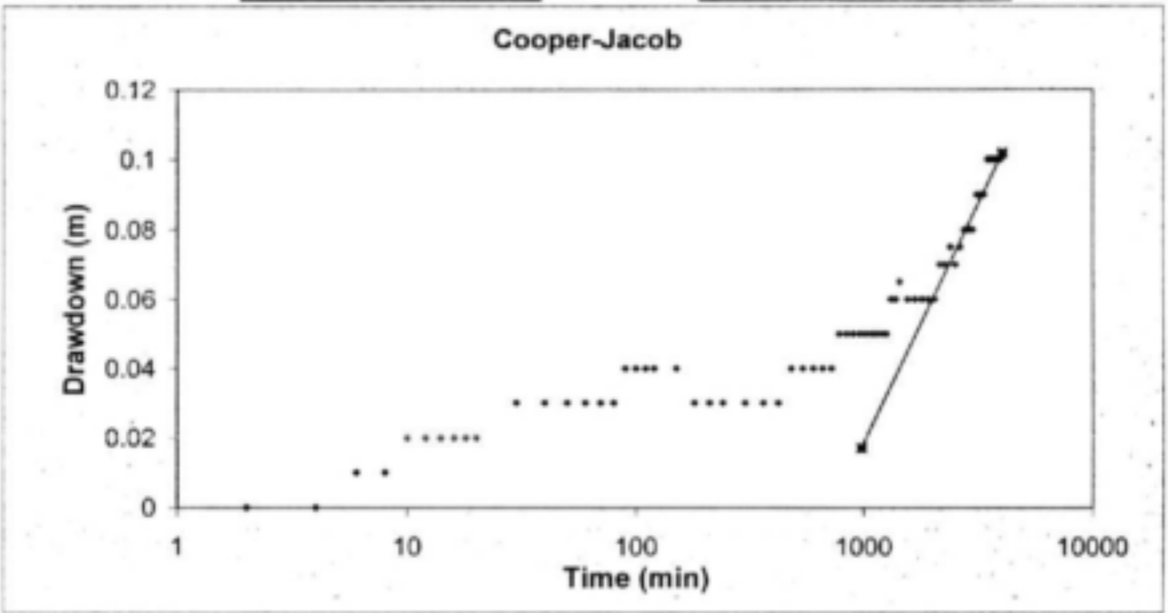


Appendix C.5

Cooper-Jacob method

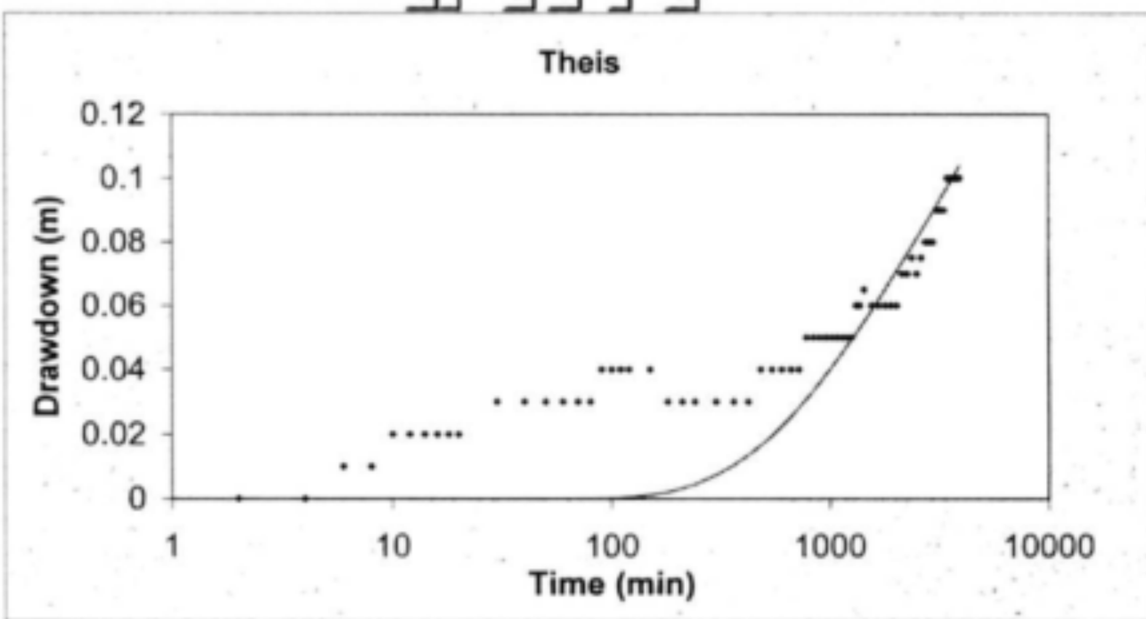
UO5-Test, Obs. BH UO28a (Matrix above)

$T(m^2/d)$ =	57.5	r_e (m)=	27.25
S =	8.89E-02	Q (l/s) =	0.5



Theis

T (m2/d)	S	r
60	9.00E-02	27.25

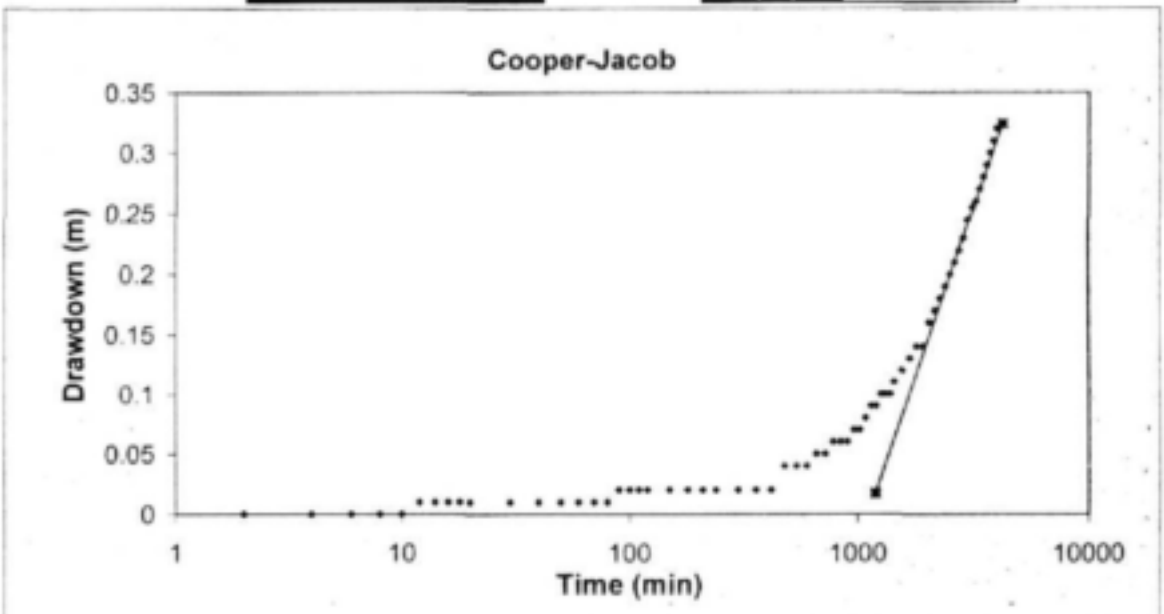


Appendix C.5

Cooper-Jacob method

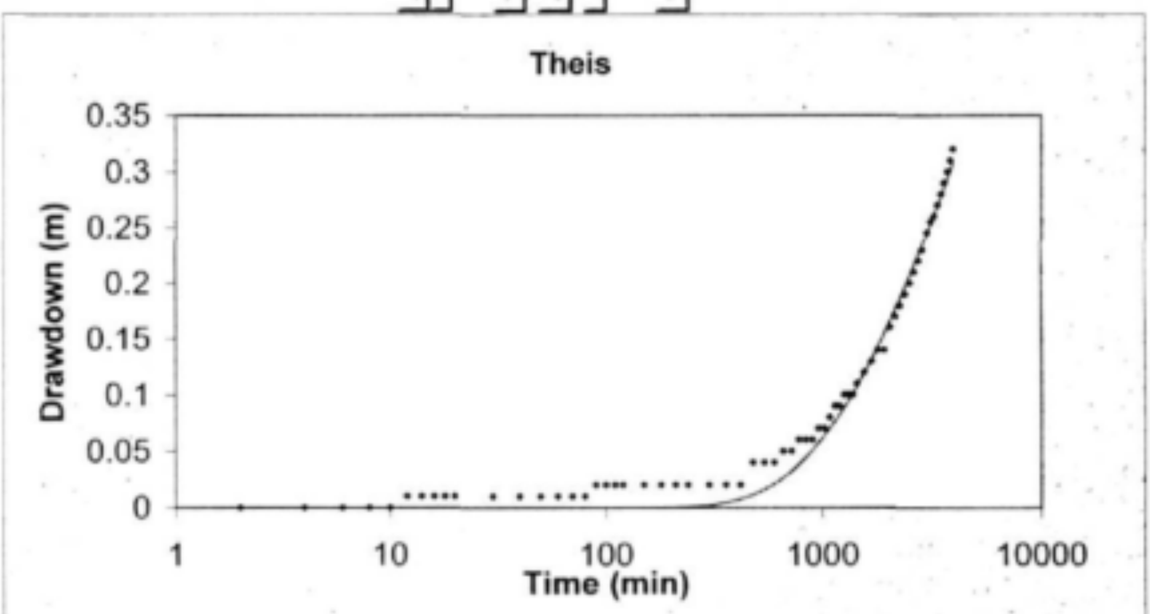
UO5-Test, Obs. BH UO28b (Matrix below)

$T(m^2/d)$ =	14.1	r_e (m)=	27.25
S =	3.31E-02	Q (l/s) =	0.5



Theis

T (m2/d)	S	r
11	4.40E-02	27.25

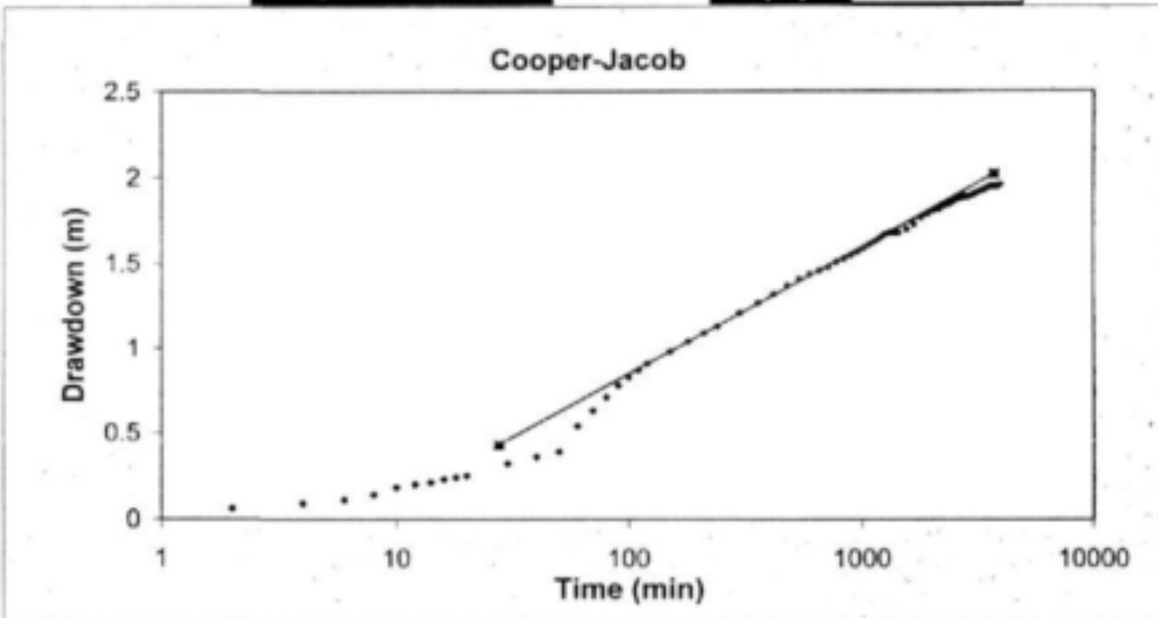


Appendix C.5

Cooper-Jacob method

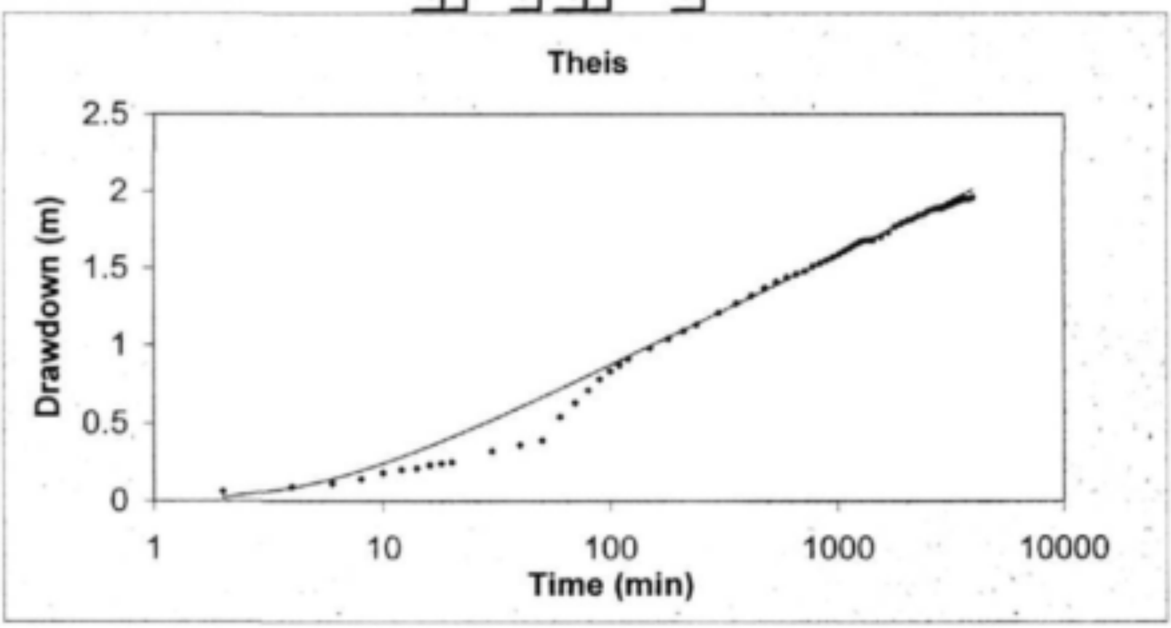
UO5-Test, Obs. BH UO29

$T(m^2/d)$ =	10.6	r_e (m)=	76.00
S =	2.10E-05	Q (l/s) =	0.5



Theis

T (m2/d)	S	r
11	1.90E-05	76.00

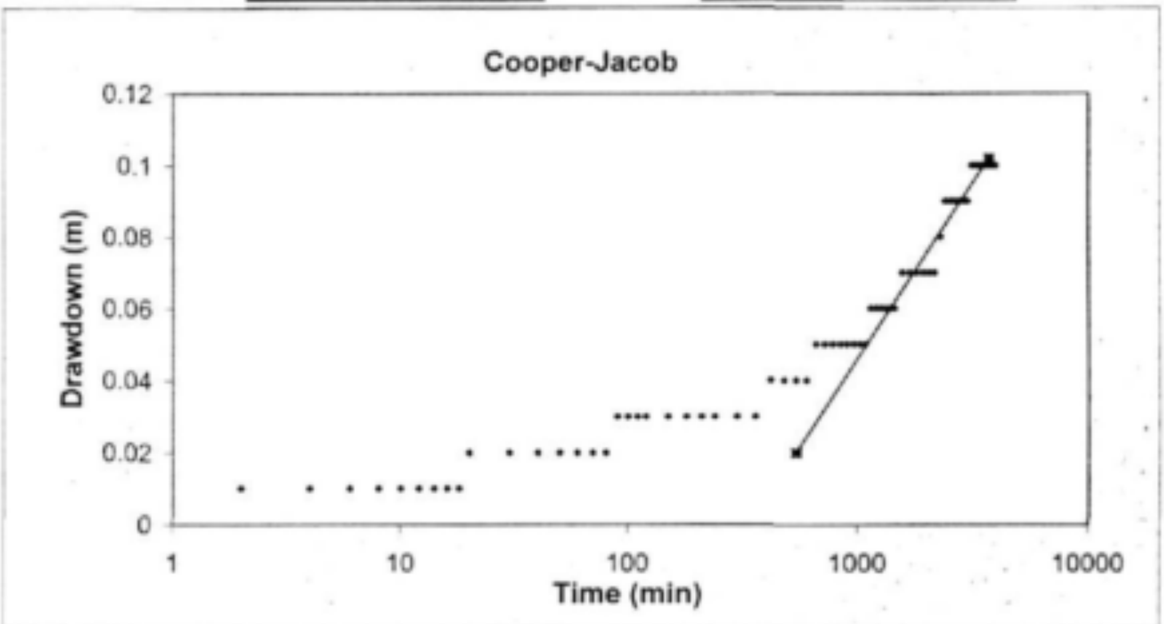


Appendix C.5

Cooper-Jacob method

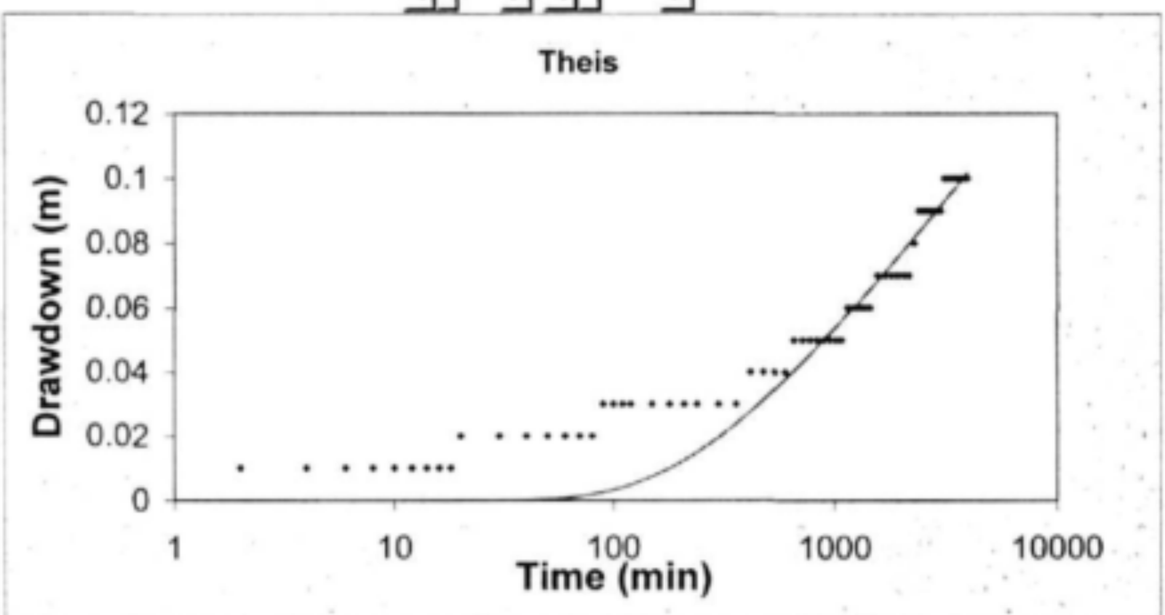
UO5-Test, Obs. BH UO29a (Matrix above)

$T (m^2/d)$ =	80.7	r_e (m)=	76.00
S =	7.39E-03	Q (l/s) =	0.5



Theis

T (m2/d)	S	r
90	7.00E-03	76.00

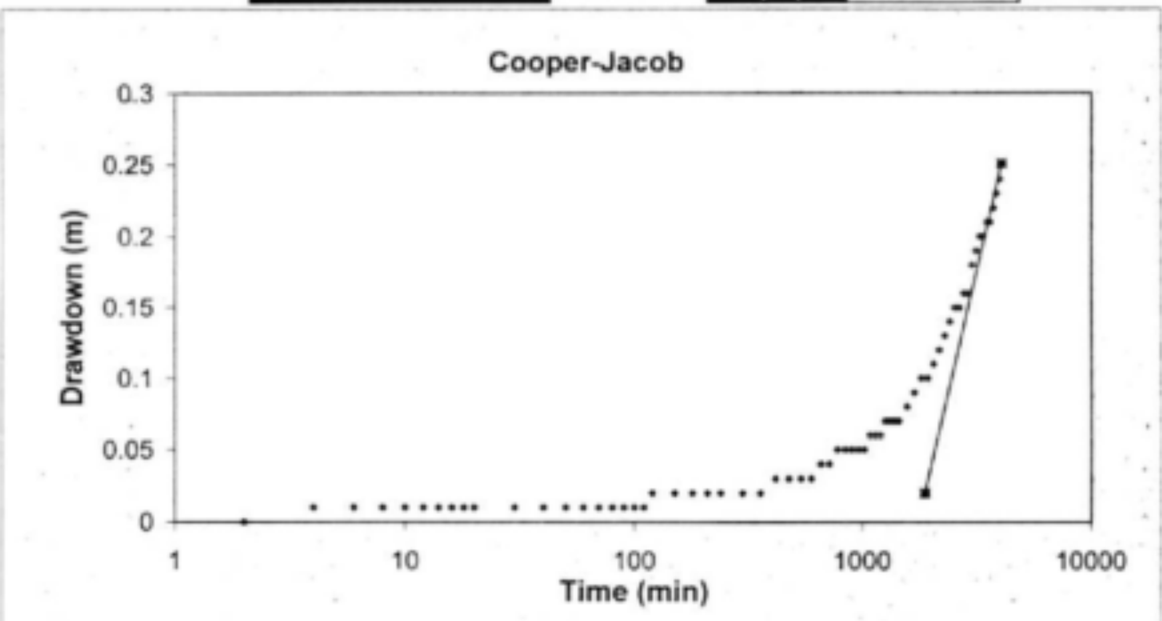


Appendix C.5

Cooper-Jacob method

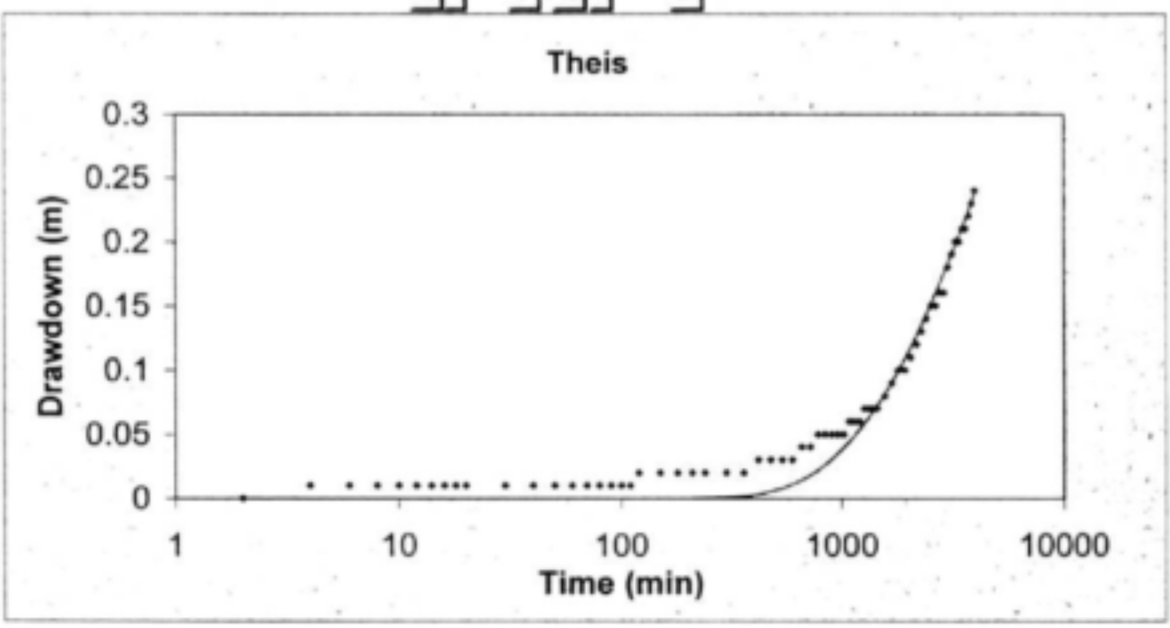
UO5-Test, Obs. BH UO29b (Matrix below)

$T(m^2/d)$ =	11.5	r_e (m)=	76.00
S =	5.43E-03	Q (l/s) =	0.5



Theis

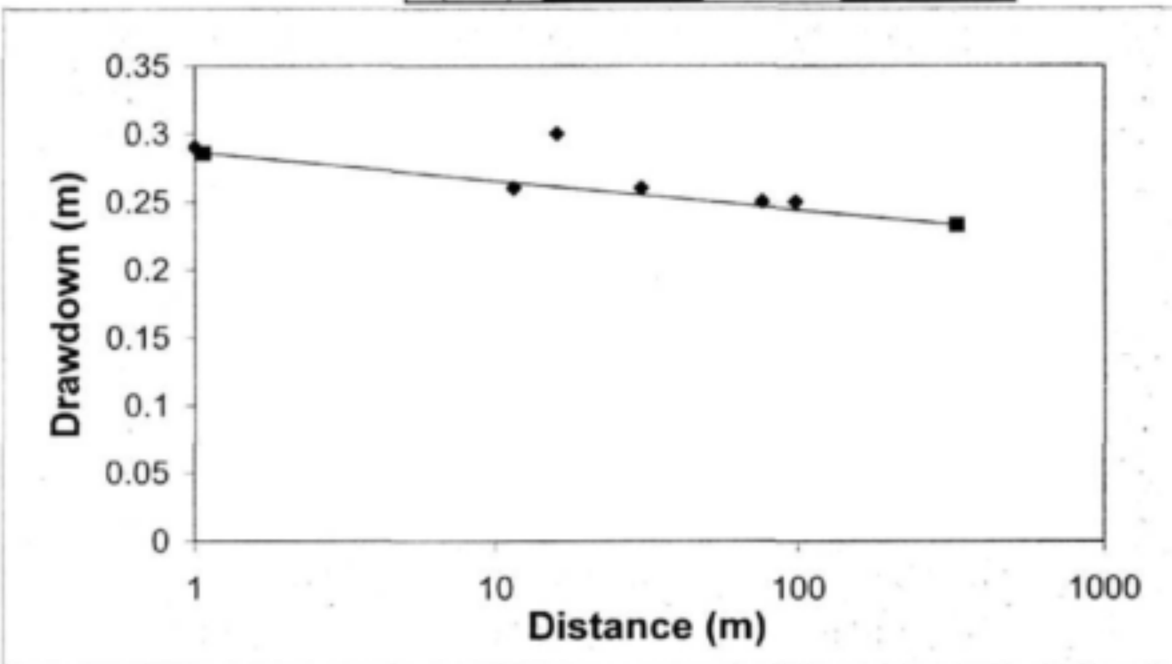
T (m2/d)	S	r
12	7.60E-03	76.00



Appendix C.5

Cooper-Jacob 2: Distance drawdown

	UO5	UO27	UO28	UO29	UO23	UO25
Distance r (m)	1	11.5	30.4	76	98	16
Drawdown (m)	0.29	0.26	0.26	0.25	0.25	0.3
Time (minutes)	20					
		T (m^2/d) =	743.32	S	2.40E-15	

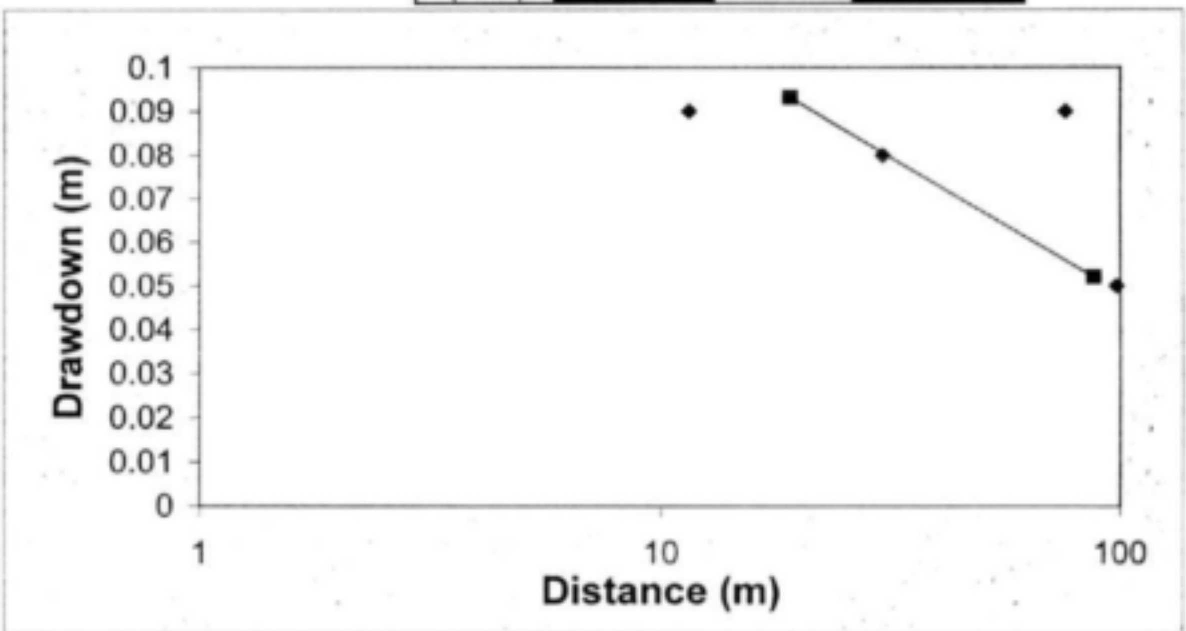


Appendix C.5

Cooper-Jacob 2: Distance drawdown

Piezometer in Matrix above the Fracture

	UO5	UO27	UO28	UO29	UO23	UO26
Distance r (m)	1	11.5	30.4	76	98	16
Drawdown (m)		0.09	0.08	0.09	0.05	
Time (minutes)	3000					
		$T (m^2/d) =$	253.84	S	2.28E-02	

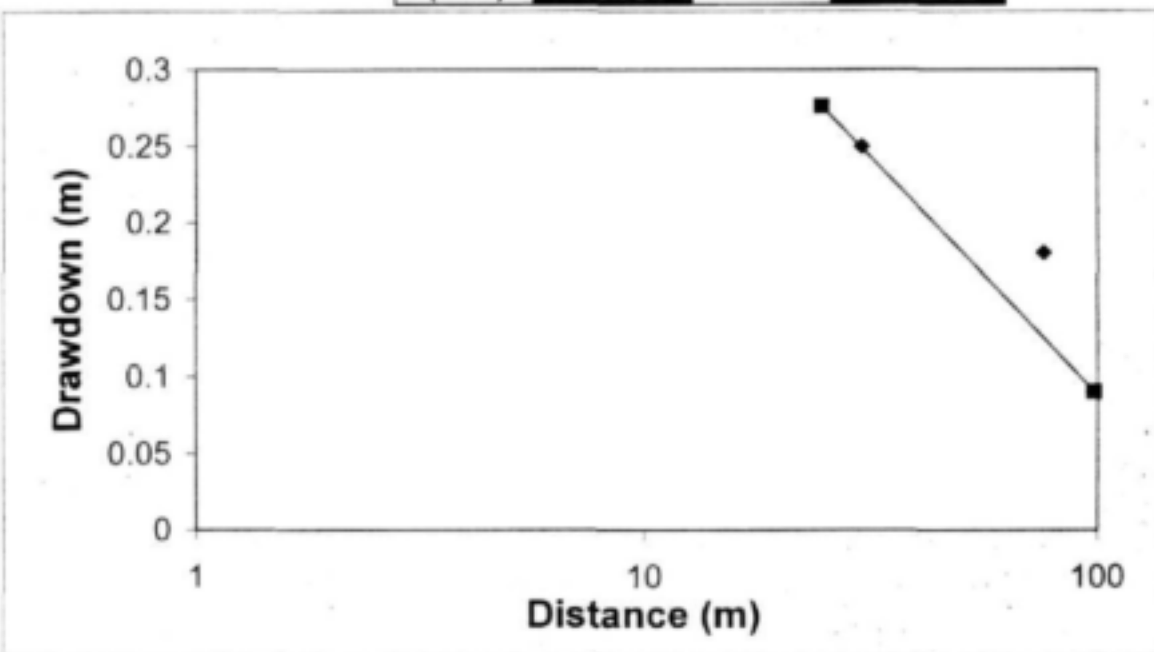


Appendix C.5

Cooper-Jacob 2: Distance drawdown

Piezometer in Matrix below the Fracture

	UO5	UO27	UO28	UO29	UO23	UO26
Distance r (m)	1	11.5	30.4	76	98	16
Drawdown (m)			0.25	0.18	0.09	
Time (minutes)	3000					
		T (m^2/d) =	50.78	S	1.26E-02	

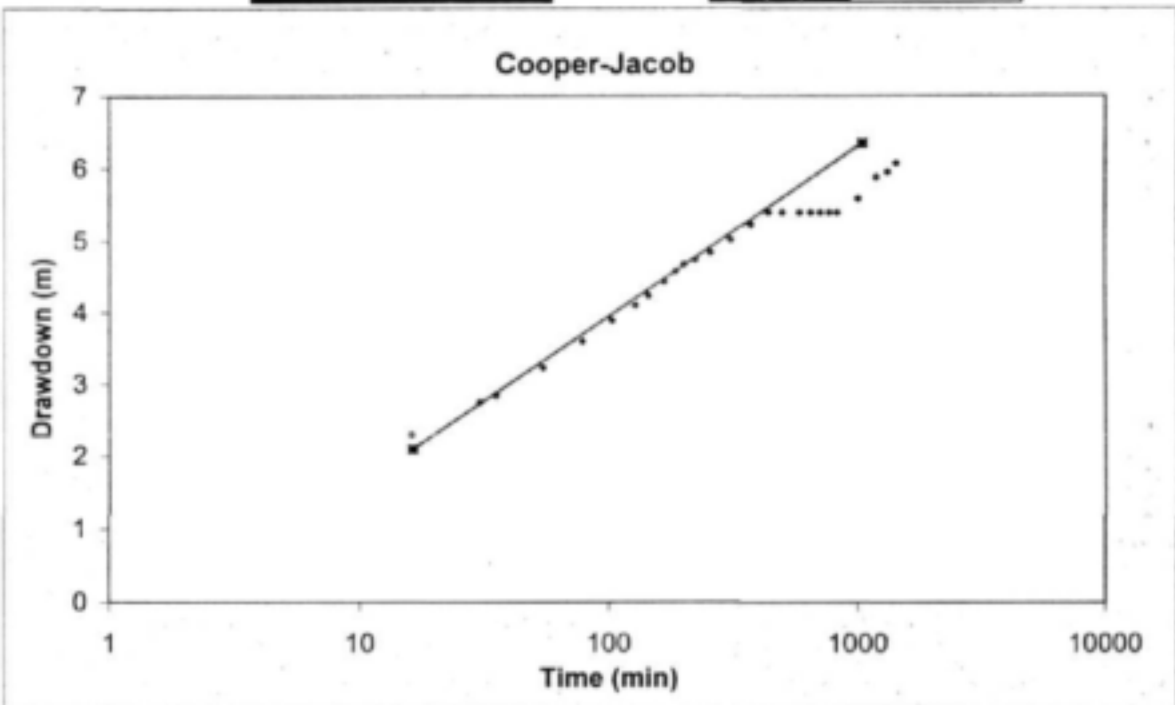


Appendix C.6

Cooper-Jacob method

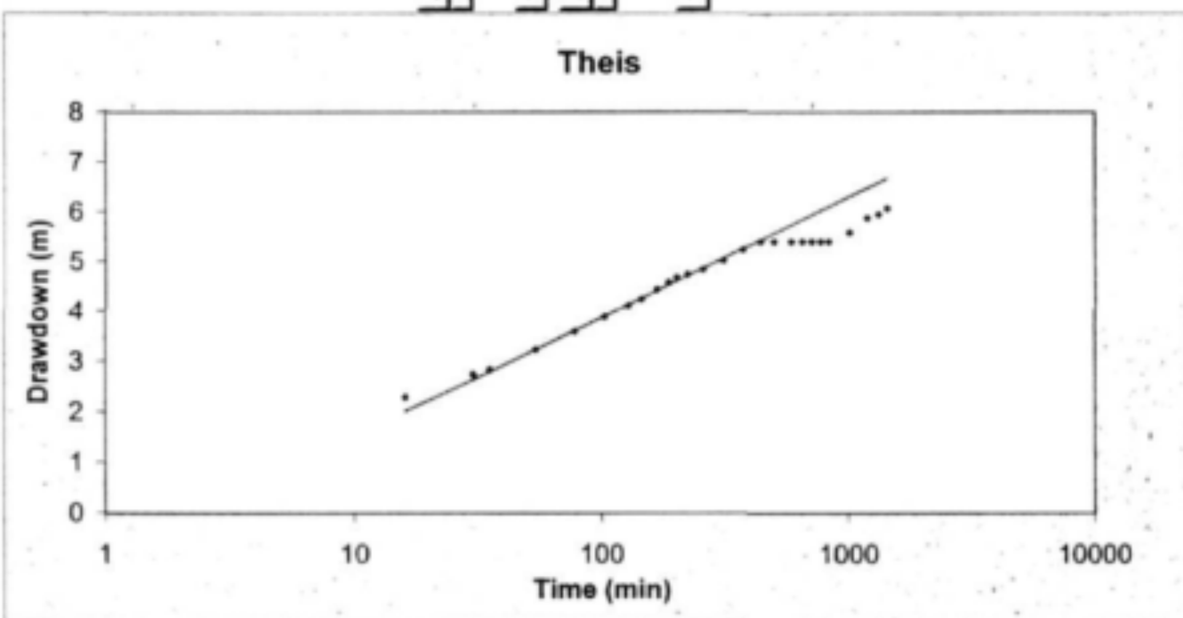
UO 5 (Sep 2000 - 2 l/s)

$T(m^2/d)$ =	13.4	r_e (m)=	50.00 →	5
S =	1.76E-03	Q (l/s) =	2	



Theis

T (m2/d)	S	r
13	2.12E-03	5.00

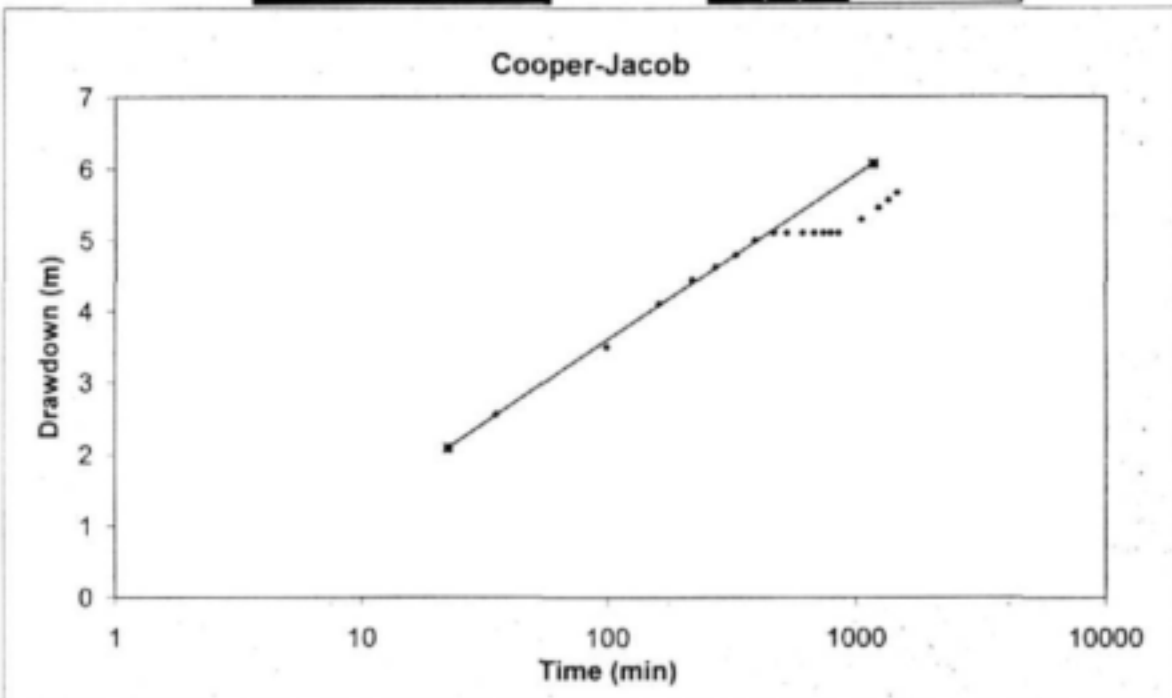


Appendix C.6

Cooper-Jacob method

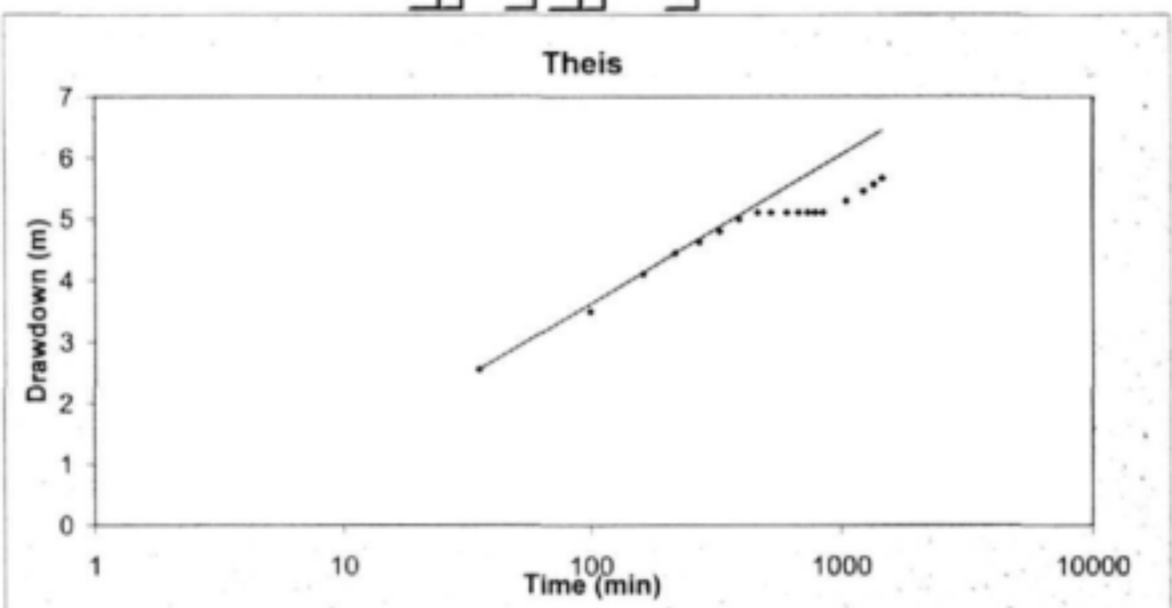
UO 5 (Sep 2000 - 2 l/s), UO23

$T(m^2/d)$ =	13.7	r_e (m)=	98.00
S =	6.22E-06	Q (l/s) =	2



Theis

T (m2/d)	S	r
13	7.00E-06	98.00

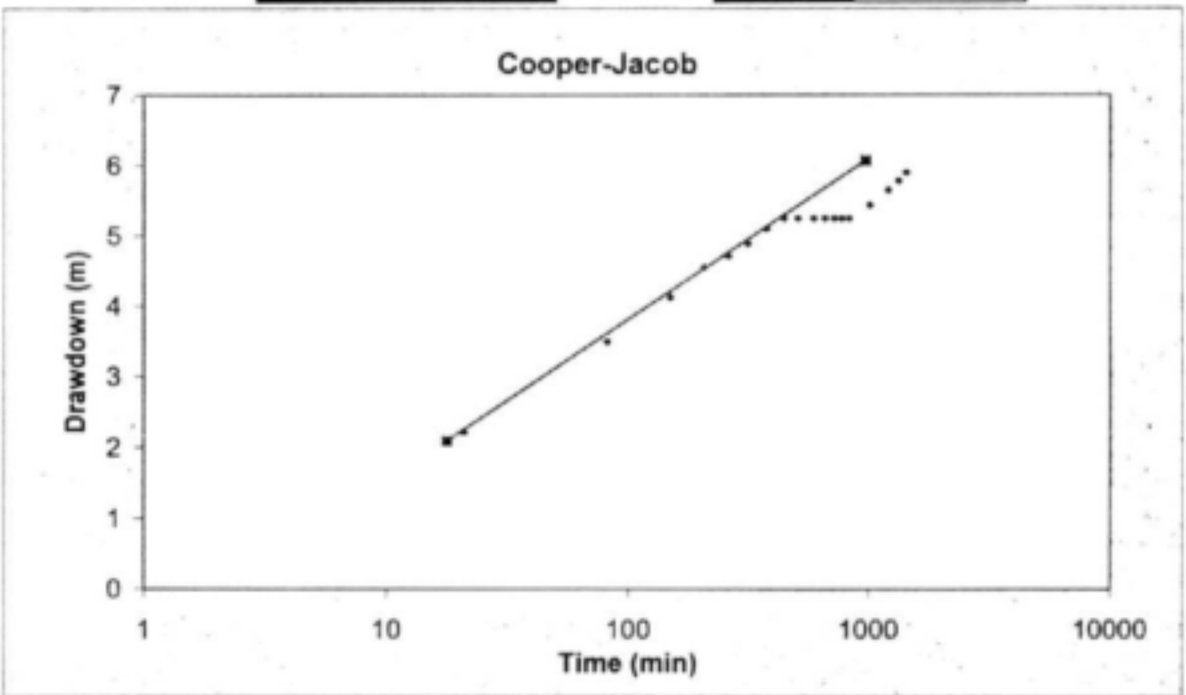


Appendix C.6

Cooper-Jacob method

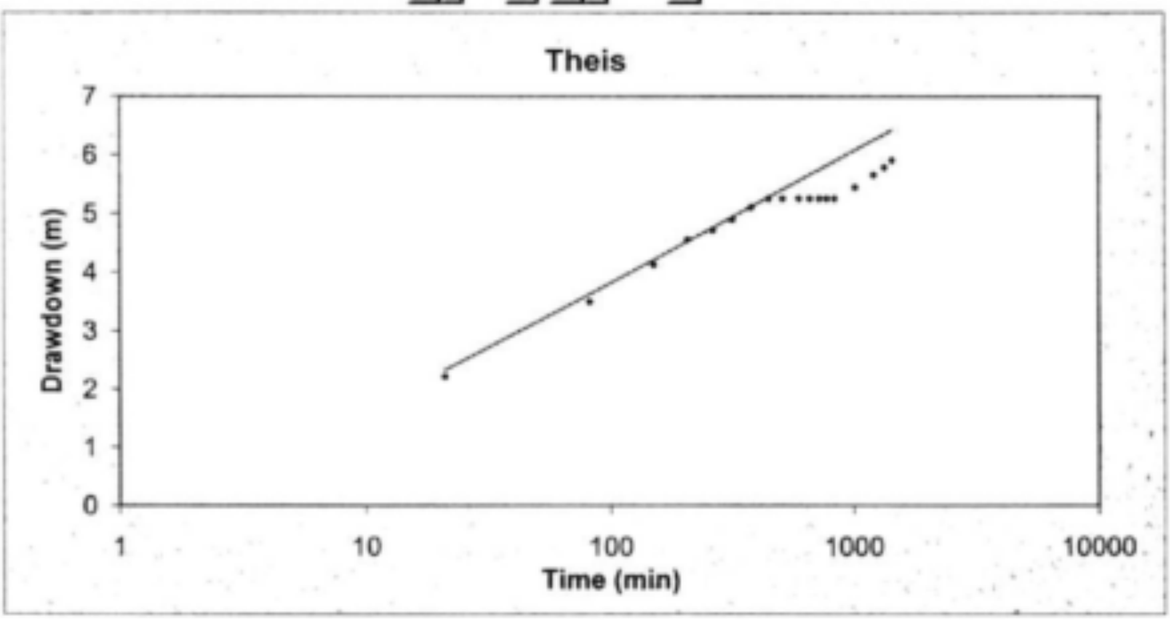
UO 5 (Sep 2000 - 2 l/s), UO27

T(m^2/d) =	13.8	r_e (m)=	11.50	11.5
S =	3.55E-04	Q (l/s) =	2	



Theis

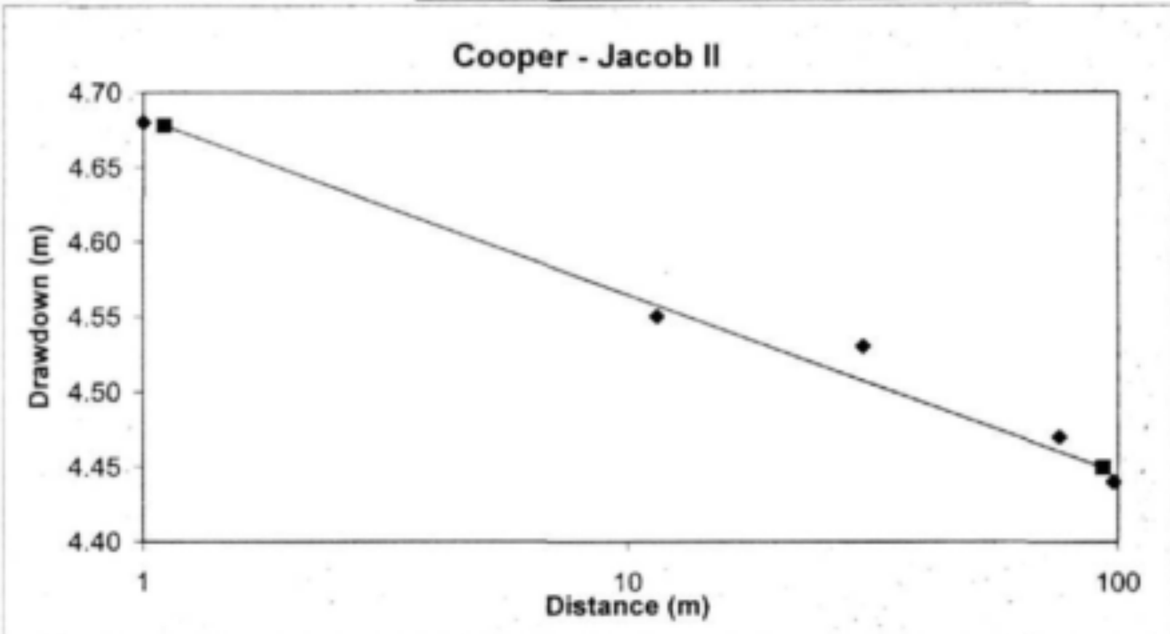
T (m2/d)	S	r
14	3.46E-04	11.50



Appendix C.6

Cooper-Jacob 2: Distance drawdown

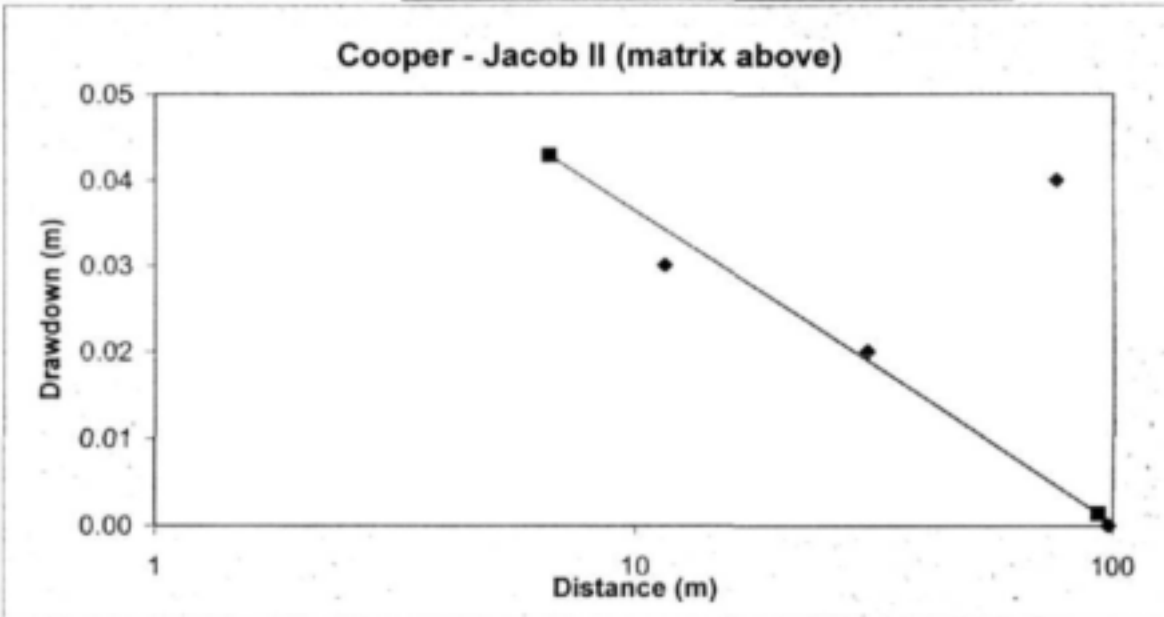
	UO5	UO27c	UO28c	UO29c	UO23c	Obs 6
Distance r (m)	1	11.5	30.4	76	98	
Drawdown (m)	4.68	4.55	4.53	4.47	4.44	
Time (minutes)	200					
		T (m^2/d) =	533.71	S	5.73E-40	



Appendix C.6

Cooper-Jacob 2: Distance drawdown

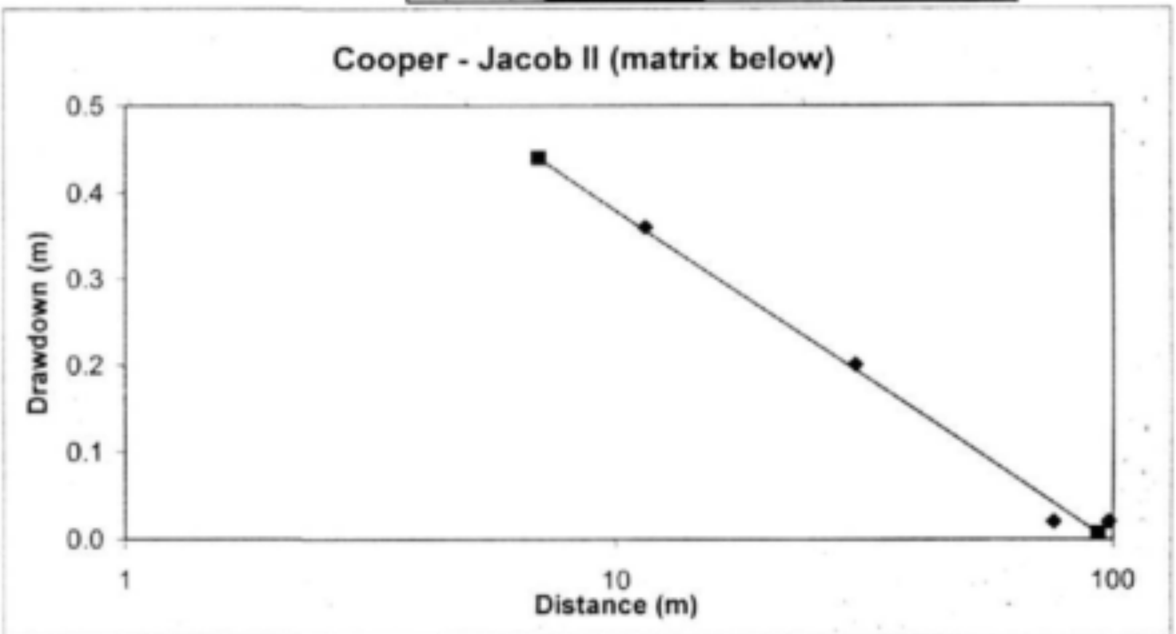
	UO5	UO27a	UO28a	UO29a	UO23a	Obs 6
Distance r (m)	1	11.5	30.4	76	98	
Drawdown (m)		0.03	0.02	0.04	0	
Time (minutes)	1000					
		T (m^2/d) =	1753.73	S	2.88E-01	



Appendix C.6

Cooper-Jacob 2: Distance drawdown

	UO5	UO27b	UO28b	UO29b	UO23b	Obs 6
Distance r (m)	1	11.5	30.4	76	98	
Drawdown (m)		0.36	0.2	0.02	0.02	
Time (minutes)	200					
		T (m^2/d) =	164.87	S	5.67E-03	



Appendix D: Data of Hydraulic Tests

D.1 **Constant Rate Test UO26, Campus Test Site**

D.2 **Multirate Test M1, Meadhurst Test Site**

D.3 **Constant Rate Test M1, Meadhurst Test Site (at 1.4l/s)**

D.4 **Constant Rate Test M1, Meadhurst Test Site (at 2l/s)**

D.5 **Constant Rate Test UO5 (at 0.5 l/s), Campus Test Site**

D.6 **Constant Rate Test UO5 (at 2.0 l/s), Campus Test Site**

Appendix D.1 **Constant Rate Test UO26**

Project & no:		Pump type used:	Submersible	Contractor:				
District:		Pump inlet depth (mbgl):		Recorder:				
Location:	IGS Test site	Saturated thickness (m):	7.55	Discharge container size:	Liter:	20	cubic m:	0.02

Pumped borehole no:	UO 26			Obsevation borehole(s):		Observation 1	Observation 2	Observation 3	Observation 4
Date started:	3/3/2000	Borehole depth before (mbgl):		Borehole number:		UO 27	UO28	UO29	
Date ended:	4/3/2000	Borehole depth after (mbgl):		Distance (m):					
X:		Casing depth (mbgl):		Borehole depth (mbgl):					
Y:		Casing diameter (m):	0.16	Casing depth (mbgl):					
Z:		Static water level (mbgl):	13.45	Casing diameter (m):		0.16	0.16	0.16	
Temp (°C)		Casing height (magl):		Static water level (mbgl):		13.28	13.54	14.64	
EC (mS/m)		Datum level (magl):		Casing height (magl):					
Ph:		Available drawdown (m):	7.55	Datum level (magl):				0.2	

Pumped borehole									*Obsevation (1)*		*Obsevation (2)*		*Observation (3)*		*Observation (4)*	
Time:		Water level (m)	Draw-down (m)	Yield (L/s)	Recovery			Elapsed time (min)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)
HH:MM	Elapsed (min)				Time HH:MM	Water level (m)	Draw-down (m)									
16:08	1	13.72	0.27		5:08	15.60	2.15	1	13.35	0.07	13.63	0.09	14.68	0.04		
	2	13.76	0.31			15.57	2.12	2	13.40	0.12	13.65	0.11	14.74	0.10		
	3	13.81	0.36			15.55	2.10	3	13.46	0.18	13.69	0.15	14.78	0.14		
	4	13.85	0.40			15.49	2.04	4	13.49	0.21	13.76	0.22	14.82	0.18		
	5	13.89	0.44	0.71		15.46	2.01	5	13.53	0.25	13.81	0.27	14.85	0.21		
	6	13.91	0.46			15.43	1.98	6	13.56	0.28	13.84	0.30	14.89	0.25		
	7	13.95	0.50			15.40	1.95	7	13.60	0.32	13.86	0.32	14.91	0.27		
	8	13.98	0.53			15.38	1.93	8	13.63	0.35	13.90	0.36	14.94	0.30		
	9	14.01	0.56			15.34	1.89	9	13.65	0.37	13.92	0.38	14.95	0.31		
16:17	10	14.04	0.59		5:17	15.32	1.87	10	13.69	0.41	13.95	0.41	14.99	0.35		
	11	14.07	0.62			15.29	1.84	11	13.71	0.43	13.98	0.44	15.03	0.39		
	12	14.09	0.64			15.27	1.82	12	13.73	0.45	14.00	0.46	15.06	0.42		
	13	14.11	0.66			15.25	1.80	13	13.76	0.48	14.02	0.48	15.08	0.44		
	14	14.14	0.69			15.23	1.78	14	13.78	0.50	14.05	0.51	15.10	0.46		
	15	14.16	0.71			15.20	1.75	15	13.81	0.53	14.08	0.54	15.13	0.49		
	16	14.18	0.73			15.18	1.73	16	13.83	0.55	14.10	0.56	15.15	0.51		
	17	14.20	0.75	0.71		15.16	1.71	17	13.85	0.57	14.12	0.58	15.17	0.53		
	18	14.22	0.77			15.14	1.69	18	13.87	0.59	14.14	0.60	15.19	0.55		
	19	14.24	0.79			15.13	1.68	19	13.88	0.60	14.15	0.61	15.21	0.57		
16:27	20	14.26	0.81		5:27	15.11	1.66	20	13.90	0.62	14.18	0.64	15.23	0.59		
16:37	30	14.38	0.93		5:37	14.97	1.52	30	14.02	0.74	14.29	0.75	15.40	0.76		
16:47	40	14.50	1.05		5:47	14.85	1.40	40	14.15	0.87	14.42	0.88	15.50	0.86		
16:57	50	14.62	1.17		5:57	14.77	1.32	50	14.26	0.98	14.53	0.99	15.61	0.97		
17:07	60	14.69	1.24		6:07	14.70	1.25	60	14.34	1.06	14.60	1.06	15.69	1.05		
	70	14.76	1.31			14.63	1.18	70	14.40	1.12	14.69	1.15	15.74	1.10		
	80	14.82	1.37			14.58	1.13	80	14.46	1.18	14.74	1.20	15.81	1.17		
	90	14.87	1.42			14.54	1.09	90	14.52	1.24	14.78	1.24	15.86	1.22		
	100	14.92	1.47			14.45	1.00	100	14.56	1.28	14.84	1.30	15.90	1.26		
18:07	120	15.01	1.56		7:07	14.42	0.97	120	14.56	1.28	14.91	1.37	15.98	1.34		
18:37	150	15.11	1.66	0.71	7:37	14.34	0.89	150	14.75	1.47	15.01	1.47	16.09	1.45		
19:27	200	15.24	1.79		8:27	14.23	0.78	200	14.88	1.60	15.15	1.61	16.21	1.57		
20:17	250	15.35	1.90	0.71	9:17	14.14	0.69	250	14.98	1.70	15.25	1.71	16.33	1.69		
21:07	300	15.43	1.98	0.70	10:07	14.07	0.62	300	15.08	1.80	15.34	1.80	16.45	1.81		
22:07	360	15.51	2.06		11:07	14.01	0.56	360	15.15	1.87	15.42	1.88	16.50	1.86		
23:07	420	15.58	2.13		12:07	13.96	0.51	420	15.22	1.94	15.49	1.95	16.57	1.93		
0:07	480	15.64	2.19	0.70	13:07	13.89	0.44	480	15.29	2.01	15.56	2.02	16.62	1.98		
1:07	540	15.70	2.25		14:07	13.86	0.41	540	15.34	2.06	15.61	2.07	16.68	2.04		
2:07	600	15.74	2.29		15:07	13.80	0.35	600	15.37	2.09	15.65	2.11	16.73	2.09		
3:07	660	15.79	2.34		16:07	13.76	0.31	660	15.43	2.15	15.69	2.15	16.77	2.13		
4:07	720	15.83	2.38	0.70	17:07	13.74	0.29	720	15.48	2.20	15.74	2.20	16.81	2.17		
5:07	780	15.89	2.44	0.70				780	15.54	2.26	15.80	2.26	16.86	2.22		

Borehole M1 - Multi rate data

First step of 3 l/s on 10 March; step of 1.5 l/s on 10 March;
step of 2 l/s on 11 March and step of 2.5 l/s on 12 March

Note: During the multi rate step of 3 l/s the yield dropped to 2.5 l/s after 60 minutes

Multi rate data							
	Step1	Step1	Step3	Step4	Step5	Step6	Step7
Q (l/s) =	1.45	2	2.5	3			
t(min)	s (m)	s (m)	s (m)	s (m)	s (m)	s (m)	s (m)
1	1.46	2.11	3.96	4.53			
2	2.05	3.02	5.55	6.8			
3	2.37	3.65	6.75	8.03			
4	2.75	3.83	7.2	8.94			
5	2.91	3.91	7.5	9.78			
6	2.53	3.99	7.7	10.23			
7	2.28	4.09	7.93	10.48			
8	2.04	4.17	8.28	10.74			
9	1.98	4.24	8.47	10.87			
10	1.95	4.25	8.62	11.07			
11	1.95	4.29	8.75	11.32			
12	1.96	4.33	8.82	11.68			
13	1.97	4.37	9.05	12			
14	1.98	4.39	9.16	12.88			
15	1.98	4.42	9.28	13.25			
16	1.98	4.44	9.36	13.53			
17	1.99	4.46	9.38	13.85			
19	1.99	4.47	9.44	14.01			
20	1.99	4.5	9.45	14.38			
30	2.15	4.7	9.44	16.03			
40	2.19	4.78	9.61	16.62			
50	2.24	4.9	9.75	17.51			
60	3.28	5.5	9.94	17.78			

Borehole M1, Constant Rate Test

Discharge Rate of 1.4 l/s

Static WL	21.22	20.62	20.72	20.17
Time (min)	M1 (0.08)	M2 (21.7)	M3 (21.9)	M5 (80.2)
1	2.46	0.36	0	0
2	3.05	0.59	0.02	0.01
3	3.37	0.73		0.01
4	3.75	0.78		0.01
5	3.91	0.86	0.06	0.02
6	5.53	0.88	0.07	0.02
7	4.28	0.89	0.07	0.02
8	3.04	0.8	0.06	0.02
9	2.98	0.78	0.07	0.02
10	2.95	0.76	0.09	0.03
11	2.95	0.76	0.09	0.03
12	2.96	0.76	0.09	0.03
13	2.97	0.76	0.09	0.03
14	2.97	0.76	0.08	0.03
15	2.98	0.76	0.08	0.03
16	2.98	0.76	0.09	0.03
17	2.98	0.76	0.09	0.03
18	2.99	0.76	0.08	0.03
19	2.99	0.77	0.08	0.03
20	2.99	0.77	0.09	0.03
30	3.15	0.78	0.09	0.03
40	3.19	0.82	0.1	0.03
50	3.24	0.83	0.11	0.03
60	3.28	0.84	0.12	0.03
70	3.3	0.85	0.12	0.04
80	3.33	0.86	0.12	0.04
90	3.34	0.86	0.12	0.04
100	3.39	0.87	0.12	0.04
120	3.44	0.88	0.12	0.04
150	3.58	0.92	0.14	0.05
200	3.63	0.94	0.14	0.05
250	3.69	0.95	0.15	0.05
300	3.74	0.97	0.17	0.055
360	3.93	1.02	0.18	0.062
420	4.01	1.05	0.19	0.068
480	4.02	1.05	0.19	0.07
540	4.07	1.055	0.19	0.07
600	4.12	1.065	0.194	0.071
660	4.14	1.07	0.2	0.075
720	4.17	1.08	0.205	0.08
780	4.21	1.093	0.21	0.082
840	4.22	1.1	0.215	0.09
900	4.23	1.1	0.215	0.09
960	4.24	1.1	0.22	0.09

Appendix D.3 **Constant Rate Test M1**

Recovery					
Time	Total time	M1 (0.08)	M2 (21.7)	M3 (21.9)	M5 (80.2)
1	961	0.7	1.12	0.22	0.09
2	962	0.45	0.32	0.19	0.09
3	963	0.33	0.27	0.17	0.09
4	964	0.27	0.22	0.14	0.08
5	965	0.24	0.2	0.135	0.07
6	966	0.22	0.17	0.13	0.07
7	967	0.2	0.17	0.125	0.07
8	968	0.19	0.16	0.12	0.07
9	969	0.18	0.16	0.115	0.06
10	970	0.17	0.155	0.11	0.06
11	971	0.165	0.155	0.105	0.06
12	972	0.16	0.15	0.1	0.06
13	973	0.16	0.15	0.1	0.06
14	974	0.155	0.145	0.095	0.06
15	975	0.15	0.14	0.095	0.06
16	976	0.15	0.14	0.095	0.06
17	977	0.145	0.14	0.09	0.06
18	978	0.14	0.14	0.09	0.06
19	979	0.14	0.13	0.085	0.06
20	980	0.135	0.13	0.085	0.05
30	990	0.12	0.115	0.07	0.04
40	1000	0.11	0.105	0.06	0.04
50	1010	0.095	0.095	0.05	0.04
60	1020	0.09	0.09	0.04	0.04
70	1030	0.08	0.084	0.04	0.04
80	1040	0.075	0.08	0.03	0.03
90	1050	0.07	0.075	0.025	0.03
100	1060	0.06	0.07	0.025	0.03
120	1080	0.06	0.06	0.015	0.02

Borehole:		Constant Rate Test Meadhurst M1, at 2l/s										
Q (l/s)=	2					Recovery data						
t (min)	s (m)	avg s'	avg s"	avg T	avg S	Time t'	Res_s	t/t'	Wl rise	s'	Rec_T
1.00	2.11					0.5	3.52	2161	3.46		
2.00	3.02					1	2.02	1081	4.96	2.99	
3.00	3.65	3.32	-1.95			2	1.72	541	5.26	2.31	
4.00	3.83	1.74	-1.64	18.01	1.35E-06	3	0.84	361	6.14	4.11	11.6
5.00	3.91	1.32	-0.73	28.58	1.35E-06	4	0.5	271	6.48	2.15	16.2
6.00	3.99	1.21	-0.09	26.90	1.35E-06	5	0.37	217	6.61	0.84	32.8
7.00	4.09	1.25	-0.21	23.49	1.35E-06	7	0.29	155.3	6.69	0.50	63.3
8.00	4.17	1.16	-1.05	25.60	1.35E-06	10	0.22	109	6.76	0.30	108.5
9.00	4.24	0.98	-1.23	33.47	1.35E-06	15	0.19	73	6.79	0.17	187.2
10.00	4.25	0.87	-0.35	39.47	1.35E-06	20	0.17	55	6.81	0.10	#DIV/0!
11.00	4.29	0.89	0.42	35.76	1.35E-06	30	0.16	37	6.82	######	#DIV/0!
12.00	4.33	0.94	0.19	31.43	1.35E-06			#####	#####	######	#DIV/0!
13.00	4.37	0.93	-0.59	33.66	1.35E-06			#####	#####	######	#DIV/0!
14.00	4.39	0.86	-1.30	36.94	1.35E-06			#####	#####	######	#DIV/0!
15.00	4.42	0.77	-1.97	39.44	1.35E-06			#####	#####	######	#DIV/0!
16.00	4.44	0.67	-1.74	46.72	1.35E-06			#####	#####	######	#DIV/0!
17.00	4.46	0.61	-0.09	57.81	1.35E-06			#####	#####	######	#DIV/0!
19.00	4.47	0.69	1.16	52.06	1.35E-06			#####	#####	######	#DIV/0!
20.00	4.5	0.85	1.50	32.01	1.35E-06			#####	#####	######	#DIV/0!
30.00	4.7	1.15	1.07	31.36	1.35E-06			#####	#####	######	#DIV/0!
40.00	4.78	1.61	1.54	20.91	1.35E-06			#####	#####	######	#DIV/0!
50.00	4.9	2.44	1.41	11.51	2.14E-05			#####	#####	######	#DIV/0!
60.00	5.33	3.04	-0.18	9.01	4.41E-05			#####	#####	######	#DIV/0!
70.00	5.6	2.50	-2.46	9.01	4.41E-05			#####	#####	######	#DIV/0!
80.00	5.64	1.58	-4.12	9.01	4.41E-05			#####	#####	######	#DIV/0!
90.00	5.7	0.89	-3.16	9.01	4.41E-05			#####	#####	######	#DIV/0!
100.00	5.74	0.71	-1.24	9.01	4.41E-05			#####	#####	######	#DIV/0!
150.00	5.85	0.81	0.70	9.01	4.41E-05			#####	#####	######	#DIV/0!
240.00	5.87	1.22	0.98	9.01	4.41E-05			#####	#####	######	#DIV/0!
360.00	6.32	1.74	0.54	9.01	4.41E-05			#####	#####	######	#DIV/0!
420.00	6.5	1.88	-0.52	9.01	4.41E-05			#####	#####	######	#DIV/0!
480.00	6.59	1.66	-1.67	9.01	4.41E-05			#####	#####	######	#DIV/0!
540.00	6.67	1.26	-2.75	9.01	4.41E-05			#####	#####	######	#DIV/0!
600.00	6.71	0.90	-3.36	9.01	4.41E-05			#####	#####	######	#DIV/0!
660.00	6.75	0.64	-3.15	9.01	4.41E-05			#####	#####	######	#DIV/0!
720.00	6.76	0.50	-1.43	9.01	4.41E-05			#####	#####	######	#DIV/0!
780.00	6.77	0.49	1.26	9.01	4.41E-05			#####	#####	######	#DIV/0!
840.00	6.79	0.60	4.29	9.01	4.41E-05			#####	#####	######	#DIV/0!
900.00	6.81	0.90	#NUM!	9.01	4.41E-05			#####	#####	######	#DIV/0!
960.00	6.83	#NUM!	#NUM!	9.01	4.41E-05			#####	#####	######	#DIV/0!
1020.00	6.87	#NUM!	#NUM!	9.01	4.41E-05			#####	#####	######	#DIV/0!
1080.00	6.98	#NUM!	#NUM!	9.01	4.41E-05			#####	#####	######	#DIV/0!
		#NUM!	#NUM!	9.01	4.41E-05			#####	#####	######	#DIV/0!
		#NUM!	#NUM!	9.01	4.41E-05			#####	#####	######	#DIV/0!
		#NUM!	#NUM!	9.01	4.41E-05			#####	#####	######	#DIV/0!
		#NUM!	#NUM!	9.01	4.41E-05			#####	#####	######	#DIV/0!
		#NUM!	#NUM!	9.01	4.41E-05			#####	#####	######	#DIV/0!
		#NUM!	#NUM!	9.01	4.41E-05			#####	#####	######	#DIV/0!
		#NUM!	#NUM!	9.01	4.41E-05			#####	#####	######	#DIV/0!
		#NUM!	#NUM!	9.01	4.41E-05			#####	#####	######	#DIV/0!
		#NUM!	#NUM!	9.01	4.41E-05			#####	#####	######	#DIV/0!
		#NUM!	#NUM!	9.01	4.41E-05			#####	#####	######	#DIV/0!
		#NUM!	#NUM!	9.01	4.41E-05			#####	#####	######	#DIV/0!
		#NUM!	#NUM!	9.01	4.41E-05			#####	#####	######	#DIV/0!

Appendix D.5 **CONSTANT RATE DISCHARGE TEST**

Project & no:	NIGS 112	Pump type used:	Grundfos	Projectleader:	W.-H. Chiang
District:	Bloemfontein	Pump inlet depth (mbgl):	25	Recorder:	K. Riemann
Location:	Campus Test Site	Possible Flowrate (l/s)	1.0		P. Dzanga

Pumped borehole no:			UO5	Observation Boreholes		UO27	UO28	UO29	UO23	UO26	UO6	UO30
Date started:		7/11/2000		Time started:	13:27:00		Borehole depth before (mbgl):					
Date ended:		7/14/2000		Time ended:	8:15:00		Borehole depth after (mbgl):					
X:				Recovery started:	7/14/00 8:15		Casing depth (mbgl):				5.00	
Y:				Recovery ended:	7/20/00 18:00		Casing diameter (m):				0.16	
Z:				Duration pumping:	66:48:00		Static water level (mbgl):				11.97	
Temp (°C)				Duration recovery:	153:45:00		Casing height (magl):					
EC (mS/m)				Average Yield (l/s)	0.5		Datum level (magl)					
Ph:				Total Discharge (l)	120240		Available drawdown (m):				10.00	

Pumped borehole										Recovery			
Time:		Water level	Draw-down	Yield	Time:		Water level	Draw-down	Yield	Time:		Water level	Draw-down
HH:MM	Elapsed (min)	(m)	(m)	(L/s)	HH:MM	Elapsed (min)	(m)	(m)	(L/s)	HH:MM	Elapsed (min)	(m)	(m)
	2	12.05	0.08			3480	13.93	1.96			1	13.84	1.87
	4	12.09	0.12			3600	13.94	1.97			2	13.80	1.83
	6	12.12	0.15			3720	13.94	1.97			3	13.78	1.81
	8	12.15	0.17			3840	13.94	1.97			4	13.75	1.78
	10					3960	13.95	1.98			5	13.73	1.76
	12	12.19	0.22					0.00			6	13.71	1.74
	14	12.21	0.24					0.00			7	13.69	1.72
	16	12.23	0.25					0.00			8	13.67	1.70
	18	12.24	0.27					0.00			9	13.65	1.68
	20	12.26	0.29					0.00			10	13.63	1.66
	25	12.29	0.32					0.00			11	13.62	1.65
	30	12.31	0.34					0.00			12	13.60	1.63
	40	12.36	0.39					0.00			13	13.59	1.62
	50	12.39	0.42					0.00			14	13.57	1.60
	60	12.55	0.57					0.00			15	13.56	1.59
	70	12.66	0.68					0.00			16	13.55	1.58
	80	12.73	0.76					0.00			17	13.54	1.57
	90	12.79	0.82					0.00			18	13.52	1.55
	100	12.84	0.87					0.00			19	13.51	1.54
	110	12.88	0.90					0.00			20	13.50	1.53
	120	12.92	0.94					0.00			30	13.41	1.44
	150	12.98	1.01					0.00			40	13.33	1.36
	180	13.05	1.08					0.00			50	13.28	1.31
	210	13.09	1.12					0.00			60	13.23	1.26
	240	13.13	1.16					0.00			70	13.19	1.22
	300	13.21	1.24					0.00			80	13.15	1.18
	360	13.27	1.30					0.00			90	13.12	1.15
	420	13.32	1.35					0.00			100	13.09	1.12
	480	13.37	1.40					0.00			110	13.06	1.09
	540	13.40	1.43					0.00			120	13.04	1.07
	600	13.43	1.46					0.00			150	12.97	1.00
	660	13.46	1.49					0.00			180	12.92	0.95
	720	13.48	1.51					0.00			210	12.87	0.90
	780	13.50	1.53					0.00			240	12.82	0.85
	840	13.53	1.56					0.00			300	12.74	0.77
	900	13.54	1.57					0.00			360	12.67	0.70
	960	13.56	1.59					0.00			420	12.62	0.65
	1020	13.58	1.61					0.00			480	12.57	0.60
	1080	13.60	1.63					0.00			540	12.54	0.57
	1140	13.62	1.65					0.00		0:00:00	945	12.40	0.43
	1200	13.65	1.68					0.00		8:00	1425	12.32	0.35
	1260	13.67	1.70					0.00		12:00	1665	12.29	0.32
	1320	13.68	1.71					0.00		16:00	1905	12.26	0.29
	1380	13.68	1.71					0.00		0:00	2385	12.26	0.29
	1440	13.69	1.72					0.00		8:00	2865	12.25	0.28
	1560	13.70	1.73					0.00		12:00	3105	12.24	0.27
	1680	13.73	1.76					0.00		16:00	3345	12.21	0.24
	1800	13.76	1.79					0.00		0:00	3825	12.19	0.22
	1920	13.78	1.81					0.00		8:00	4305	12.17	0.20
	2040	13.80	1.83					0.00		17:30	4875	12.13	0.16
	2160	13.81	1.84					0.00		9:00	5805	12.09	0.12
	2280	13.83	1.86					0.00			5865		-11.97
	2400	13.85	1.88					0.00			5925		-11.97
	2520	13.85	1.88					0.00			5985		-11.97
	2640	13.87	1.90					0.00			6045		-11.97
	2760	13.88	1.91					0.00			6105		-11.97
	2880	13.88	1.91					0.00			6165		-11.97
	3000	13.88	1.91					0.00			6225		-11.97
	3120	13.89	1.92					0.00			6285		-11.97
	3240	13.91	1.94					0.00			6345		-11.97
	3360	13.93	1.96					0.00			6405		-11.97

CONSTANT RATE DISCHARGE TEST

Project & no:	NIGS 112	Pumping Borehole No.	UO5	Projectleader:	W.-H. Chiang
District:	Bloemfontein	Date starting Recovery	7/14/2000	Recorder:	K. Riemann
Location:	Campus Test Site	Time starting Recovery	8:15:00		P. Dzanga

	Observation 1	Observation 2	Observation 3	Observation 4	Observation 5	Observation 6
Borehole number:	UO 26	UO 6_f	UO 6_m	UO 30	UO 7	UO 20
Distance (m):	16.1	5.3		92.5	7.0	16.2
Borehole depth (mbdl):	30.4	30.0		30.4	30.0	30.0
Wellscreen top (mbdl):	no Wellscreen			no Wellscreen		
Wellscreen bottom (mbdl):						
Static water level (mbdl):	12.50	11.96	13.13	13.86	12.12	12.14
Wellscreen diamter (m):	0.16	0.03	0.03	0.16	0.16	0.16
Datum level (magl)						

Time:			UO 26		UO 6_f		UO 6_m		UO 30		UO 7		UO 20	
Date	HH:mm	Elapsed (min)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)
		2		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		4		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		6		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		8		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		10		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		12		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		14		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		16		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		18		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		20	14.10	1.60	12.04	0.08	13.14	0.01		-13.86	13.62	1.50	13.65	1.51
		30	13.94	1.44	12.04	0.08	13.14	0.01	15.35	1.49	13.54	1.42	13.56	1.42
		40	13.87	1.37	12.04	0.08	13.14	0.01	15.27	1.41	13.48	1.36	13.50	1.36
		50	13.82	1.32	12.04	0.08	13.14	0.01	15.20	1.34	13.41	1.29	13.43	1.29
		60	13.77	1.27	12.04	0.08	13.14	0.01	15.15	1.29	13.37	1.25	13.39	1.25
		70	13.73	1.23	12.04	0.08	13.14	0.01	15.10	1.24	13.33	1.21	13.34	1.20
		80	13.69	1.19	12.04	0.08	13.14	0.01	15.06	1.20	13.30	1.18	13.31	1.17
		90	13.66	1.16	12.04	0.08	13.14	0.01	15.03	1.17	13.27	1.15	13.28	1.14
		100	13.63	1.13	12.04	0.08	13.14	0.01	15.00	1.14	13.24	1.12	13.26	1.12
		110	13.60	1.10	12.04	0.08	13.14	0.01	14.97	1.11	13.21	1.09	13.23	1.09
		120	13.58	1.08	12.04	0.08	13.14	0.01	14.95	1.09	13.19	1.07	13.21	1.07
		150	13.51	1.01	12.05	0.09	13.14	0.01	14.86	1.00	13.12	1.00	13.14	1.00
		180	13.46	0.96	12.05	0.09	13.14	0.01	14.82	0.96	13.06	0.94	13.09	0.95
		210	13.39	0.89	12.05	0.09	13.14	0.01	14.77	0.91	13.01	0.89	13.03	0.89
		240	13.35	0.85	12.05	0.09	13.14	0.01	14.72	0.86	12.96	0.84	13.00	0.86
		300	13.28	0.78	12.05	0.09	13.14	0.01	14.63	0.77	12.88	0.76	12.91	0.77
		360	13.21	0.71	12.05	0.09	13.14	0.01	14.57	0.71	12.82	0.70	12.85	0.71
		420	13.15	0.65	12.05	0.09	13.14	0.01	14.51	0.65	12.76	0.64	12.78	0.64
		480	13.11	0.61	12.05	0.09	13.14	0.01	14.48	0.62	12.71	0.59	12.74	0.60
		540	13.07	0.57	12.05	0.09	13.14	0.01	14.42	0.56	12.68	0.56	12.70	0.56
		945	12.92	0.42	12.07	0.11	13.14	0.01	14.27	0.41	12.54	0.42	12.55	0.41
		1425	12.84	0.34	12.08	0.12	13.15	0.02	14.19	0.33	12.46	0.34	12.48	0.34
		1665	12.81	0.31	12.08	0.12	13.15	0.02	14.16	0.30	12.43	0.31	12.44	0.30
		1905	12.77	0.27	12.09	0.13	13.15	0.02	14.13	0.27	12.40	0.28	12.42	0.28
		2385	12.76	0.26	12.09	0.13	13.15	0.02	14.12	0.26	12.40	0.28	12.41	0.27
		2865	12.75	0.25	12.10	0.14	13.16	0.03	14.11	0.25	12.40	0.28	12.40	0.26
		3105	12.75	0.25	12.10	0.14	13.15	0.02	14.10	0.24	12.38	0.26	12.39	0.25
		3345	12.72	0.22	12.09	0.13	13.14	0.01	14.08	0.22	12.35	0.23	12.35	0.21
		3825	12.71	0.21	12.10	0.14	13.15	0.02	14.06	0.20	12.33	0.21	12.33	0.19
		4305	12.69	0.19	12.11	0.15	13.15	0.02	14.04	0.18	12.31	0.19	12.31	0.17
		4875	12.65	0.15	12.10	0.14	13.14	0.01	13.99	0.13	12.27	0.15	12.29	0.15
		5805	12.61	0.11	12.11	0.15	13.14	0.01	13.95	0.09	12.23	0.11	12.24	0.10
		5865		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		5925		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		5985		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		6045		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		6105		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		6165		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		6225		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		6285		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		6345		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		6405		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		6465		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		6525		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		6585		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		6645		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		6705		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		6765		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		6825		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		6885		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		6945		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		7005		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		7065		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		7125		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		7185		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		7245		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		7305		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14
		7365		-12.50		-11.96		-13.13		-13.86		-12.12		-12.14

Appendix D.5

CONSTANT RATE DISCHARGE TEST

Project & no:	NIGS 112	Pumping Borehole No.	UO6	Projectleader:	W.-H. Chiang
District:	Bloemfontein	Date starting Recovery	7/14/2000	Recorder:	K. Riemann
Location:	Campus Test Site	Time starting Recovery	8:15:00		P. Dzanga

Obsevation borehole(s):	Observation 1	Observation 2	Observation 3	Observation 4	Observation 5	Observation 6
Borehole number:	UO 27a	UO 27b	UO 27c	UO 28a	UO 28b	UO 28c
Distance (m):		11.5			27.2	
Borehole depth (mbdl):		30.4			30.4	
Wellscreen top (mbdl):	18.0	23.0	20.0	18.7	23.7	20.0
Wellscreen bottom (mbdl):	19.0	24.0	22.0	19.3	24.3	23.0
Static water level (mbdl):	7.68	12.31	12.34	9.95	12.34	12.60
Wellscreen diamter (m):	0.03	0.03	0.05	0.03	0.03	0.05
Datum level (magl)						

Time:			*UO 27a*		*UO 27b*		*UO 27c*		*UO 28a*		*UO 28b*		*UO 28c*	
Date	HH:mm	Elapsed (min)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)
		2	7.79	0.11	13.91	1.60	14.25	1.91	10.04	0.09	12.67	0.33	14.38	1.78
		4	7.79	0.11	13.91	1.60	14.13	1.79	10.05	0.10	12.67	0.33	14.35	1.75
		6	7.79	0.11	13.91	1.60	14.08	1.74	10.05	0.10	12.67	0.33	14.31	1.71
		8	7.79	0.11	13.91	1.60	14.05	1.71	10.06	0.11	12.67	0.33	14.30	1.70
		10	7.80	0.12	13.91	1.60	14.01	1.67	10.06	0.11	12.67	0.33	14.28	1.68
		12	7.80	0.12	13.91	1.60	13.98	1.64	10.06	0.11	12.67	0.33	14.25	1.65
		14	7.80	0.12	13.91	1.60	13.95	1.61	10.06	0.11	12.67	0.33	14.22	1.62
		16	7.80	0.12	13.91	1.60	13.92	1.58	10.06	0.11	12.67	0.33	14.19	1.59
		18	7.80	0.12	13.91	1.60	13.90	1.56	10.06	0.11	12.67	0.33	14.17	1.57
		20	7.80	0.12	13.91	1.60	13.88	1.54	10.06	0.11	12.67	0.33	14.14	1.54
		30	7.80	0.12	13.91	1.60	13.79	1.45	10.07	0.12	12.67	0.33	14.05	1.45
		40	7.80	0.12	13.91	1.60	13.71	1.37	10.07	0.12	12.68	0.34	13.98	1.38
		50	7.81	0.13	13.91	1.60	13.65	1.31	10.07	0.12	12.68	0.34	13.92	1.32
		60	7.81	0.13	13.91	1.60	13.60	1.26	10.07	0.12	12.68	0.34	13.87	1.27
		70	7.81	0.13	13.91	1.60	13.56	1.22	10.07	0.12	12.68	0.34	13.83	1.23
		80	7.81	0.13	13.91	1.60	13.52	1.18	10.07	0.12	12.68	0.34	13.79	1.19
		90	7.81	0.13	13.91	1.60	13.49	1.15	10.07	0.12	12.69	0.35	13.75	1.15
		100	7.81	0.13	13.91	1.60	13.46	1.12	10.07	0.12	12.69	0.35	13.72	1.12
		110	7.81	0.13	13.91	1.60	13.43	1.09	10.07	0.12	12.69	0.35	13.70	1.10
		120	7.82	0.14	13.90	1.59	13.41	1.07	10.08	0.13	12.69	0.35	13.68	1.08
		150	7.83	0.15	13.88	1.57	13.34	1.00	10.08	0.13	12.69	0.35	13.62	1.02
		180	7.83	0.15	13.88	1.57	13.29	0.95	10.14	0.19	12.71	0.37	13.56	0.96
		210	7.83	0.15	13.87	1.56	13.23	0.89	10.09	0.14	12.70	0.36	13.49	0.89
		240	7.83	0.15	13.85	1.54	13.19	0.85	10.07	0.12	12.69	0.35	13.45	0.85
		300	7.83	0.15	13.83	1.52	13.10	0.76	10.06	0.11	12.69	0.35	13.37	0.77
		360	7.84	0.16	13.80	1.49	13.04	0.70	10.06	0.11	12.69	0.35	13.30	0.70
		420	7.84	0.16	13.78	1.47	12.99	0.65	10.08	0.13	12.70	0.36	13.25	0.65
		480	7.84	0.16	13.75	1.44	12.95	0.61	10.08	0.13	12.70	0.36	13.21	0.61
		540	7.84	0.16	13.73	1.42	12.90	0.56	10.08	0.13	12.70	0.36	13.16	0.56
		945	7.84	0.16	13.53	1.22	12.75	0.41	10.08	0.13	12.70	0.36	13.01	0.41
		1425	7.86	0.18	13.33	1.02	12.68	0.34	10.09	0.14	12.72	0.38	12.94	0.34
		1665	7.85	0.17	13.24	0.93	12.64	0.30	10.09	0.14	12.72	0.38	12.90	0.30
		1905	7.85	0.17	13.13	0.82	12.61	0.27	10.09	0.14	12.72	0.38	12.87	0.27
		2385	7.85	0.17	13.02	0.71	12.60	0.26	10.09	0.14	12.72	0.38	12.86	0.26
		2865	7.86	0.18	12.91	0.60	12.59	0.25	10.09	0.14	12.73	0.39	12.86	0.26
		3105	7.86	0.18	12.87	0.56	12.59	0.25	10.09	0.14	12.72	0.38	12.84	0.24
		3345	7.87	0.19	12.82	0.51	12.59	0.25	10.09	0.14	12.72	0.38	12.83	0.23
		3825	7.87	0.19	12.76	0.45	12.55	0.21	10.10	0.15	12.72	0.38	12.80	0.20
		4305	7.87	0.19	12.70	0.39	12.51	0.17	10.10	0.15	12.72	0.38	12.78	0.18
		4875	7.89	0.21	12.64	0.33	12.49	0.15	10.10	0.15	12.71	0.37	12.75	0.15
		5805	7.90	0.22	12.56	0.25	12.44	0.10	10.11	0.16	12.69	0.35	12.71	0.11
		5865		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60
		5925		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60
		5985		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60
		6045		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60
		6105		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60
		6165		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60
		6225		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60
		6285		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60
		6345		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60
		6405		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60
		6465		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60
		6525		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60
		6585		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60
		6645		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60
		6705		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60
		6765		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60
		6825		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60
		6885		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60
		6945		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60
		7005		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60
		7065		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60
		7125		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60
		7185		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60
		7245		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60
		7305		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60
		7365		-7.68		-12.31		-12.34		-9.95		-12.34		-12.60

Appendix D.5

CONSTANT RATE DISCHARGE TEST

Project & no:	NIGS 112	Pumping Borehole No.	UO5	Projectleader:	W.-H. Chiang
District:	Bloemfontein	Date starting Recovery	7/14/2000	Recorder:	K. Riemann
Location:	Campus Test Site	Time starting Recovery	8:15:00		P. Dzanga

Obsevation borehole(s):			Observation 1		Observation 2		Observation 3		Observation 4		Observation 5		Observation 6	
Borehole number:			UO 29a		UO 29b		UO 29c		UO 23a		UO 23b		UO 23c	
Distance (m):			75.9						97.9					
Borehole depth (mbdl):			30.4						46.5					
Wellscreen top (mbdl):			18.0		23.0		20.0		19.2		22.2		20.5	
Wellscreen bottom (mbdl):			19.0		24.0		22.0		19.8		22.8		21.5	
Static water level (mbdl):			12.25		13.45		13.68		7.15		12.76		13.96	
Wellscreen diamter (m):			0.03		0.03		0.05		0.03		0.03		0.05	
Datum level (magl)														
			UO 29a		UO 29b		UO 29c		UO 23a		UO 23b		UO 23c	
Time:			Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)
Date	HH:mm	Elapsed (min)												
		2	12.34	0.09	13.69	0.24	15.55	1.87	7.25	0.10	12.88	0.12		
		4	12.35	0.10	13.69	0.24	15.49	1.81	7.25	0.10	12.88	0.12		
		6	12.35	0.10	13.69	0.24	15.46	1.78	7.25	0.10	12.88	0.12	15.70	1.74
		8	12.35	0.10	13.69	0.24	15.44	1.76	7.25	0.10	12.88	0.12		
		10	12.35	0.10	13.69	0.24	15.36	1.68	7.25	0.10	12.88	0.12	15.63	1.67
		12	12.35	0.10	13.69	0.24	15.34	1.66	7.25	0.10	12.88	0.12	15.60	1.64
		14	12.36	0.11	13.69	0.24	15.31	1.63	7.26	0.11	12.88	0.12	15.55	1.59
		16	12.36	0.11	13.69	0.24	15.27	1.59	7.26	0.11	12.88	0.12	15.55	1.59
		18	12.36	0.11	13.69	0.24	15.26	1.58	7.27	0.12	12.88	0.12	15.52	1.56
		20	12.36	0.11	13.69	0.24	15.23	1.55	7.26	0.11	12.88	0.12	15.50	1.54
		30	12.37	0.12	13.70	0.25	15.14	1.46	7.26	0.11	12.88	0.12	15.43	1.47
		40	12.37	0.12	13.70	0.25	15.07	1.39	7.26	0.11	12.88	0.12	15.36	1.40
		50	12.38	0.13	13.70	0.25	15.00	1.32	7.26	0.11	12.88	0.12	15.30	1.34
		60	12.38	0.13	13.70	0.25	14.95	1.27	7.27	0.12	12.88	0.12	15.24	1.28
		70	12.38	0.13	13.70	0.25	14.91	1.23	7.27	0.12	12.88	0.12	15.20	1.24
		80	12.38	0.13	13.70	0.25	14.87	1.19	7.27	0.12	12.88	0.12	15.16	1.20
		90	12.38	0.13	13.70	0.25	14.84	1.16	7.27	0.12	12.88	0.12	15.14	1.18
		100	12.39	0.14	13.70	0.25	14.81	1.13	7.27	0.12	12.88	0.12	15.10	1.14
		110	12.39	0.14	13.70	0.25	14.78	1.10	7.28	0.13	12.88	0.12	15.06	1.10
		120	12.39	0.14	13.70	0.25	14.76	1.08	7.28	0.13	12.89	0.13	15.05	1.09
		150	12.40	0.15	13.70	0.25	14.70	1.02	7.28	0.13	12.90	0.14	15.01	1.05
		180	12.40	0.15	13.70	0.25	14.64	0.96	7.28	0.13	12.89	0.13	14.93	0.97
		210	12.40	0.15	13.71	0.26	14.59	0.91	7.29	0.14	12.89	0.13	14.88	0.92
		240	12.40	0.15	13.71	0.26	14.54	0.86	7.29	0.14	12.89	0.13	14.84	0.88
		300	12.40	0.15	13.71	0.26	14.46	0.78	7.29	0.14	12.89	0.13	14.74	0.78
		360	12.40	0.15	13.71	0.26	14.40	0.72	7.30	0.15	12.89	0.13	14.68	0.72
		420	12.40	0.15	13.72	0.27	14.35	0.67	7.31	0.16	12.89	0.13	14.62	0.66
		480	12.41	0.16	13.73	0.28	14.30	0.62	7.31	0.16	12.89	0.13	14.57	0.61
		540	12.41	0.16	13.73	0.28	14.26	0.58	7.32	0.17	12.89	0.13	14.53	0.57
		945	12.40	0.15	13.73	0.28	14.11	0.43	7.34	0.19	12.89	0.13	14.38	0.42
		1425	12.40	0.15	13.76	0.31	14.03	0.35	7.37	0.22	12.92	0.16	14.32	0.36
		1665	12.41	0.16	13.77	0.32	13.99	0.31	7.38	0.23	12.91	0.15	14.28	0.32
		1905	12.41	0.16	13.76	0.31	13.96	0.28	7.39	0.24	12.92	0.16	14.25	0.29
		2385	12.41	0.16	13.77	0.32	13.95	0.27	7.39	0.24	12.92	0.16	14.24	0.28
		2865	12.40	0.15	13.77	0.32	13.94	0.26	7.40	0.25	12.93	0.17	14.23	0.27
		3105	12.42	0.17	13.78	0.33	13.94	0.26	7.40	0.25	12.93	0.17	14.23	0.27
		3345	12.42	0.17	13.78	0.33	13.92	0.24	7.40	0.25	12.93	0.17	14.20	0.24
		3825	12.42	0.17	13.78	0.33	13.90	0.22	7.40	0.25	12.93	0.17	14.18	0.22
		4305	12.42	0.17	13.78	0.33	13.88	0.20	7.40	0.25	12.93	0.17	14.16	0.20
		4875	12.43	0.18	13.77	0.32	13.84	0.16	7.40	0.25	12.93	0.17	14.12	0.16
		5805	12.43	0.18	13.77	0.32	13.80	0.12	7.39	0.24	12.92	0.16	14.05	0.09
		5865		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96
		5925		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96
		5985		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96
		6045		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96
		6105		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96
		6165		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96
		6225		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96
		6285		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96
		6345		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96
		6405		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96
		6465		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96
		6525		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96
		6585		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96
		6645		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96
		6705		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96
		6765		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96
		6825		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96
		6885		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96
		6945		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96
		7005		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96
		7065		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96
		7125		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96
		7185		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96
		7245		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96
		7305		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96
		7365		-12.25		-13.45		-13.68		-7.15		-12.76		-13.96

Appendix D.5

CONSTANT RATE DISCHARGE TEST

Project & no:	NIGS 112	Pumping Borehole No.	UO5	Projectleader:	W.-H. Chiang
District:	Bloemfontein	Date starting pumping	7/11/2000	Recorder:	K. Riemann
Location:	Campus Test Site	Time starting pumping	13:27:00		P. Dzanga

Obsevation borehole(s):	Obsevation 1		Observation 2		Observation 3		Observation 4		Obsevation 5		Observation 6	
Borehole number:	UO 26		UO 6_f		UO 6_m		UO 30		UO 7		UO 20	
Distance (m):	16.1		5.3				92.5		7.0		16.2	
Borehole depth (mbdl):	30.4		30.0				30.4		30.0		30.0	
Wellscreen top (mbdl):	no Wellscreen						no Wellscreen					
Wellscreen bottom (mbdl):												
Static water level (mbdl):	12.50		11.96		13.13		13.86		12.12		12.14	
Wellscreen diamter (m):	0.16		0.03		0.03		0.16		0.16		0.16	
Datum level (magl)												

Time:			UO 26		UO 6_f		UO 6_m		UO 30		UO 7		UO 20	
Date	HH:mm	Elapsed (min)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)
		2												
		4												
		6												
		8												
		10												
		12												
		14												
		16												
		18												
		20	12.80	0.30	11.96	0.00	13.13	0.00	14.02	0.16	12.41	0.29	12.42	0.28
		30	12.84	0.34	11.96	0.00	13.14	0.01			12.45	0.33	12.47	0.33
		40	12.88	0.38	11.96	0.00	13.14	0.01			12.50	0.38	12.50	0.36
		50	12.92	0.42	11.96	0.00	13.14	0.01			12.53	0.41	12.55	0.41
		60	13.07	0.57	11.96	0.00	13.14	0.01	14.30	0.44	12.69	0.57	12.71	0.57
		70	13.18	0.68	11.96	0.00	13.14	0.01			12.79	0.67	12.81	0.67
		80	13.25	0.75	11.96	0.00	13.14	0.01			12.87	0.75	12.89	0.75
		90	13.31	0.81	11.96	0.00	13.14	0.01			12.92	0.80	12.94	0.80
		100	13.36	0.86	11.96	0.00	13.14	0.01	14.60	0.74	12.96	0.84	12.98	0.84
		110	13.39	0.89	11.96	0.00	13.14	0.01			13.00	0.88	13.02	0.88
		120	13.42	0.92	11.96	0.00	13.14	0.01			13.04	0.92	13.05	0.91
		150	13.49	0.99	11.96	0.00	13.14	0.01	14.77	0.91	13.11	0.99	13.13	0.99
		180	13.55	1.05	11.96	0.00	13.14	0.01	14.85	0.99	13.17	1.05	13.18	1.04
		210	13.60	1.10	11.96	0.00	13.14	0.01	14.90	1.04	13.21	1.09	13.23	1.09
		240	13.65	1.15	11.96	0.00	13.14	0.01	14.94	1.08	13.26	1.14	13.28	1.14
		300	13.70	1.20	11.96	0.00	13.14	0.01	15.02	1.16	13.33	1.21	13.35	1.21
		360	13.78	1.28	11.96	0.00	13.14	0.01	15.09	1.23	13.41	1.29	13.44	1.30
		420	13.83	1.33	11.96	0.00	13.14	0.01	15.14	1.28	13.44	1.32	13.47	1.33
		480	13.87	1.37	11.96	0.00	13.14	0.01	15.18	1.32	13.50	1.38	13.51	1.37
		540	13.91	1.41	11.97	0.01	13.14	0.01	15.22	1.36	13.53	1.41	13.54	1.40
		600	13.94	1.44	11.97	0.01	13.14	0.01	15.25	1.39	13.56	1.44	13.58	1.44
		660	13.97	1.47	11.97	0.01	13.14	0.01	15.27	1.41	13.59	1.47	13.60	1.46
		720	13.99	1.49	11.97	0.01	13.14	0.01	15.29	1.43	13.61	1.49	13.63	1.49
		780	14.02	1.52	11.97	0.01	13.14	0.01	15.32	1.46	13.64	1.52	13.65	1.51
		840	14.04	1.54	11.97	0.01	13.14	0.01	15.34	1.48	13.66	1.54	13.67	1.53
		900	14.06	1.56	11.97	0.01	13.14	0.01	15.36	1.50	13.68	1.56	13.69	1.55
		960	14.08	1.58	11.97	0.01	13.14	0.01	15.38	1.52	13.69	1.57	13.71	1.57
		1020	14.10	1.60	11.97	0.01	13.14	0.01	15.40	1.54	13.72	1.60	13.73	1.59
		1080	14.12	1.62	11.97	0.01	13.14	0.01	15.42	1.56	13.74	1.62	13.75	1.61
		1140	14.15	1.65	11.97	0.01	13.14	0.01	15.44	1.58	13.76	1.64	13.76	1.62
		1200	14.15	1.65	11.98	0.01	13.14	0.01	15.46	1.60	13.78	1.66	13.79	1.65
		1260	14.18	1.68	11.98	0.01	13.14	0.01	15.48	1.62	13.79	1.67	13.81	1.67
		1320	14.19	1.69	11.98	0.01	13.14	0.01	15.50	1.64	13.80	1.68	13.82	1.68
		1380	14.19	1.69	11.98	0.01	13.14	0.01	15.50	1.64	13.80	1.68	13.82	1.68
		1440	14.19	1.69	11.98	0.02	13.14	0.01	15.50	1.64	13.82	1.70	13.82	1.68
		1560	14.22	1.72	11.98	0.02	13.14	0.01	15.51	1.65	13.84	1.72	13.85	1.71
		1680	14.25	1.75	11.98	0.02	13.14	0.01	15.53	1.67	13.86	1.74	13.87	1.73
		1800	14.28	1.78	11.99	0.03	13.14	0.01	15.56	1.70	13.89	1.77	13.92	1.78
		1920	14.30	1.80	12.00	0.04	13.15	0.02	15.59	1.73	13.92	1.80	13.93	1.79
		2040	14.32	1.82	12.00	0.04	13.15	0.02	15.61	1.75	13.94	1.82	13.95	1.81
		2160	14.32	1.82	12.00	0.04	13.15	0.02	15.63	1.77	13.95	1.83	13.95	1.81
		2280	14.34	1.84	12.01	0.05	13.15	0.02	15.63	1.77	13.96	1.84	13.97	1.83
		2400	14.35	1.85	12.01	0.05	13.15	0.02	15.65	1.79	13.97	1.85	13.99	1.85
		2520	14.37	1.87	12.01	0.05	13.15	0.02	15.66	1.80	13.99	1.87	14.00	1.86
		2640	14.39	1.89	12.01	0.05	13.14	0.01	15.67	1.81	14.01	1.89	14.03	1.89
		2760	14.40	1.90	12.01	0.05	13.14	0.01	15.68	1.82	14.01	1.89	14.03	1.89
		2880	14.40	1.90	12.02	0.06	13.14	0.01	15.68	1.82	14.01	1.89	14.02	1.88
		3000	14.40	1.90	12.02	0.06	13.14	0.01	15.68	1.82	14.01	1.89	14.02	1.88
		3120	14.41	1.91	12.03	0.07	13.14	0.01	15.69	1.83	14.02	1.90	14.05	1.91
		3240	14.42	1.92	12.03	0.07	13.14	0.01	15.71	1.85	14.04	1.92	14.06	1.92
		3360	14.44	1.94	12.03	0.07	13.14	0.01	15.73	1.87	14.06	1.94	14.07	1.93
		3480	14.45	1.95	12.04	0.08	13.14	0.01	15.74	1.88	14.07	1.95	14.08	1.94
		3600	14.45	1.95	12.04	0.08	13.14	0.01	15.74	1.88	14.07	1.95	14.08	1.94
		3720	14.45	1.95	12.04	0.08	13.14	0.01	15.74	1.88	14.07	1.95	14.08	1.94
		3840	14.45	1.95	12.04	0.08	13.14	0.01	15.74	1.88	14.08	1.96	14.09	1.95
		3960	14.46	1.96	12.04	0.08	13.14	0.01	15.74	1.88	14.09	1.97	14.10	1.96
		4008												

CONSTANT RATE DISCHARGE TEST

Project & no:	NIGS 112	Pumping Borehole No.	UO5	Projectleader:	W.-H. Chiang
District:	Bloemfontein	Date starting pumping	7/11/2000	Recorder:	K. Riemann
Location:	Campus Test Site	Time starting pumping	13:27:00		P. Dzanga

Obsevation borehole(s):	Observation 1	Observation 2	Observation 3	Observation 4	Observation 5	Observation 6
Borehole number:	UO 27a	UO 27b	UO 27c	UO 28a	UO 28b	UO 28c
Distance (m):		11.5			27.2	
Borehole depth (mbdl):		30.4			30.4	
Wellscreen top (mbdl):	18.0	23.0	20.0	18.7	23.7	20.0
Wellscreen bottom (mbdl):	19.0	24.0	22.0	19.3	24.3	23.0
Static water level (mbdl):	7.68	12.31	12.34	9.95	12.34	12.60
Wellscreen diamter (m):	0.03	0.03	0.05	0.03	0.03	0.05
Datum level (magl)						

Time:			UO 27a		UO 27b		UO 27c		UO 28a		UO 28b		UO 28c	
Date	HH:mm	Elapsed (min)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)
		2	7.68	0.00	12.31	0.00	12.39	0.05	9.95	0.00	12.34	0.00	12.65	0.05
		4	7.69	0.01	12.31	0.00	12.43	0.09	9.95	0.00	12.34	0.00	12.69	0.09
		6	7.69	0.01	12.32	0.01	12.46	0.12	9.96	0.01	12.34	0.00	12.72	0.12
		8	7.70	0.02	12.32	0.01	12.48	0.14	9.96	0.01	12.34	0.00	12.75	0.15
		10	7.70	0.02	12.32	0.01	12.51	0.17	9.97	0.02	12.34	0.00	12.78	0.18
		12	7.70	0.02	12.32	0.01	12.53	0.19	9.97	0.02	12.35	0.01	12.80	0.20
		14	7.70	0.02	12.33	0.02	12.55	0.21	9.97	0.02	12.35	0.01	12.81	0.21
		16	7.70	0.02	12.33	0.02	12.57	0.23	9.97	0.02	12.35	0.01	12.82	0.22
		18	7.70	0.02	12.33	0.02	12.58	0.24	9.97	0.02	12.35	0.01	12.84	0.24
		20	7.70	0.02	12.33	0.02	12.60	0.26	9.97	0.02	12.35	0.01	12.86	0.26
		30	7.70	0.02	12.33	0.02	12.66	0.32	9.98	0.03	12.35	0.01	12.92	0.32
		40	7.70	0.02	12.33	0.02	12.71	0.37	9.98	0.03	12.35	0.01	12.97	0.37
		50	7.70	0.02	12.33	0.02	12.74	0.40	9.98	0.03	12.35	0.01	13.00	0.40
		60	7.70	0.02	12.33	0.02	12.87	0.53	9.98	0.03	12.35	0.01	13.13	0.53
		70	7.70	0.02	12.33	0.02	12.99	0.65	9.98	0.03	12.35	0.01	13.25	0.65
		80	7.70	0.02	12.33	0.02	13.07	0.73	9.98	0.03	12.35	0.01	13.32	0.72
		90	7.71	0.03	12.34	0.03	13.13	0.79	9.99	0.04	12.36	0.02	13.40	0.80
		100	7.71	0.03	12.34	0.03	13.17	0.83	9.99	0.04	12.36	0.02	13.43	0.83
		110	7.71	0.03	12.35	0.04	13.21	0.87	9.99	0.04	12.36	0.02	13.47	0.87
		120	7.71	0.03	12.35	0.04	13.24	0.90	9.99	0.04	12.36	0.02	13.50	0.90
		150	7.71	0.03	12.37	0.06	13.32	0.98	9.99	0.04	12.36	0.02	13.57	0.97
		180	7.71	0.03	12.39	0.08	13.38	1.04	9.98	0.03	12.36	0.02	13.64	1.04
		210	7.71	0.03	12.40	0.09	13.43	1.09	9.98	0.03	12.36	0.02	13.68	1.08
		240	7.71	0.03	12.43	0.12	13.47	1.13	9.98	0.03	12.36	0.02	13.73	1.13
		300	7.71	0.03	12.45	0.14	13.55	1.21	9.98	0.03	12.36	0.02	13.80	1.20
		360	7.71	0.03	12.49	0.18	13.61	1.27	9.98	0.03	12.36	0.02	13.86	1.26
		420	7.71	0.03	12.53	0.22	13.66	1.32	9.98	0.03	12.36	0.02	13.93	1.33
		480	7.71	0.03	12.57	0.26	13.71	1.37	9.99	0.04	12.38	0.04	13.96	1.36
		540	7.71	0.03	12.60	0.29	13.74	1.40	9.99	0.04	12.38	0.04	14.00	1.40
		600	7.71	0.03	12.64	0.33	13.77	1.43	9.99	0.04	12.38	0.04	14.03	1.43
		660	7.71	0.03	12.68	0.37	13.79	1.45	9.99	0.04	12.39	0.05	14.06	1.46
		720	7.71	0.03	12.72	0.41	13.81	1.47	9.99	0.04	12.39	0.05	14.08	1.48
		780	7.72	0.04	12.75	0.44	13.84	1.50	10.00	0.05	12.40	0.06	14.10	1.50
		840	7.72	0.04	12.79	0.48	13.86	1.52	10.00	0.05	12.40	0.06	14.13	1.53
		900	7.72	0.04	12.82	0.51	13.88	1.54	10.00	0.05	12.40	0.06	14.14	1.54
		960	7.72	0.04	12.85	0.54	13.90	1.56	10.00	0.05	12.41	0.07	14.16	1.56
		1020	7.73	0.04	12.88	0.57	13.93	1.59	10.00	0.05	12.41	0.07	14.18	1.58
		1080	7.73	0.05	12.92	0.61	13.94	1.60	10.00	0.05	12.42	0.08	14.20	1.60
		1140	7.73	0.05	12.95	0.64	13.97	1.63	10.00	0.05	12.43	0.09	14.23	1.63
		1200	7.73	0.05	12.98	0.67	13.99	1.65	10.00	0.05	12.43	0.09	14.27	1.67
		1260	7.73	0.05	13.01	0.70	14.01	1.67	10.00	0.05	12.44	0.10	14.27	1.67
		1320	7.74	0.06	13.04	0.73	14.02	1.68	10.01	0.06	12.44	0.10	14.28	1.68
		1380	7.74	0.06	13.07	0.76	14.02	1.68	10.01	0.06	12.44	0.10	14.28	1.68
		1440	7.74	0.06	13.10	0.79	14.02	1.68	10.02	0.07	12.45	0.11	14.29	1.69
		1560	7.74	0.06	13.16	0.85	14.04	1.70	10.01	0.06	12.46	0.12	14.31	1.71
		1680	7.74	0.06	13.21	0.90	14.08	1.74	10.01	0.06	12.47	0.13	14.34	1.74
		1800	7.75	0.07	13.26	0.95	14.10	1.76	10.01	0.06	12.48	0.14	14.37	1.77
		1920	7.75	0.07	13.31	1.00	14.13	1.79	10.01	0.06	12.48	0.14	14.39	1.79
		2040	7.75	0.07	13.36	1.05	14.15	1.81	10.01	0.06	12.50	0.16	14.41	1.81
		2160	7.75	0.07	13.41	1.10	14.16	1.82	10.02	0.07	12.51	0.17	14.42	1.82
		2280	7.75	0.07	13.45	1.14	14.17	1.83	10.02	0.07	12.52	0.18	14.43	1.83
		2400	7.75	0.07	13.50	1.19	14.19	1.85	10.03	0.08	12.53	0.19	14.45	1.85
		2520	7.77	0.09	13.54	1.23	14.20	1.86	10.02	0.07	12.54	0.20	14.46	1.86
		2640	7.76	0.08	13.57	1.26	14.22	1.88	10.03	0.08	12.55	0.21	14.48	1.88
		2760	7.77	0.09	13.61	1.30	14.23	1.89	10.03	0.08	12.56	0.22	14.49	1.89
		2880	7.77	0.09	13.64	1.33	14.22	1.88	10.03	0.08	12.57	0.23	14.49	1.89
		3000	7.77	0.09	13.68	1.37	14.23	1.89	10.03	0.08	12.59	0.25	14.50	1.90
		3120	7.78	0.10	13.71	1.40	14.24	1.90	10.04	0.09	12.60	0.26	14.50	1.90
		3240	7.77	0.09	13.74	1.43	14.25	1.91	10.04	0.09	12.60	0.26	14.52	1.92
		3360	7.78	0.10	13.77	1.46	14.27	1.93	10.04	0.09	12.61	0.27	14.53	1.93
		3480	7.78	0.10	13.80	1.49	14.28	1.94	10.05	0.10	12.62	0.28	14.54	1.94
		3600	7.79	0.11	13.83	1.52	14.29	1.95	10.05	0.10	12.63	0.29	14.55	1.95
		3720	7.79	0.11	13.86	1.55	14.29	1.95	10.05	0.10	12.64	0.30	14.55	1.95
		3840	7.79	0.11	13.88	1.57	14.29	1.95	10.05	0.10	12.65	0.31	14.55	1.95
		3960	7.79	0.11	13.90	1.59	14.29	1.95	10.05	0.10	12.66	0.32	14.55	1.95
		4008												

Appendix D.5 **CONSTANT RATE DISCHARGE TEST**

Project & no:	NIGS 112	Pumping Borehole No.	UO5	Projectleader:	W.-H. Chiang
District:	Bloemfontein	Date starting pumping	7/11/2000	Recorder:	K. Riemann
Location:	Campus Test Site	Time starting pumping	13:27:00		P. Dzanga

Observation borehole(s):	Observation 1	Observation 2	Observation 3	Observation 4	Observation 5	Observation 6
Borehole number:	UO 29a	UO 29b	UO 29c	UO 23a	UO 23b	UO 23c
Distance (m):		75.9			97.9	
Borehole depth (mbdl):		30.4			48.5	
Wellscreen top (mbdl):	18.0	23.0	20.0	19.2	22.2	20.5
Wellscreen bottom (mbdl):	19.0	24.0	22.0	19.8	22.8	21.5
Static water level (mbdl):	12.25	13.45	13.68	7.15	12.76	13.96
Wellscreen diamter (m):	0.03	0.03	0.05	0.03	0.03	0.05
Datum level (magl)						

Time:			*UO 29a*		*UO 29b*		*UO 29c*		*UO 23a*		*UO 23b*		*UO 23c*	
Date	HH:mm	Elapsed (min)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)	Water level (m)	Draw-down (m)
		2	12.26	0.01	13.45	0.00	13.74	0.06	7.15	0.00	12.76	0.00	14.01	0.05
		4	12.26	0.01	13.46	0.01	13.77	0.09	7.15	0.00	12.76	0.00	14.04	0.08
		6	12.26	0.01	13.46	0.01	13.79	0.11	7.15	0.00	12.77	0.01	14.08	0.12
		8	12.26	0.01	13.46	0.01	13.82	0.14	7.16	0.01	12.77	0.01	14.11	0.15
		10	12.26	0.01	13.46	0.01	13.86	0.18	7.16	0.01	12.77	0.01	14.13	0.17
		12	12.26	0.01	13.46	0.01	13.88	0.20	7.16	0.01	12.77	0.01	14.15	0.19
		14	12.26	0.01	13.46	0.01	13.89	0.21	7.16	0.01	12.77	0.01	14.16	0.20
		16	12.26	0.01	13.46	0.01	13.91	0.23	7.16	0.01	12.77	0.01	14.18	0.22
		18	12.26	0.01	13.46	0.01	13.92	0.24	7.17	0.01	12.77	0.01	14.20	0.24
		20	12.27	0.02	13.46	0.01	13.93	0.25	7.17	0.01	12.77	0.01	14.22	0.25
		30	12.27	0.02	13.46	0.01	14.00	0.32	7.17	0.01	12.77	0.01	14.27	0.31
		40	12.27	0.02	13.46	0.01	14.04	0.36	7.17	0.01	12.77	0.01	14.32	0.36
		50	12.27	0.02	13.46	0.01	14.07	0.39	7.17	0.01	12.77	0.01	14.36	0.40
		60	12.27	0.02	13.46	0.01	14.22	0.54	7.17	0.01	12.77	0.01	14.49	0.53
		70	12.27	0.02	13.46	0.01	14.31	0.63	7.17	0.01	12.77	0.01	14.59	0.63
		80	12.27	0.02	13.46	0.01	14.39	0.71	7.17	0.01	12.77	0.01	14.68	0.72
		90	12.28	0.03	13.46	0.01	14.46	0.78	7.17	0.01	12.78	0.02	14.75	0.79
		100	12.28	0.03	13.46	0.01	14.51	0.83	7.17	0.01	12.78	0.02	14.78	0.82
		110	12.28	0.03	13.46	0.01	14.55	0.87	7.17	0.01	12.78	0.02	14.83	0.87
		120	12.28	0.03	13.47	0.02	14.59	0.91	7.17	0.01	12.78	0.02	14.86	0.90
		150	12.28	0.03	13.47	0.02	14.66	0.98	7.17	0.01	12.77	0.01	14.94	0.98
		180	12.28	0.03	13.47	0.02	14.72	1.04	7.17	0.01	12.77	0.01	15.00	1.04
		210	12.28	0.03	13.47	0.02	14.77	1.09	7.16	0.01	12.77	0.01	15.05	1.09
		240	12.28	0.03	13.47	0.02	14.81	1.13	7.17	0.02	12.77	0.01	15.09	1.13
		300	12.28	0.03	13.47	0.02	14.89	1.21	7.17	0.02	12.78	0.02	15.16	1.20
		360	12.28	0.03	13.47	0.02	14.95	1.27	7.17	0.02	12.77	0.01	15.23	1.27
		420	12.29	0.04	13.48	0.03	15.00	1.32	7.16	0.01	12.78	0.02	15.28	1.32
		480	12.29	0.04	13.48	0.03	15.05	1.37	7.16	0.01	12.78	0.02	15.32	1.36
		540	12.29	0.04	13.48	0.03	15.09	1.41	7.16	0.01	12.78	0.02	15.36	1.40
		600	12.29	0.04	13.48	0.03	15.12	1.44	7.16	0.01	12.78	0.02	15.39	1.43
		660	12.30	0.05	13.49	0.04	15.14	1.46	7.16	0.01	12.78	0.02	15.41	1.45
		720	12.30	0.05	13.49	0.04	15.16	1.48	7.16	0.01	12.79	0.03	15.44	1.48
		780	12.30	0.05	13.50	0.05	15.19	1.51	7.16	0.01	12.79	0.03	15.46	1.50
		840	12.30	0.05	13.50	0.05	15.21	1.53	7.16	0.01	12.79	0.03	15.48	1.52
		900	12.30	0.05	13.50	0.05	15.23	1.55	7.16	0.01	12.79	0.03	15.50	1.54
		960	12.30	0.05	13.50	0.05	15.25	1.57	7.16	0.01	12.79	0.03	15.52	1.56
		1020	12.30	0.05	13.50	0.05	15.27	1.59	7.16	0.01	12.80	0.04	15.54	1.58
		1080	12.30	0.05	13.51	0.06	15.29	1.61	7.16	0.01	12.80	0.04	15.56	1.60
		1140	12.31	0.06	13.51	0.06	15.31	1.63	7.16	0.01	12.80	0.04	15.59	1.63
		1200	12.31	0.06	13.51	0.06	15.33	1.65	7.15	0.00	12.80	0.04	15.61	1.65
		1260	12.31	0.06	13.52	0.07	15.35	1.67	7.15	0.00	12.80	0.04	15.63	1.67
		1320	12.31	0.06	13.52	0.07	15.36	1.68	7.15	0.00	12.80	0.04	15.64	1.68
		1380	12.31	0.06	13.52	0.07	15.36	1.68	7.15	0.00	12.81	0.05	15.65	1.69
		1440	12.31	0.06	13.52	0.07	15.36	1.68	7.15	0.00	12.81	0.05	15.66	1.70
		1560	12.32	0.07	13.53	0.08	15.38	1.70	7.15	0.00	12.81	0.05	15.66	1.70
		1680	12.32	0.07	13.54	0.09	15.41	1.73	7.15	0.00	12.81	0.05	15.69	1.73
		1800	12.32	0.07	13.55	0.10	15.45	1.77	7.16	0.00	12.81	0.05	15.73	1.77
		1920	12.32	0.07	13.55	0.10	15.47	1.79	7.16	0.01	12.83	0.07	15.75	1.79
		2040	12.32	0.07	13.56	0.11	15.49	1.81	7.17	0.02	12.83	0.07	15.77	1.81
		2160	12.32	0.07	13.57	0.12	15.50	1.82	7.17	0.02	12.83	0.07	15.79	1.83
		2280	12.33	0.08	13.58	0.13	15.52	1.84	7.17	0.02	12.83	0.07	15.80	1.84
		2400	12.34	0.09	13.59	0.14	15.53	1.85	7.18	0.03	12.83	0.07	15.81	1.85
		2520	12.34	0.09	13.60	0.15	15.55	1.87	7.18	0.03	12.83	0.07	15.82	1.86
		2640	12.34	0.09	13.60	0.15	15.56	1.88	7.18	0.03	12.83	0.07	15.83	1.87
		2760	12.34	0.09	13.61	0.16	15.57	1.89	7.19	0.04	12.83	0.07	15.84	1.88
		2880	12.34	0.09	13.61	0.16	15.57	1.89	7.20	0.05	12.84	0.08	15.85	1.89
		3000	12.34	0.09	13.63	0.18	15.58	1.90	7.21	0.05	12.85	0.09	15.85	1.89
		3120	12.35	0.10	13.64	0.19	15.59	1.91	7.21	0.06	12.86	0.10	15.86	1.90
		3240	12.35	0.10	13.65	0.20	15.60	1.92	7.21	0.06	12.86	0.10	15.88	1.92
		3360	12.35	0.10	13.65	0.20	15.61	1.93	7.21	0.06	12.86	0.10	15.89	1.93
		3480	12.35	0.10	13.66	0.21	15.62	1.94	7.21	0.06	12.86	0.10	15.90	1.94
		3600	12.35	0.10	13.66	0.21	15.63	1.95	7.22	0.07	12.86	0.10	15.91	1.95
		3720	12.35	0.10	13.67	0.22	15.63	1.95	7.23	0.08	12.86	0.10	15.91	1.95
		3840	12.35	0.10	13.68	0.23	15.63	1.95	7.24	0.09	12.87	0.11	15.91	1.95
		3960	12.35	0.10	13.69	0.24	15.64	1.96	7.25	0.10	12.88	0.12	15.91	1.95
		4008												

Appendix D.6

Constant Rate Test UO5, September 2000

Pumping Borehole UO5				Observation Borehole UO6 TOP				Observation Borehole UO6 BOTTOM			
Static Water Level: 13.16 m				Static Water Level: 12.48 m				Static Water Level: 13.1 m			
Pumping Rate: 2 l/s											
Time gap	Elapsed time	Water level	Drawdown UO5	Time gap	Elapsed time	Water level	Drawdown UO6TOP	Time gap	Elapsed time	Water level	Drawdown UO6BOT
0	0	13.16	0	0	0	12.48	0	0	0	13.1	0
16	16	15.45	2.29	8	18	12.49	0.01	19	19	13.09	-0.01
14	30	15.9	2.74	14	32	12.49	0.01	15	34	13.09	-0.01
5	35	16	2.84	47	79	12.49	0.01	46	80	13.08	-0.02
19	54	16.39	3.23	50	129	12.49	0.01	67	147	13.09	-0.01
24	78	16.76	3.6	17	146	12.49	0.01	23	170	13.1	0
25	103	17.05	3.89	23	169	12.5	0.02	18	188	13.1	0
25	128	17.27	4.11	19	188	12.5	0.02	15	203	13.1	0
17	145	17.4	4.24	15	203	12.5	0.02	56	259	13.1	0
23	168	17.6	4.44	56	259	12.5	0.02	54	313	13.1	0
19	187	17.74	4.58	54	313	12.5	0.02	65	378	13.1	0
15	202	17.84	4.68	64	377	12.5	0.02	65	443	13.1	0
22	224	17.9	4.74	66	443	12.5	0.02	64	507	13.1	0
34	258	18	4.84	62	505	12.505	0.025	85	592	13.1	0
54	312	18.18	5.02	87	592	12.507	0.027	63	655	13.1	0
64	376	18.39	5.23	62	654	12.512	0.032	59	714	13.105	0.005
66	442	18.56	5.4	60	714	12.515	0.035	58	772	13.11	0.01
60	502	18.56	5.4	58	772	12.52	0.04	60	832	13.11	0.01
88	590	18.56	5.4	60	832	12.52	0.04	180	1012	13.11	0.01
62	652	18.56	5.4	180	1012	12.52	0.04	180	1192	13.11	0.01
60	712	18.56	5.4	180	1192	12.53	0.05	137	1329	13.11	0.01
62	774	18.56	5.4	137	1329	12.54	0.06	105	1434	13.11	0.01
60	834	18.56	5.4	105	1434	12.54	0.06				
178	1012	18.75	5.59								
180	1192	19.04	5.88								
130	1322	19.11	5.95								
110	1432	19.23	6.07								

Observation Borehole UO27 FRACTURE				Observation Borehole UO27 TOP				Observation Borehole UO27 BOTTOM			
Static Water Level: 13.51 m				Static Water Level: 8.45 m				Static Water Level: 13.50 m			
Time gap	Elapsed time	Water level	Drawdown UO27FRA	Time gap	Elapsed time	Water level	Drawdown UO27TOP	Time gap	Elapsed time	Water level	Drawdown UO27BOT
0	0	13.51	0	0	0	8.45	0	0	0	13.5	0
21	21	15.72	2.21	21	21	8.45	0	21	21	13.52	0.02
61	82	17	3.49	61	82	8.43	-0.02	61	82	13.62	0.12
68	150	17.63	4.12	68	150	8.44	-0.01	68	150	13.74	0.24
57	207	18.06	4.55	57	207	8.47	0.02	57	207	13.86	0.36
55	262	18.22	4.71	55	262	8.47	0.02	55	262	13.98	0.48
54	316	18.4	4.89	54	316	8.47	0.02	54	316	14.09	0.59
63	379	18.61	5.1	63	379	8.47	0.02	63	379	14.22	0.72
69	448	18.76	5.25	69	448	8.47	0.02	69	448	14.37	0.87
63	511	18.76	5.25	63	511	8.47	0.02	63	511	14.5	1
84	595	18.76	5.25	84	595	8.47	0.02	84	595	14.67	1.17
66	661	18.76	5.25	66	661	8.48	0.03	66	661	14.79	1.29
61	722	18.76	5.25	61	722	8.48	0.03	61	722	14.905	1.405
55	777	18.76	5.25	55	777	8.48	0.03	55	777	15.005	1.505
59	836	18.76	5.25	59	836	8.48	0.03	59	836	15.11	1.61
180	1016	18.95	5.44	180	1016	8.48	0.03	180	1016	15.42	1.92
192	1208	19.16	5.65	192	1208	8.49	0.04	192	1208	15.71	2.21
126	1334	19.29	5.78	126	1334	8.49	0.04	126	1334	15.9	2.4
102	1436	19.41	5.9	102	1436	8.49	0.04	102	1436	16.06	2.56

Observation Borehole UO28 FRACTURE				Observation Borehole UO28 TOP				Observation Borehole UO28 BOTTOM			
Static Water Level: 13.77 m				Static Water Level: 10.1 m				Static Water Level: 13.68 m			
Time gap	Elapsed time	Water level	Drawdown UO28FRA	Time gap	Elapsed time	Water level	Drawdown UO28TOP	Time gap	Elapsed time	Water level	Drawdown UO28BOT
0	0	13.77	0	0	0	10.1	0	0	0	13.68	0
31	31	16.13	2.36	31	31	10.1	0	31	31	13.7	0.02
56	87	17.3	3.53	56	87	10.1	0	56	87	13.71	0.03
69	156	17.91	4.14	69	156	10.1	0	69	156	13.77	0.09
55	211	18.3	4.53	55	211	10.1	0	55	211	13.88	0.2
55	266	18.48	4.71	55	266	10.1	0	55	266	14.02	0.34
54	320	18.65	4.88	54	320	10.1	0	54	320	14.15	0.47
64	384	18.86	5.09	64	384	10.1	0	64	384	14.32	0.64
73	457	19	5.23	73	457	10.1	0	73	457	14.49	0.81
60	517	19	5.23	60	517	10.11	0.01	60	517	14.65	0.97
84	601	19	5.23	84	601	10.12	0.02	84	601	14.84	1.16
67	668	19	5.23	67	668	10.12	0.02	67	668	14.97	1.29
60	728	19	5.23	60	728	10.12	0.02	60	728	15.07	1.39
55	783	19	5.23	55	783	10.12	0.02	55	783	15.16	1.48
57	840	19	5.23	57	840	10.12	0.02	57	840	15.24	1.56
200	1040	19.19	5.42	200	1040	10.12	0.02	200	1040	15.51	1.83
175	1215	19.31	5.54	175	1215	10.13	0.03	175	1215	15.73	2.05
125	1340	19.52	5.75	125	1340	10.123	0.023	125	1340	15.88	2.2
102	1442	19.623	5.853	102	1442	10.13	0.03	102	1442	16	2.32

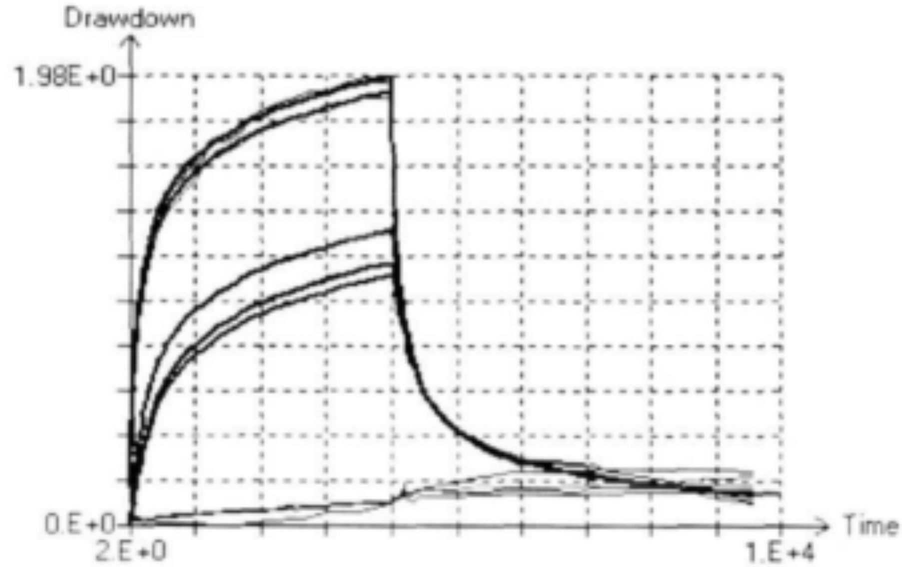
Observation Borehole UO29 FRACTURE				Observation Borehole UO29 TOP				Observation Borehole UO29 BOTTOM			
Static Water Level: 14.86 m				Static Water Level: 12.8 m				Static Water Level: 14.48 m			
Time gap	Elapsed time	Water level	Drawdown UO29FRA	Time gap	Elapsed time	Water level	Drawdown UO29TOP	Time gap	Elapsed time	Water level	Drawdown UO29BOT
0	0	14.86	0	0	0	12.8	0	0	0	14.48	0
32	32	17.23	2.37	32	32	12.8	0	32	32	14.48	0
58	90	18.34	3.48	58	90	12.8	0	58	90	14.5	0.02
67	157	18.95	4.09	67	157	12.81	0.01	67	157	14.5	0.02
58	215	19.33	4.47	58	215	12.81	0.01	58	215	14.5	0.02
53	268	19.52	4.66	53	268	12.81	0.01	53	268	14.51	0.03
57	325	19.7	4.84	57	325	12.82	0.02	57	325	14.51	0.03
63	388	19.9	5.04	63	388	12.82	0.02	63	388	14.51	0.03
73	461	20.03	5.17	73	461	12.82	0.02	73	461	14.52	0.04
59	520	20.03	5.17	59	520	12.825	0.025	59	520	14.54	0.06
84	604	20.03	5.17	84	604	12.83	0.03	84	604	14.55	0.07
74	678	20.02	5.16	74	678	12.83	0.03	74	678	14.56	0.08
54	732	20.02	5.16	54	732	12.83	0.03	54	732	14.57	0.09
55	787	20.02	5.16	55	787	12.83	0.03	55	787	14.58	0.1
59	846	20.01	5.15	59	846	12.84	0.04	59	846	14.595	0.115
196	1042	20.2	5.34	196	1042	12.84	0.04	196	1042	14.62	0.14
178	1220	20.36	5.5	178	1220	12.84	0.04	178	1220	14.66	0.18
123	1343	20.48	5.62	123	1343	12.84	0.04	123	1343	14.68	0.2
103	1446	20.58	5.72	103	1446	12.86	0.06	103	1446	14.7	0.22

Observation Borehole UO20				Observation Borehole UO26				Observation Borehole UO7			
Static Water Level: 13.3 m				Static Water Level: 13.67 m				Static Water Level: 13.29 m			
Time gap	Elapsed time	Water level	Drawdown UO20	Time gap	Elapsed time	Water level	Drawdown UO26	Time gap	Elapsed time	Water level	Drawdown UO7
0	0	13.3	0	0	0	13.67	0	0	0	13.29	0
23	23	15.6	2.3	29	29	16.04	2.37	19	19	15.53	2.24
62	85	17.19	3.89	57	86	16.85	3.18	61	80	16.8	3.51
67	152	17.8	4.5	65	151	17.8	4.13	68	148	17.44	4.15
57	209	17.88	4.58	59	210	18.23	4.56	56	204	17.86	4.57
54	263	18.03	4.73	54	264	18.4	4.73	56	260	18.03	4.74
54	317	18.2	4.9	55	319	18.58	4.91	55	315	18.2	4.91
64	381	18.4	5.1	63	382	18.78	5.11	63	378	18.42	5.13
71	452	18.5	5.2	72	454	18.92	5.25	68	446	18.57	5.28
60	512	18.57	5.27	62	516	18.92	5.25	64	510	18.57	5.28
85	597	18.57	5.27	84	600	18.92	5.25	83	593	18.575	5.285
67	664	18.57	5.27	66	666	18.92	5.25	66	659	18.575	5.285
61	725	18.57	5.27	60	726	18.92	5.25	60	719	18.58	5.29
55	780	18.57	5.27	56	782	18.93	5.26	56	775	18.58	5.29
59	839	18.57	5.27	58	840	18.93	5.26	60	835	18.58	5.29
198	1037	18.76	5.46	199	1039	19.12	5.45	180	1015	18.78	5.49
173	1210	18.97	5.67	173	1212	19.33	5.66	191	1206	18.99	5.7
126	1336	19.11	5.81	126	1338	19.48	5.81	127	1333	19.13	5.84
103	1439	19.22	5.92	102	1440	19.59	5.92	102	1435	19.24	5.95

Observation Borehole UO30				Observation Borehole UO23 FRACTURE				Observation Borehole UO23 TOP				Observation Borehole UO23 BOTTOM			
Static Water Level: 15.04 m				Static Water Level: 15.15 m				Static Water Level: 7.94 m				Static Water Level: 13.48 m			
Time gap	Elapsed time	Water level	Drawdown UO30	Time gap	Elapsed time	Water level	Drawdown UO23FRA	Time gap	Elapsed time	Water level	Drawdown UO23TOP	Time gap	Elapsed time	Water level	Drawdown UO23BOT
0	0	15.04	0	0	0	15.15	0	0	0	7.94	0	0	0	13.48	0
34	34	16.59	1.55	35	35	17.7	2.55	35	35	7.93	-0.01	35	35	13.48	0
62	96	17.94	2.9	64	99	18.64	3.49	64	99	7.93	-0.01	64	99	13.48	0
64	160	18.66	3.62	63	162	19.25	4.1	63	162	7.93	-0.01	63	162	13.49	0.01
57	217	19.1	4.06	56	218	19.59	4.44	56	218	7.93	-0.01	56	218	13.5	0.02
53	270	19.35	4.31	54	272	19.77	4.62	54	272	7.93	-0.01	54	272	13.5	0.02
57	327	19.53	4.49	57	329	19.94	4.79	57	329	7.93	-0.01	57	329	13.5	0.02
63	390	19.72	4.68	63	392	20.14	4.99	63	392	7.92	-0.02	63	392	13.5	0.02
74	464	19.87	4.83	74	466	20.25	5.1	74	466	7.92	-0.02	74	466	13.51	0.03
60	524	19.93	4.89	60	526	20.25	5.1	60	526	7.92	-0.02	60	526	13.515	0.035
83	607	19.93	4.89	83	609	20.25	5.1	83	609	7.92	-0.02	83	609	13.52	0.04
73	680	19.93	4.89	68	677	20.25	5.1	68	677	7.92	-0.02	68	677	13.52	0.04
55	735	19.93	4.89	60	737	20.25	5.1	60	737	7.91	-0.03	60	737	13.53	0.05
54	789	19.93	4.89	53	790	20.25	5.1	53	790	7.91	-0.03	53	790	13.53	0.05
59	848	19.93	4.89	59	849	20.25	5.1	59	849	7.92	-0.02	59	849	13.54	0.06
199	1047	20.09	5.05	201	1050	20.44	5.29	201	1050	7.94	0	201	1050	13.54	0.06
178	1225	20.26	5.22	177	1227	20.6	5.45	177	1227	7.94	0	177	1227	13.55	0.07
122	1347	20.37	5.33	122	1349	20.71	5.56	122	1349	7.98	0.04	122	1349	13.55	0.07
104	1451	20.46	5.42	109	1458	20.81	5.66	109	1458	7.99	0.05	109	1458	13.56	0.08

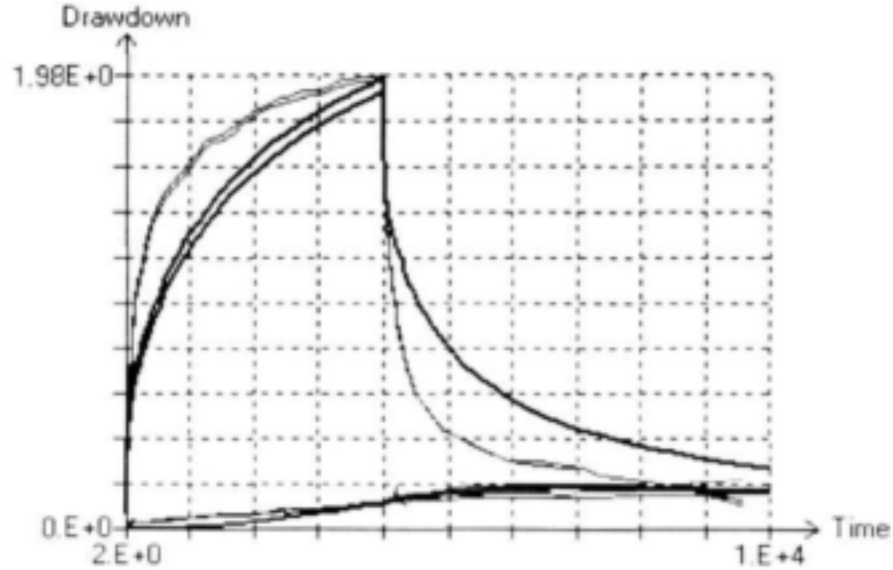
Appendix E: Results of Numerical Models

6a

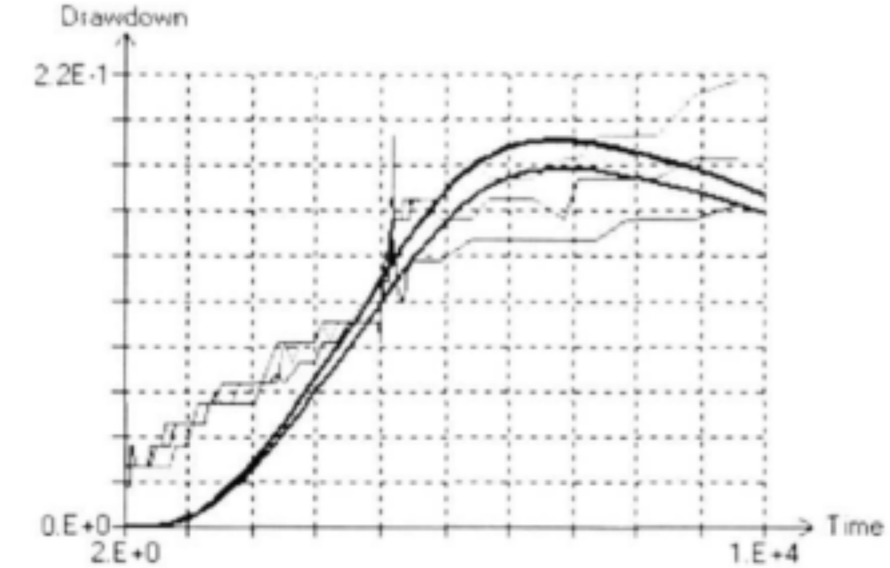


T matrix	4.55E-04
T matrix (0.5m)	2.27E-04
T matrix (0.2m)	9.10E-05
T fracture	4.30E-01
S matrix	2.25E-05
S matrix (0.5m)	1.13E-05
S matrix (0.2m)	4.50E-06
S fracture	2.76E-05
Leakage m (1-1)	7.04E-07
Leakage m (1-.5)	9.38E-07
Leakage m (.5-.5)	1.41E-06
Leakage m (.5-.2)	2.02E-06
Leakage fracture	2.82E-06

Run6b



T matrix	4.55E-04
T fracture	4.30E-01
S matrix above	3.92E-04
S fracture	2.76E-05
S matrix below	4.85E-04
Leakage m above	7.58E-08
Leakage to fractur	7.41E-07
Leakage m below	3.16E-07
Leakage to fractur	1.27E-06

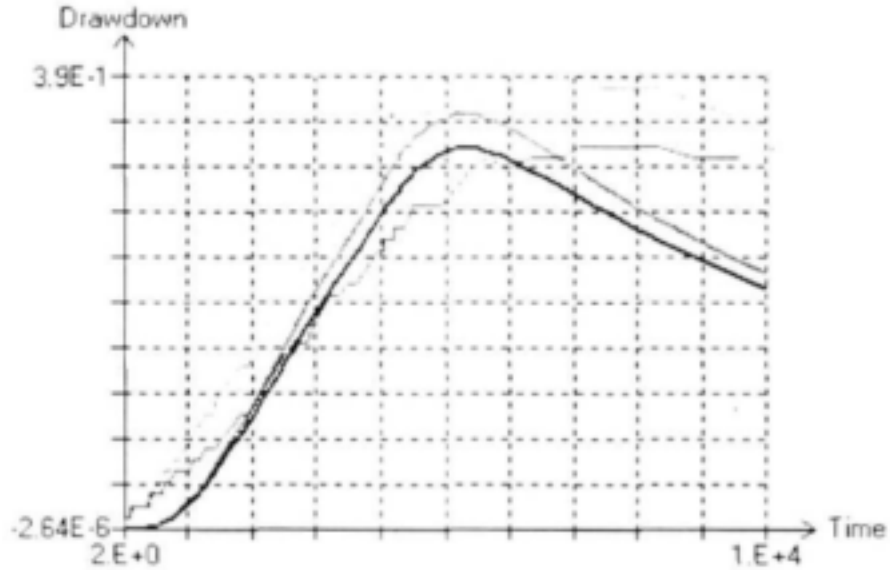


Piezometer above

UO27a

UO29a

UO28a

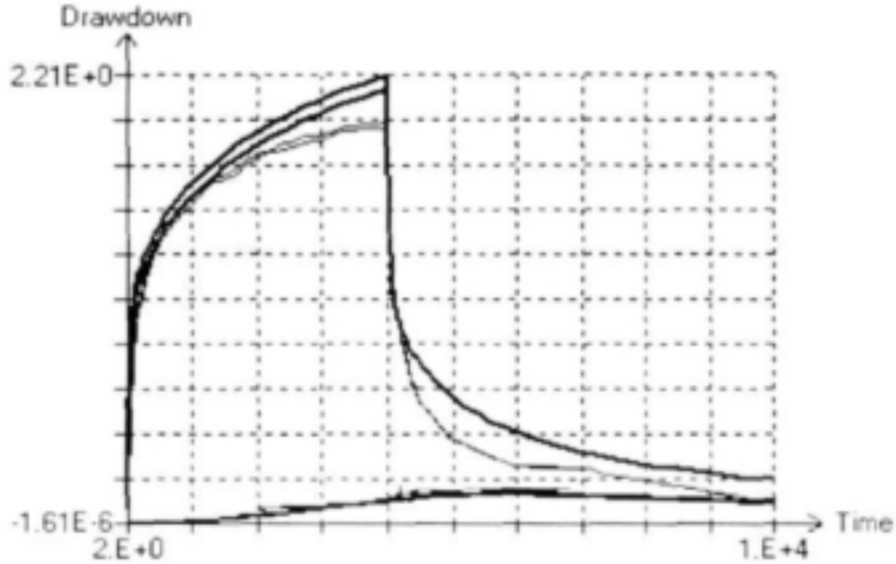


Piezometer below

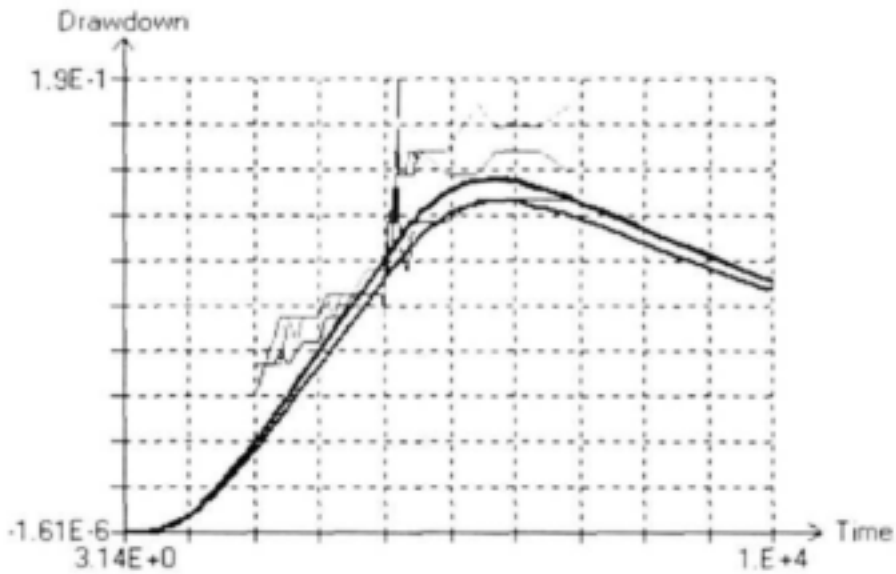
UO28b

UO29b

Run6c



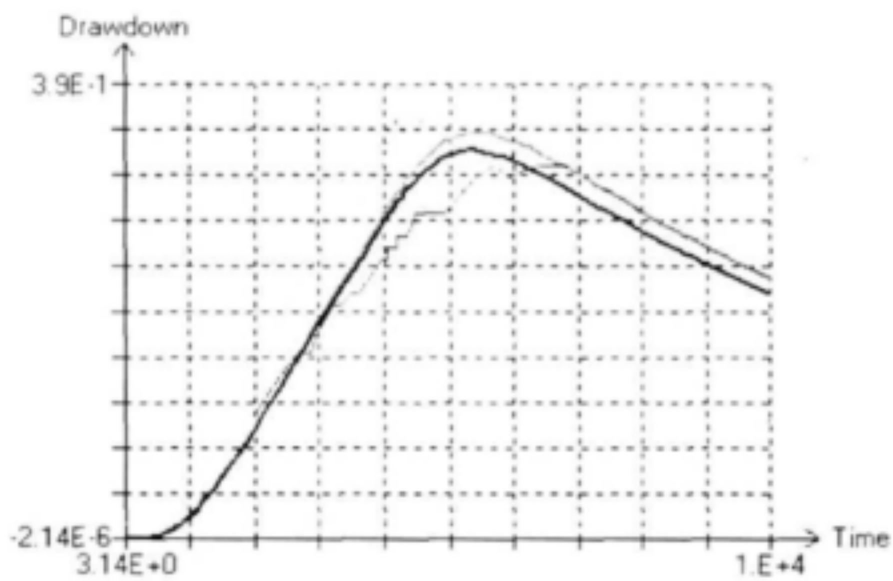
T matrix	4.55E-04
T fracture	4.30E-01
S matrix above	3.10E-04
S fracture	2.76E-05
S matrix below	7.66E-04
Leakage m above	8.15E-08
Leakage to fractur	2.24E-07
Leakage m below	6.51E-07
Leakage to fractur	4.57E-07



Piezometer above

UO27a

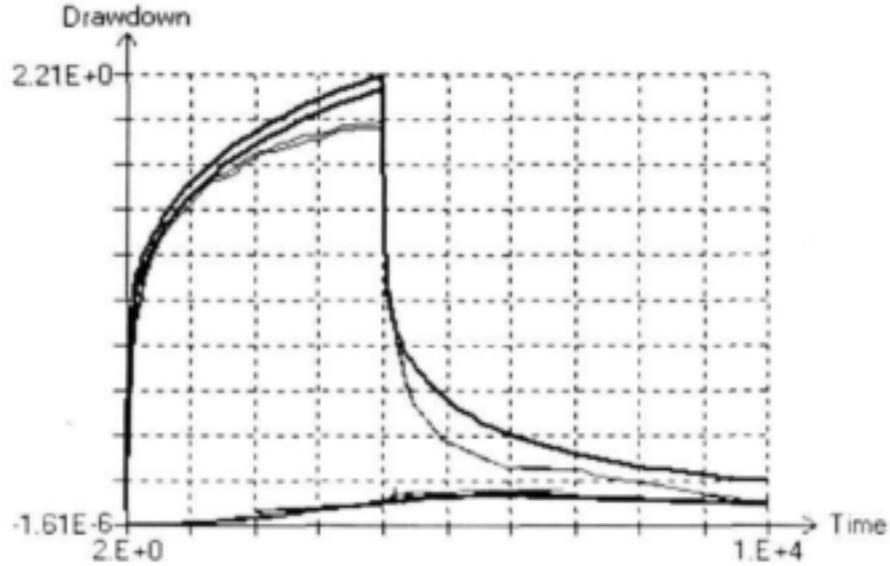
UO29a
UO28a



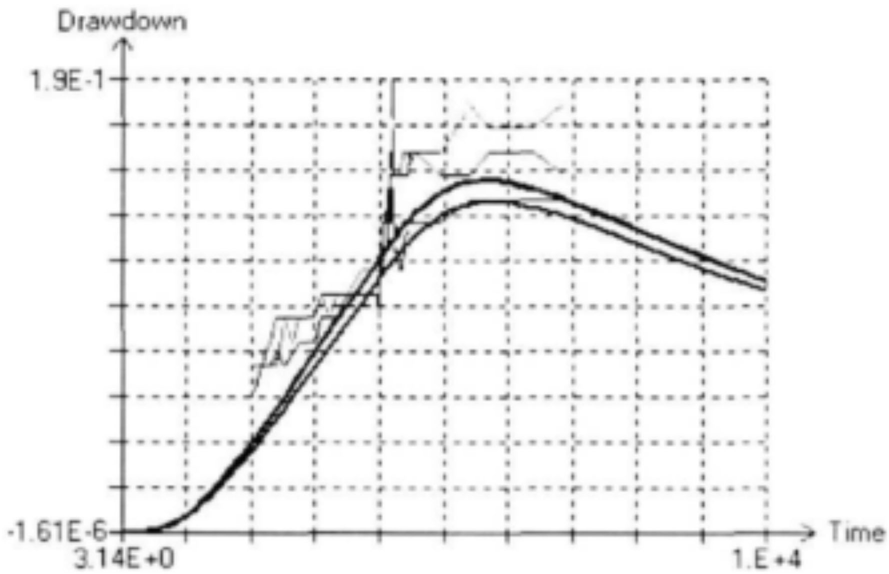
Piezometer below

UO28b
UO29b

Run6c



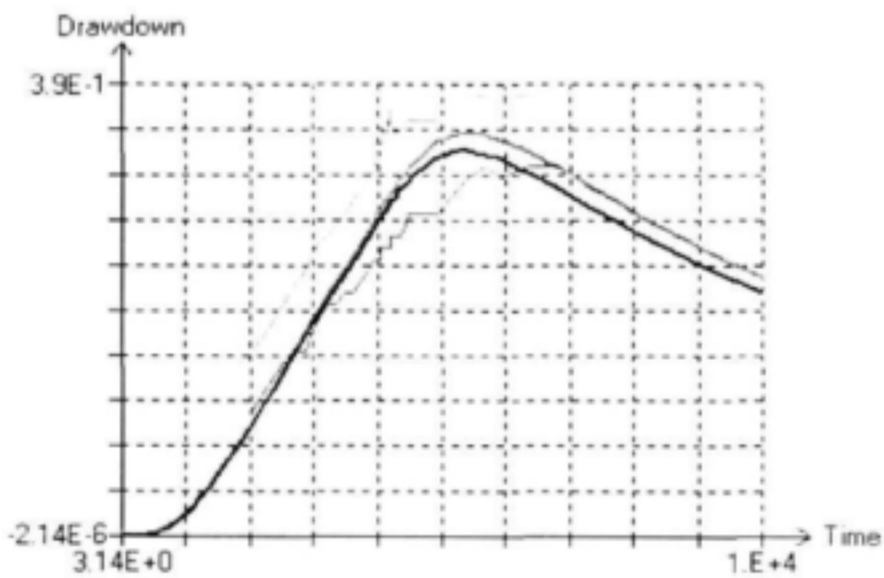
T matrix	4.55E-04
T fracture	4.30E-01
S matrix above	3.10E-04
S fracture	2.76E-05
S matrix below	7.66E-04
Leakage m above	8.15E-08
Leakage to fractu	2.24E-07
Leakage m below	6.51E-07
Leakage to fractu	4.57E-07



Piezometer above

UO27a

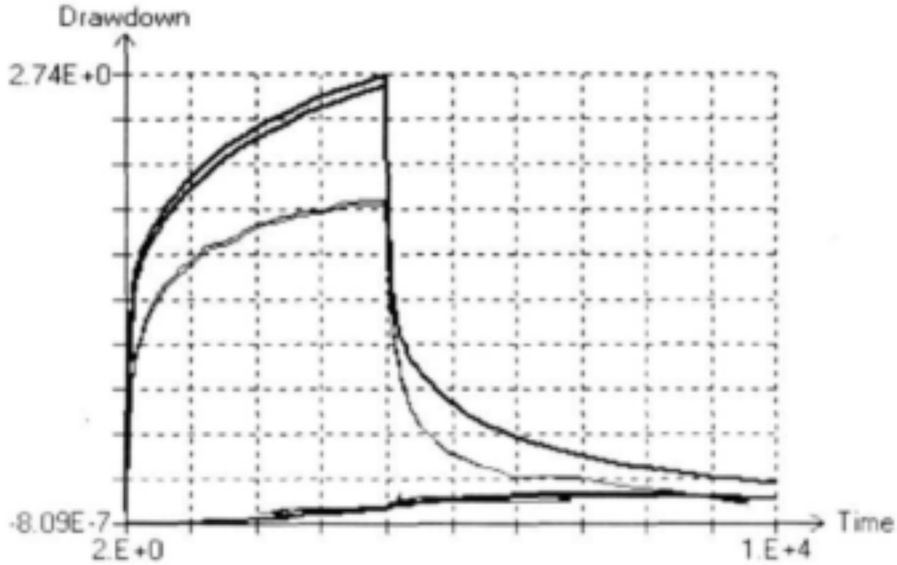
UO29a
UO28a



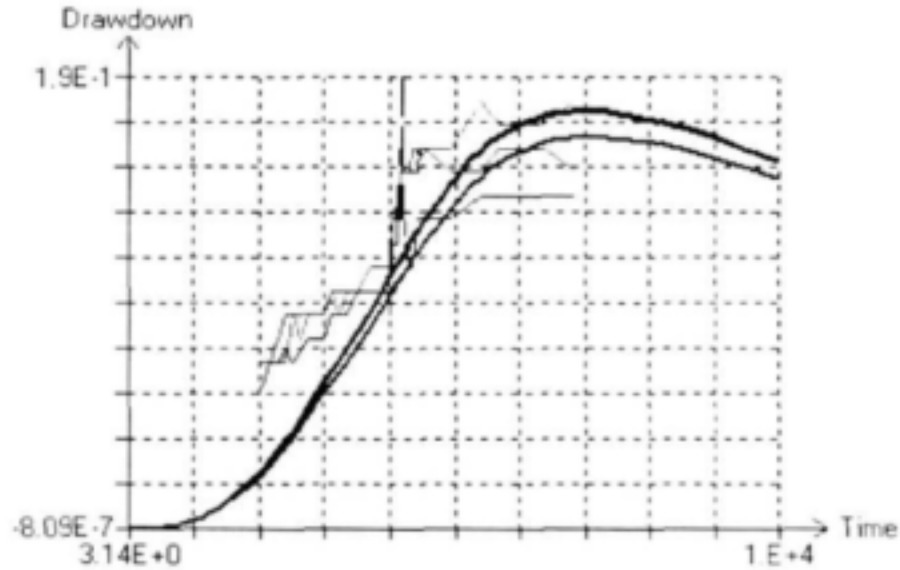
Piezometer below

UO28b
UO29b

Run6d



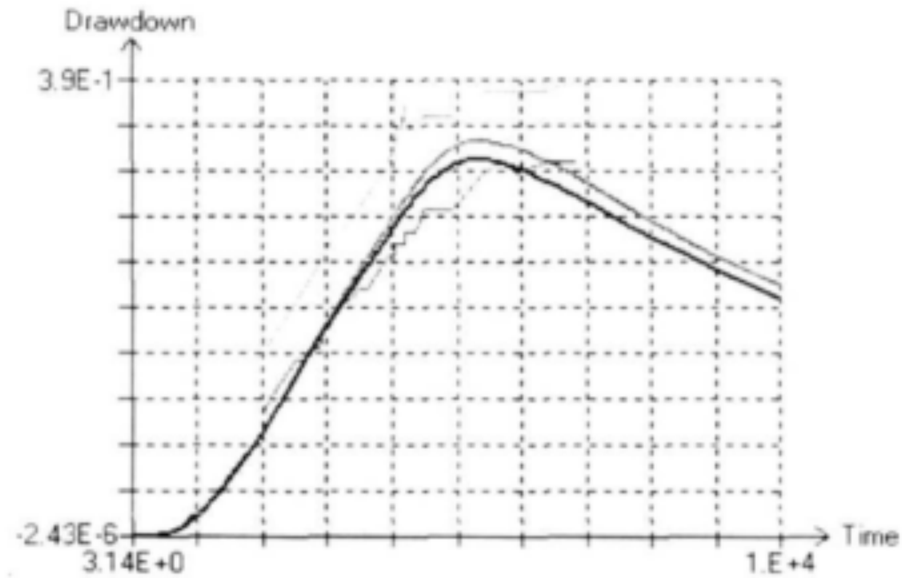
T matrix	4.55E-04
T fracture	4.30E-01
S matrix above	3.92E-04
S fracture	2.76E-05
S matrix below	4.85E-04
Leakage m above	7.04E-08
Leakage to fractur	2.24E-07
Leakage m below	3.61E-07
Leakage to fractur	2.24E-07



Piezometer above

UO27a

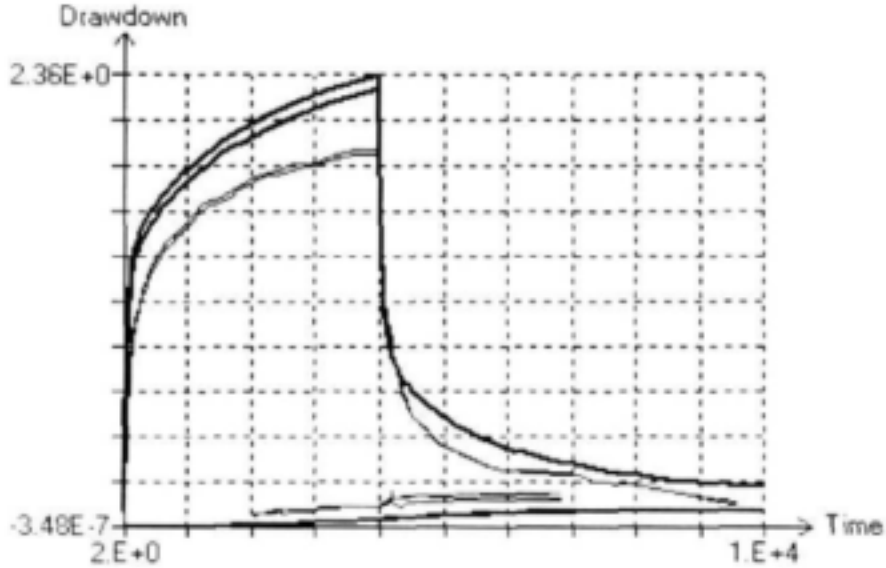
UO29a
UO28a



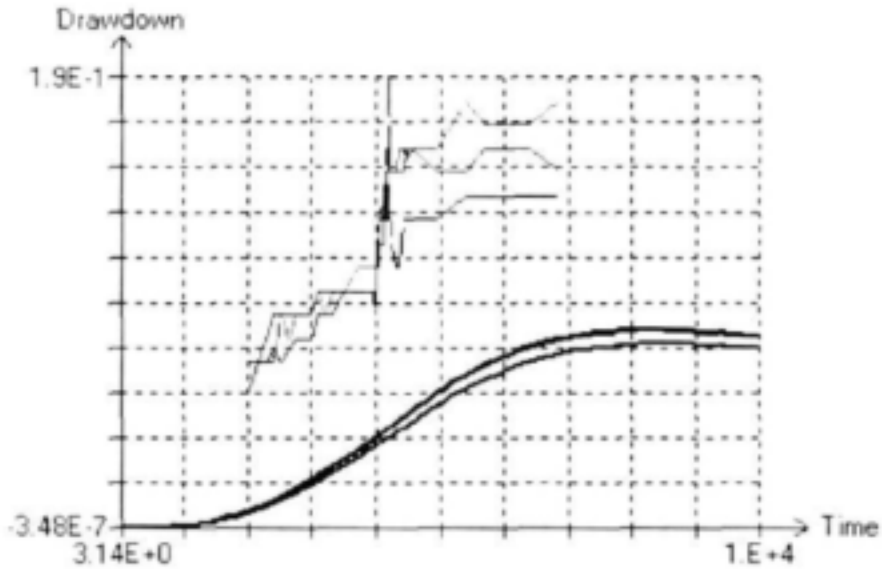
Piezometer below

UO28b
UO29b

Run6e



T matrix	4.55E-04
T fracture	4.30E-01
S matrix above	3.40E-04
S fracture	2.76E-05
S matrix below	6.40E-04
Leakage m above	7.04E-08
Leakage to fractu	2.24E-07
Leakage m below	3.61E-07
Leakage to fractu	4.57E-07

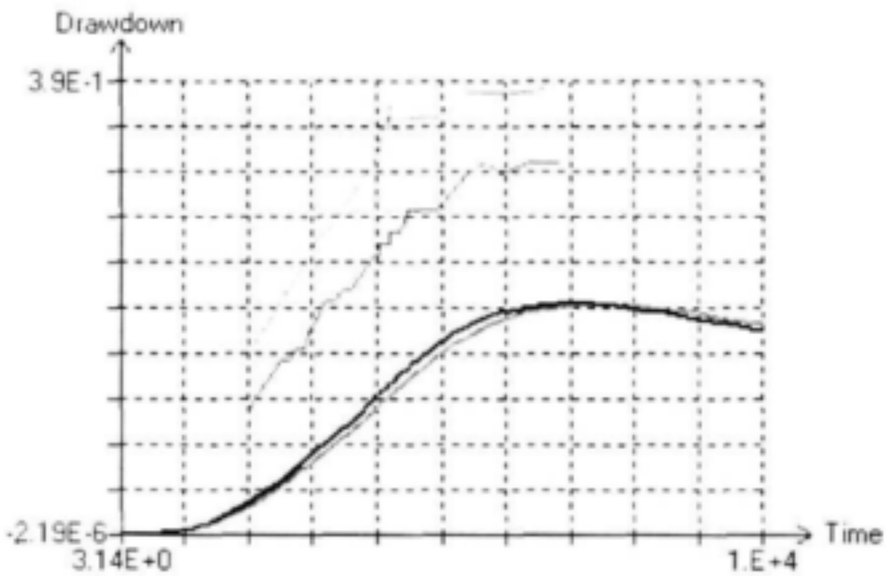


Piezometer above

UO27a

UO29a

UO28a

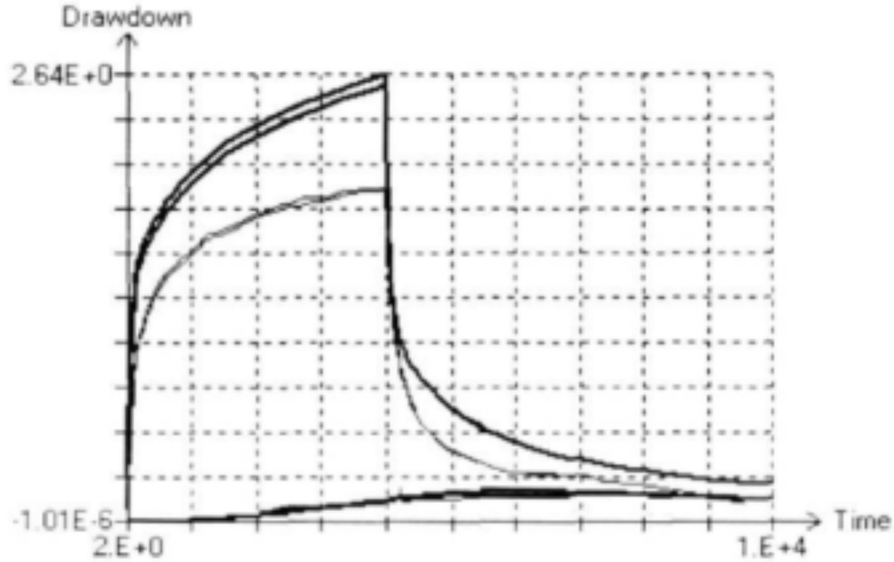


Piezometer below

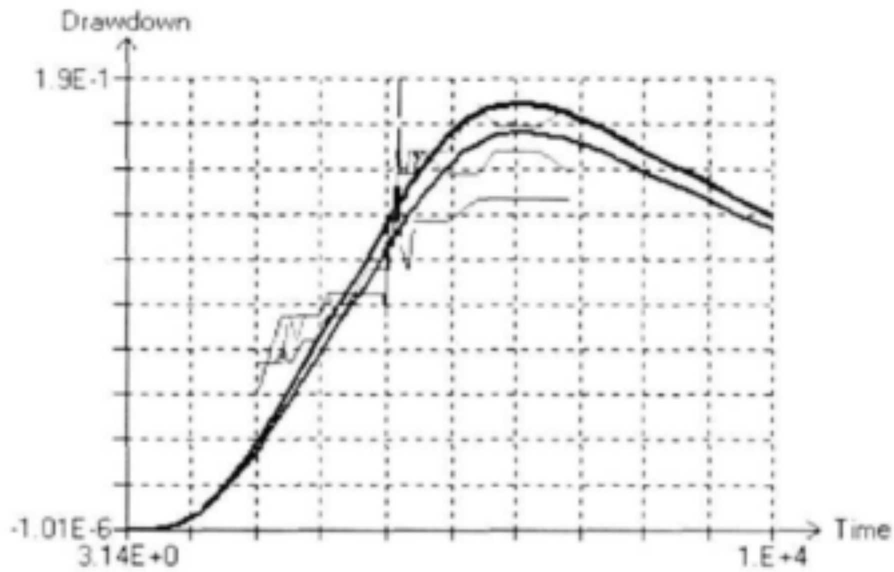
UO28b

UO29b

Run6f



T matrix	4.55E-04
T fracture	4.30E-01
S matrix above	3.25E-04
S fracture	2.76E-05
S matrix below	5.82E-04
Leakage m above	1.21E-07
Leakage to fractur	2.24E-07
Leakage m below	5.20E-07
Leakage to fractur	2.24E-07

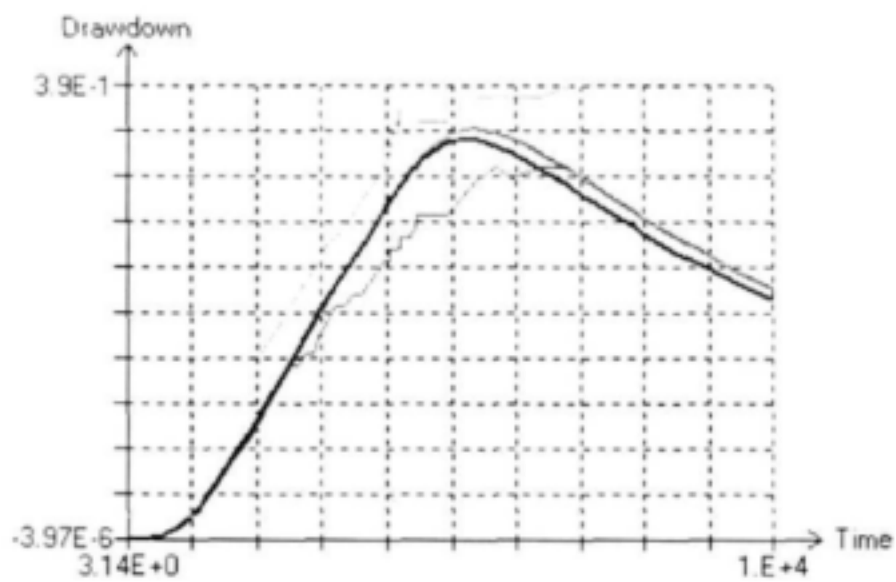


Piezometer above

UO27a

UO29a

UO28a

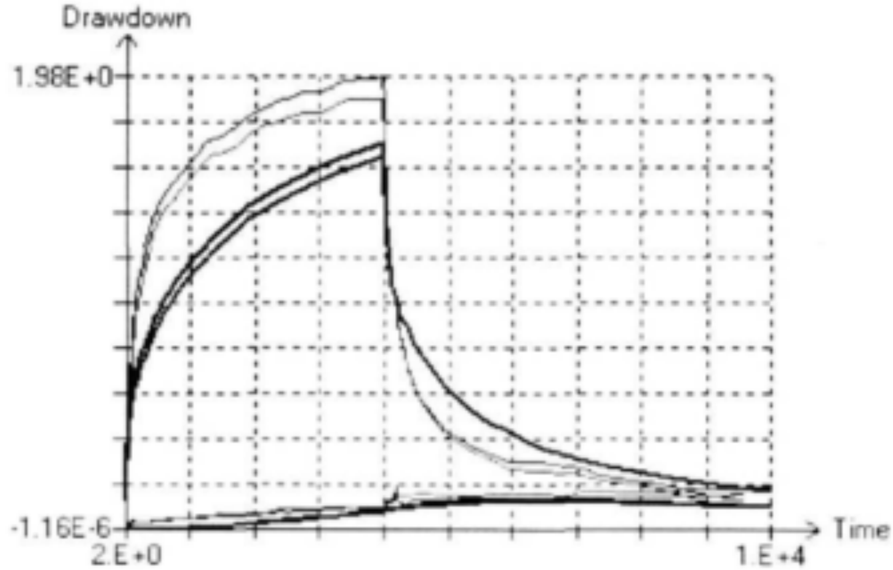


Piezometer below

UO28b

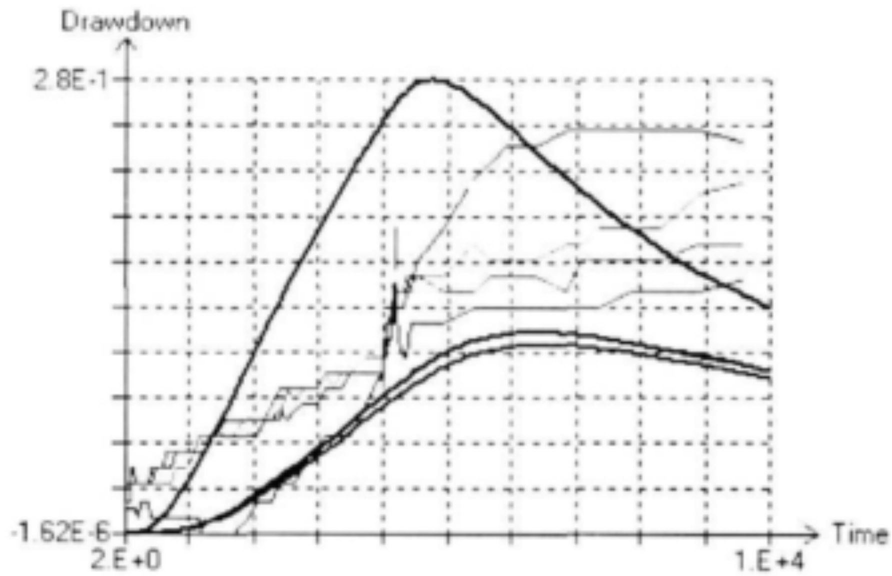
UO29b

7a



Fracture Observation

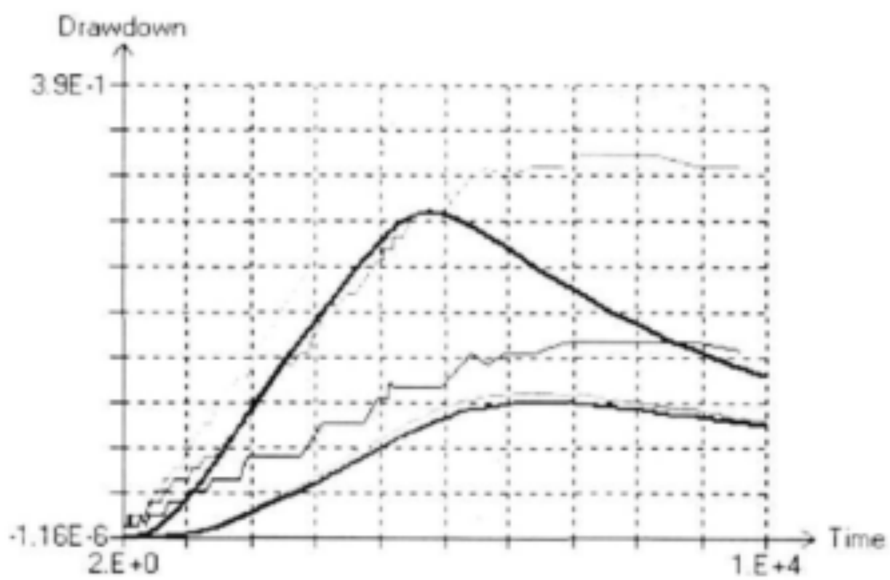
T matrix	1.10E-03
T matrix (0.5m)	5.49E-04
T matrix (0.2m)	2.20E-04
T fracture	4.50E-01
S matrix	4.86E-04
S matrix (0.5m)	2.43E-04
S matrix (0.2m)	9.73E-05
S fracture	5.11E-05
Leakage m (1-1)	1.68E-07
Leakage m (1-.5)	2.24E-07
Leakage m (.5-.5)	3.36E-07
Leakage m (.5-.2)	4.82E-07
Leakage fracture	6.71E-07



Piezometer above

UO 23a
UO 27a

UO 29a
UO 28a



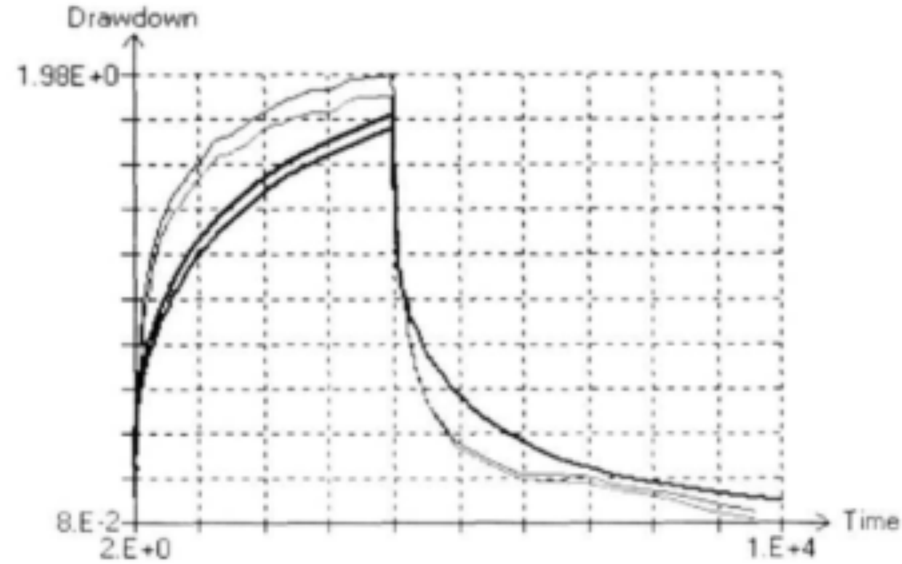
Piezometer below

UO 29b

UO 28b

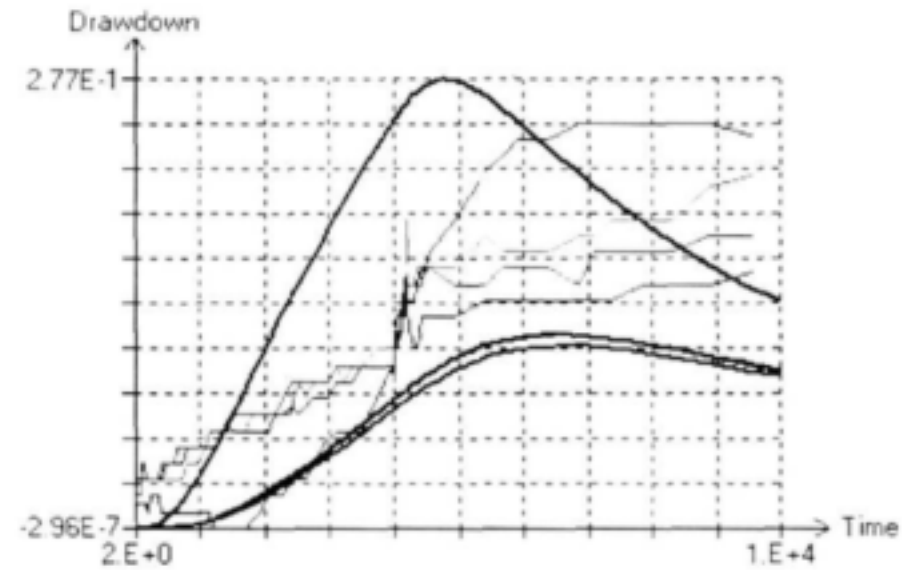
UO 23b

7b



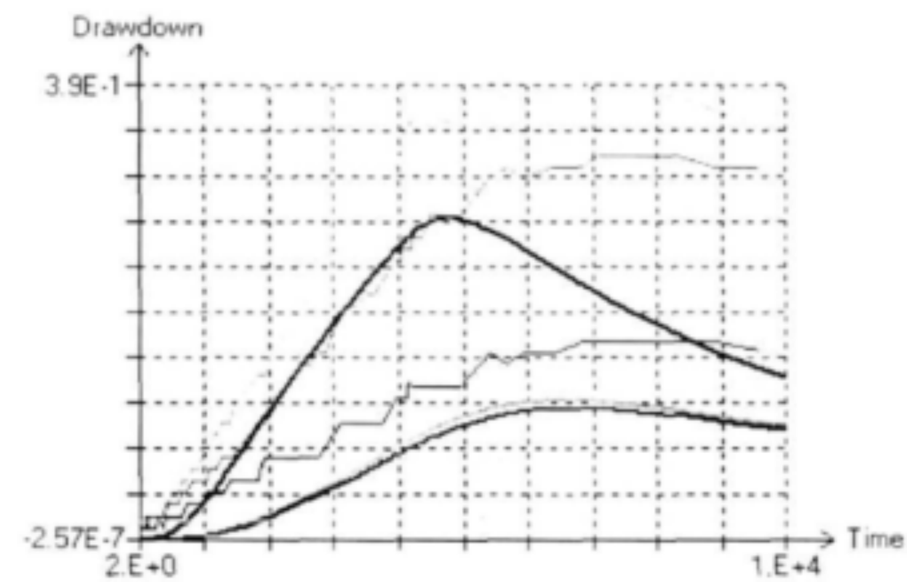
Fracture Observation

T matrix	1.10E-03
T matrix (0.5m)	5.51E-04
T matrix (0.2m)	2.20E-04
T fracture	4.30E-01
S matrix	5.03E-04
S matrix (0.5m)	2.52E-04
S matrix (0.2m)	1.01E-04
S fracture	2.76E-05
Leakage m (1-1)	1.68E-07
Leakage m (1-.5)	2.24E-07
Leakage m (.5-.5)	3.36E-07
Leakage m (.5-.2)	4.82E-07
Leakage fracture	6.71E-07



Piezometer above

UO 23a
UO 27a
UO 29a
UO 28a



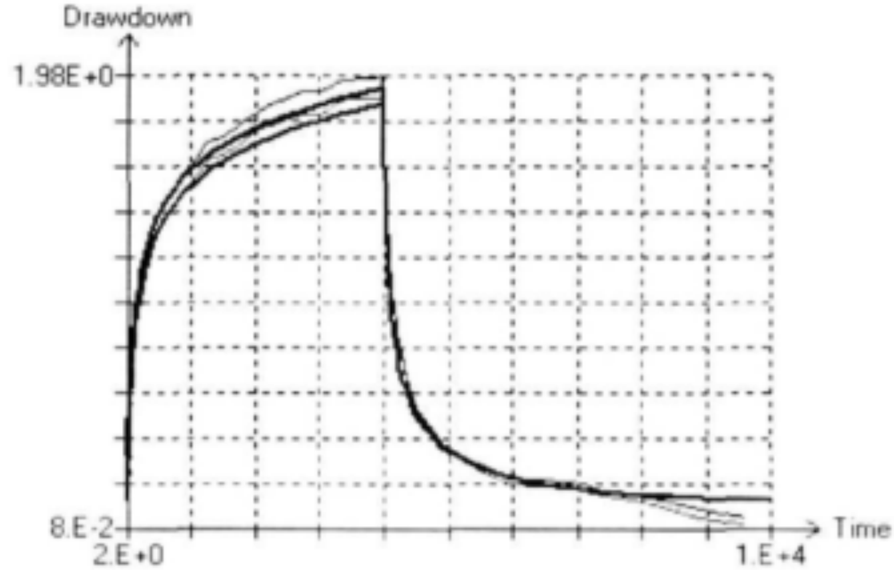
Piezometer below

UO 29b

UO 28b

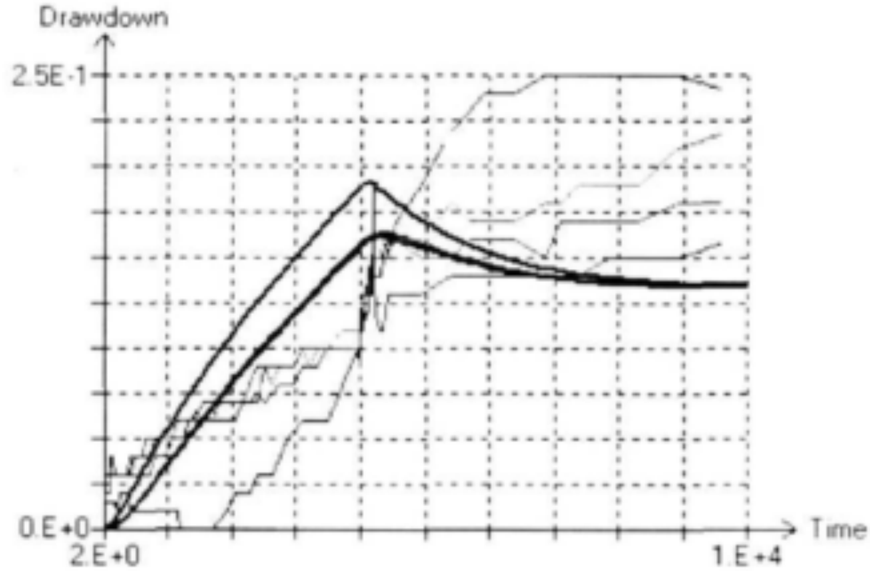
UO 23b

7c



Fracture Observation

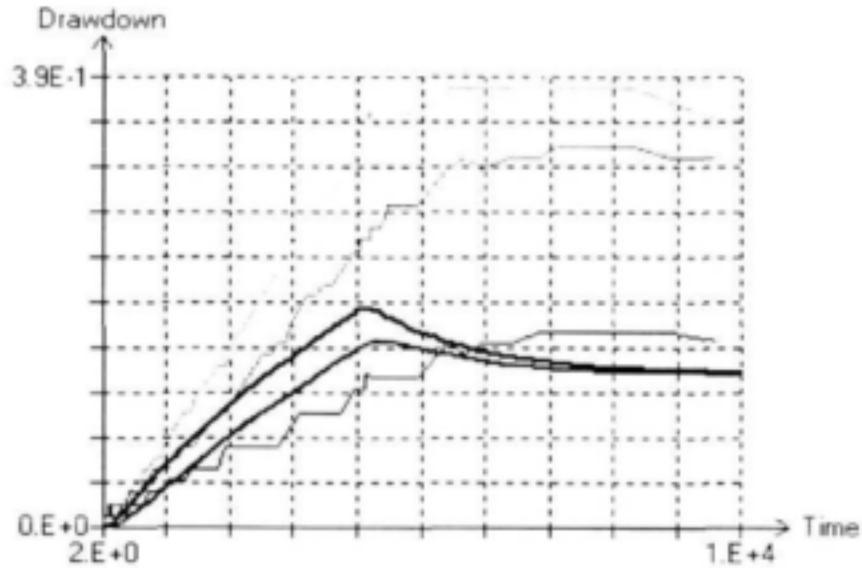
T matrix	4.08E-06
T matrix (0.5m)	2.04E-06
T matrix (0.2m)	8.15E-07
T fracture	4.30E-01
S matrix	1.25E-03
S matrix (0.5m)	6.26E-04
S matrix (0.2m)	2.50E-04
S fracture	2.76E-05
Leakage m (1-1)	1.00E-05
Leakage m (1-.5)	1.33E-05
Leakage m (.5-.5)	2.00E-05
Leakage m (.5-.2)	2.87E-05
Leakage fracture	2.48E-07



Piezometer above

UO 23a
UO 27a

UO 29a
UO 28a



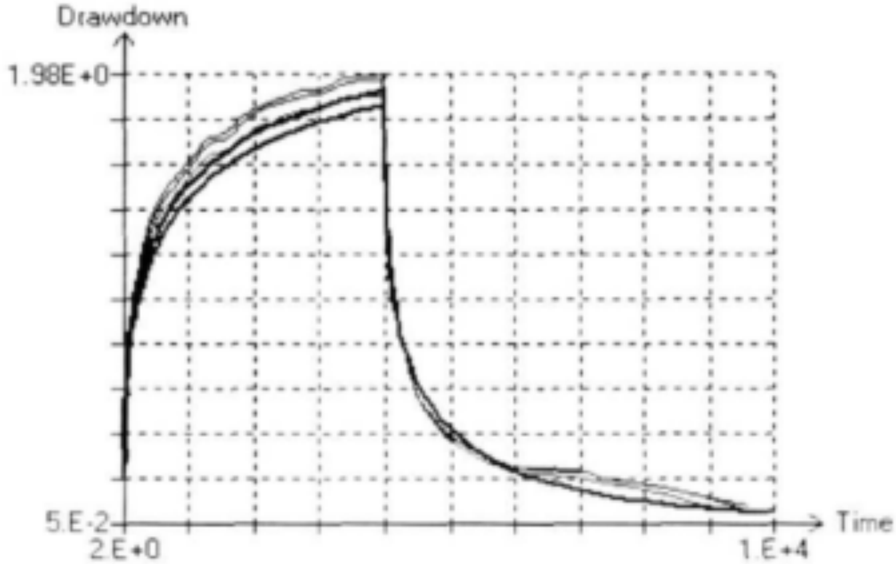
Piezometer below

UO 29b

UO 28b

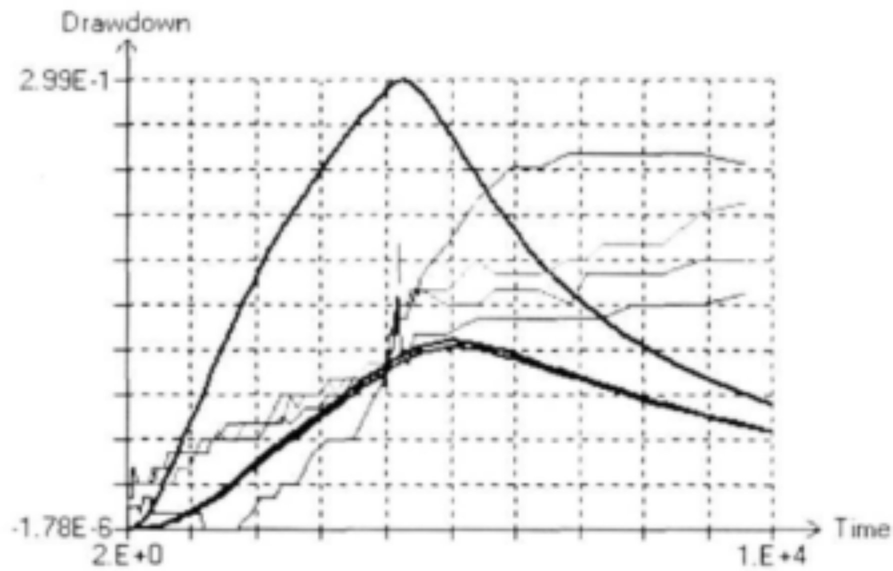
UO 23b

9a



Fracture Observation

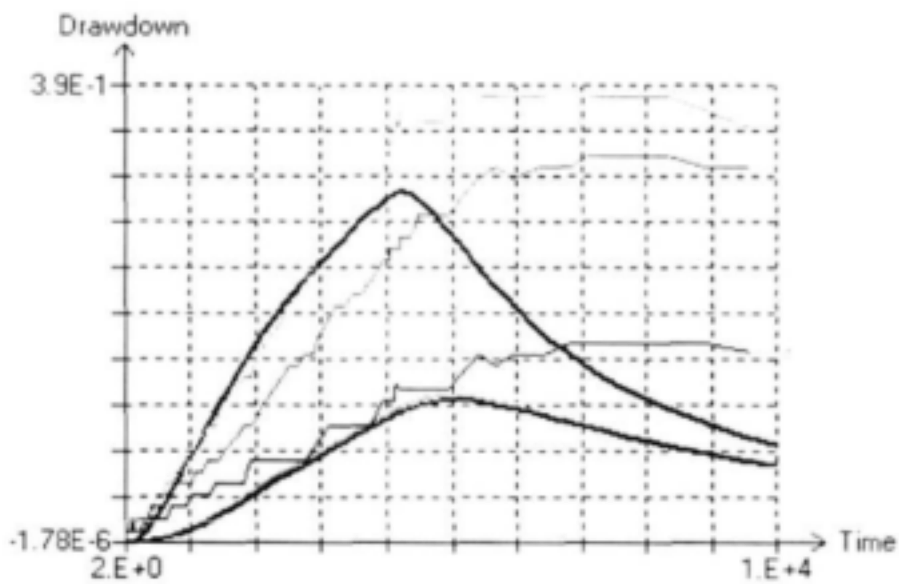
T matrix	1.63E-03
T matrix (0.5m)	8.14E-04
T matrix (0.2m)	3.26E-04
T fracture	7.40E-01
S matrix	2.87E-04
S matrix (0.5m)	1.44E-04
S matrix (0.2m)	5.74E-05
S fracture	2.14E-05
Leakage m (1-1)	1.24E-07
Leakage m (1-.5)	1.65E-07
Leakage m (.5-.5)	2.48E-07
Leakage m (.5-.2)	3.55E-07
Leakage fracture	4.95E-07



Piezometer above

UO 23a
UO 27a

UO 29a
UO 28a



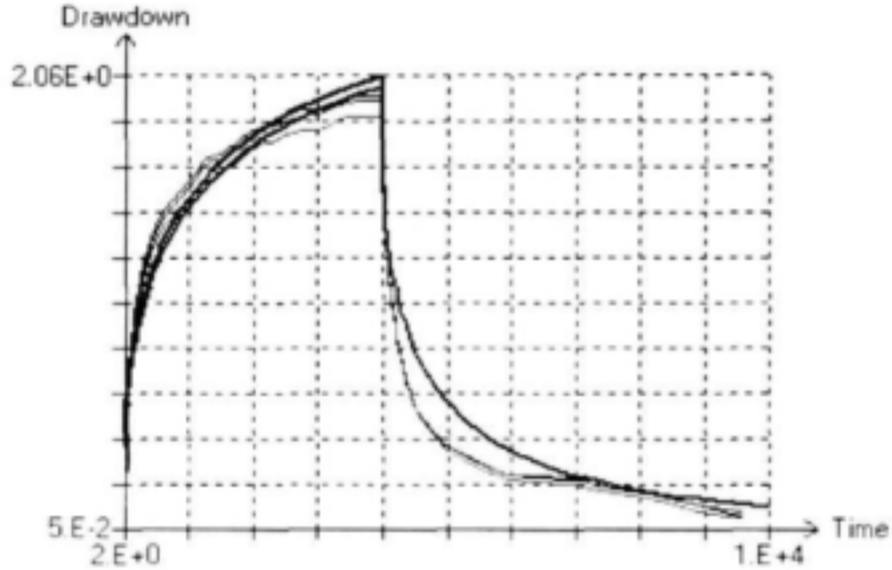
Piezometer below

UO 29b

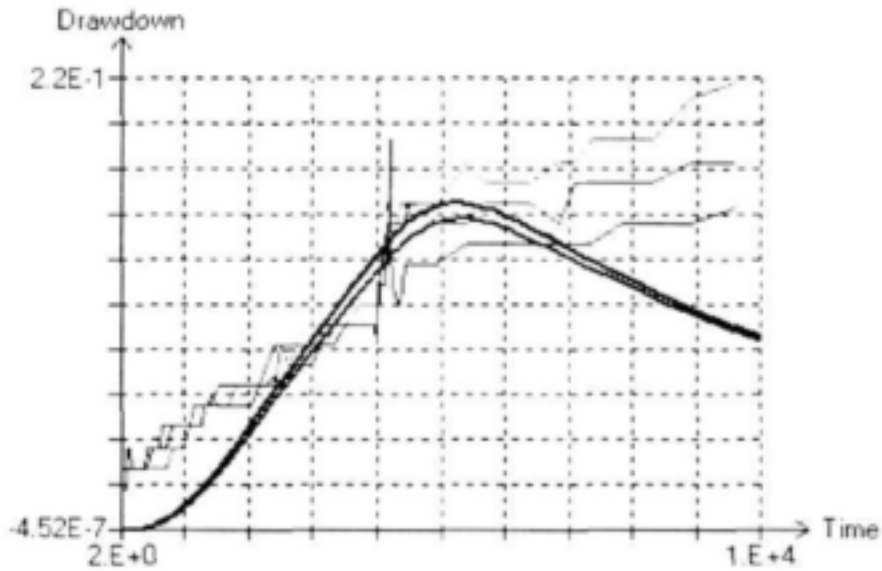
UO 28b

UO 23b

Run21



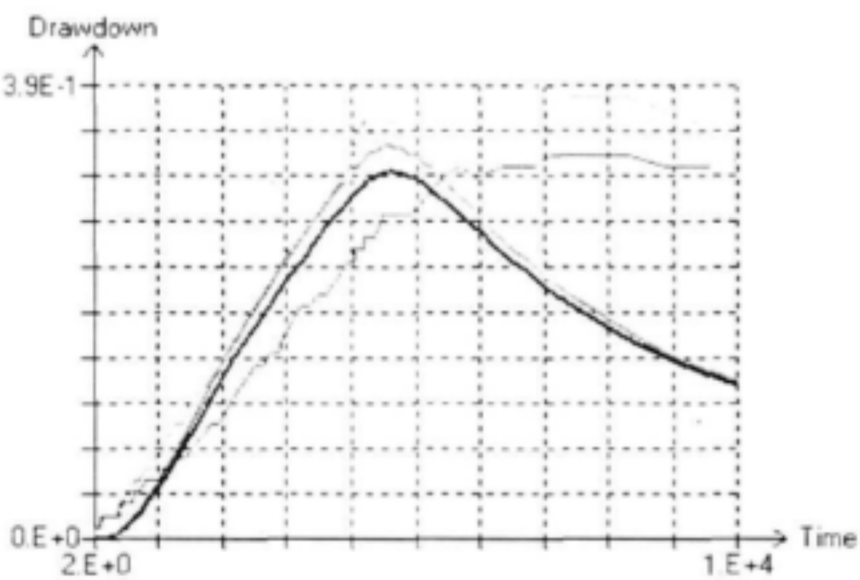
T matrix	8.63E-04
T fracture	6.09E-01
S matrix above	2.20E-04
S fracture	3.99E-06
S matrix below	3.05E-04
Leakage m above	1.17E-07
Leakage to fractur	4.68E-07
Leakage m below	2.66E-07
Leakage to fractur	1.06E-06



Piezometer above

UO27a

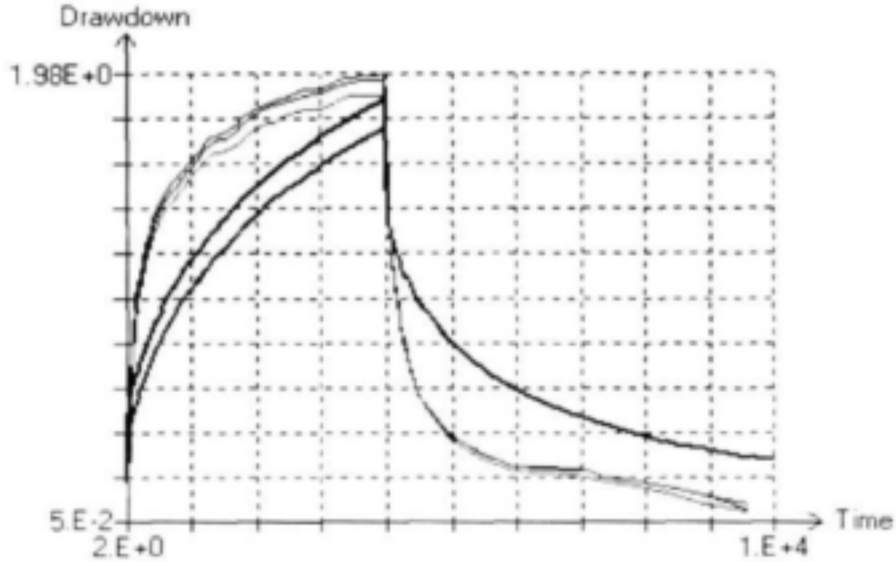
UO29a
UO28a



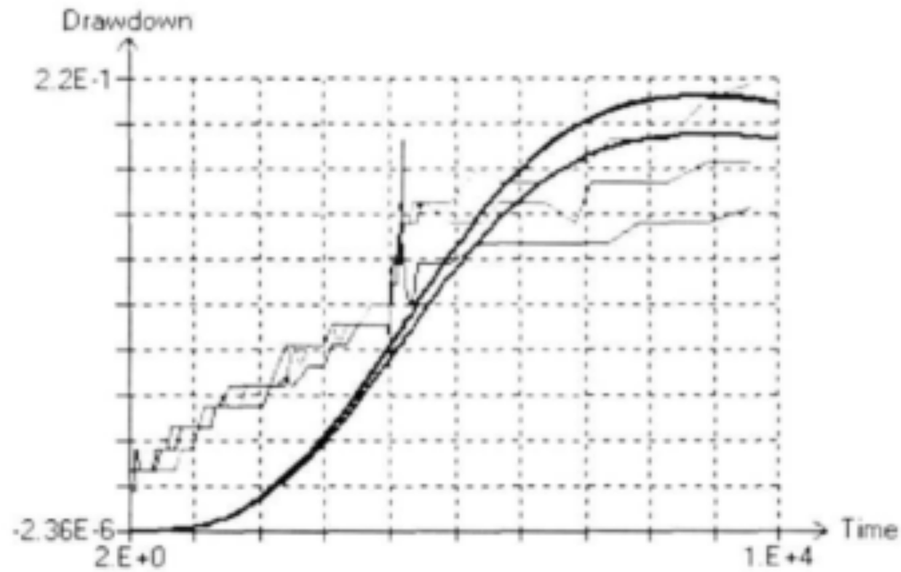
Piezometer below

UO28b
UO29b

Run22a



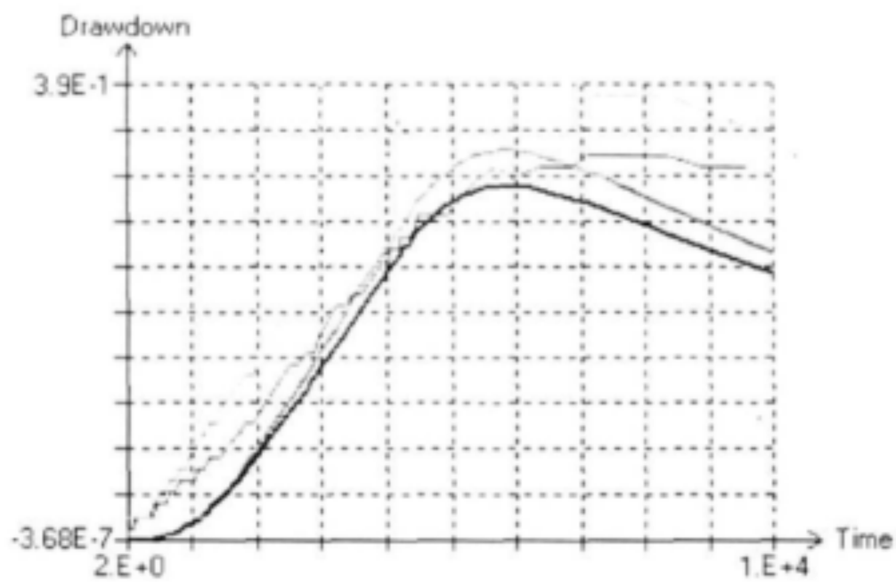
T matrix	2.70E-04
T fracture	2.15E-01
S matrix above	**1.00E-03**
S fracture	1.74E-05
S matrix below	**5.00E-04**
Leakage m above	2.69E-07
Leakage to fractur	1.08E-06
Leakage m below	2.85E-07
Leakage to fractur	1.14E-06



Piezometer above

UO27a

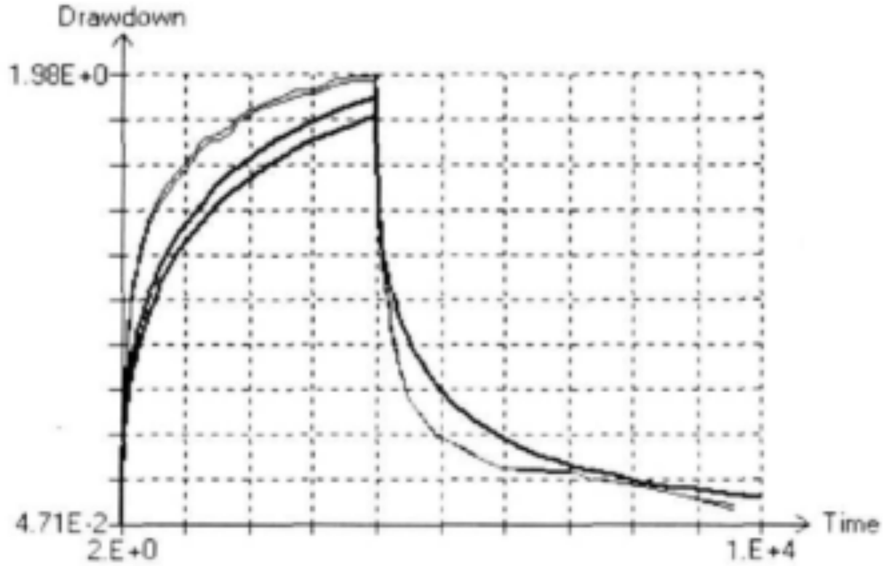
UO29a
UO28a



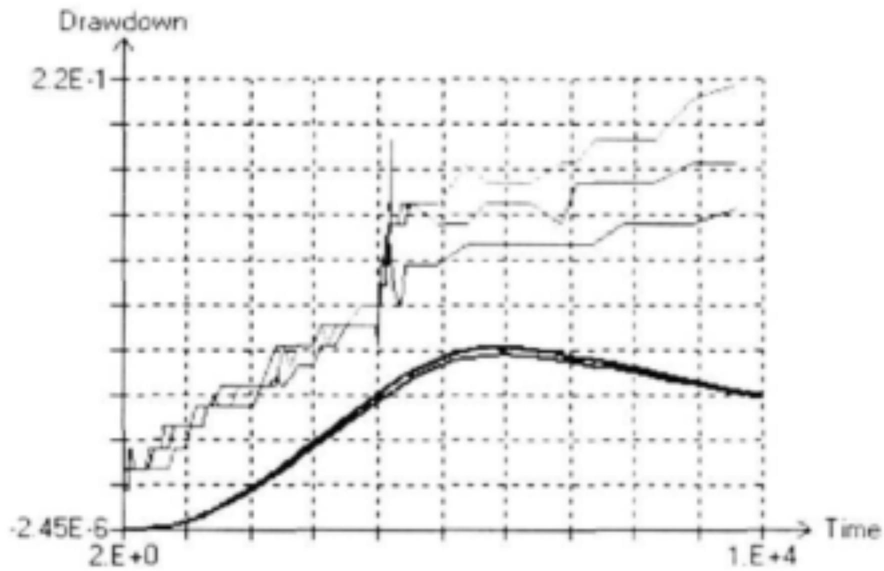
Piezometer below

UO28b
UO29b

23/24



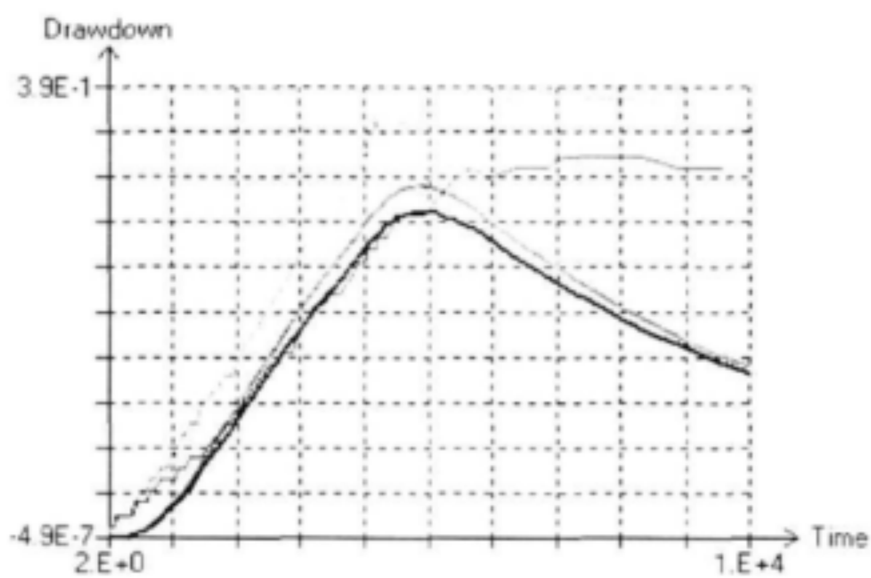
T matrix	4.42E-04
T fracture	4.20E-01
S matrix above	4.98E-04
S fracture	2.58E-05
S matrix below	5.47E-04
Leakage m above	1.69E-07
Leakage to fractu	6.77E-07
Leakage m below	3.45E-07
Leakage to fractu	1.38E-06



Piezometer above

UO27a

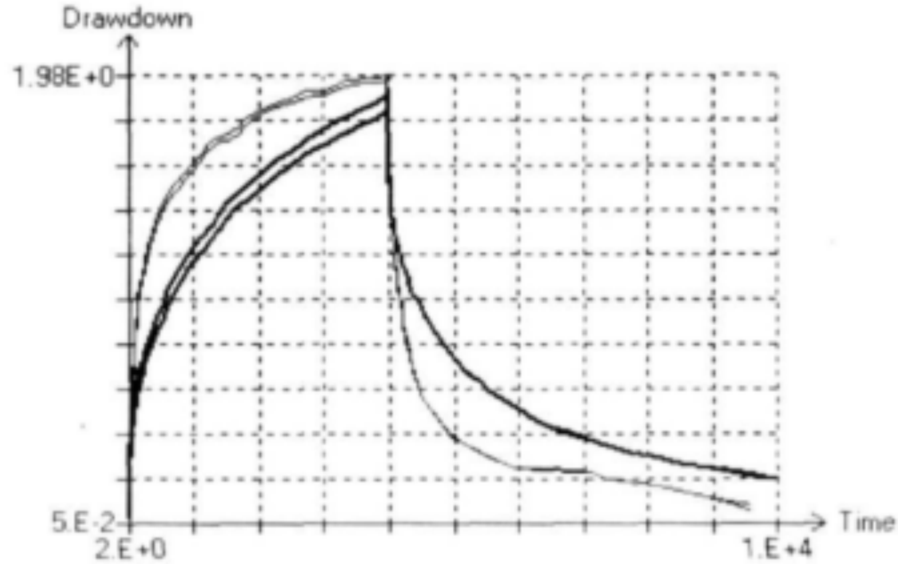
UO29a
UO28a



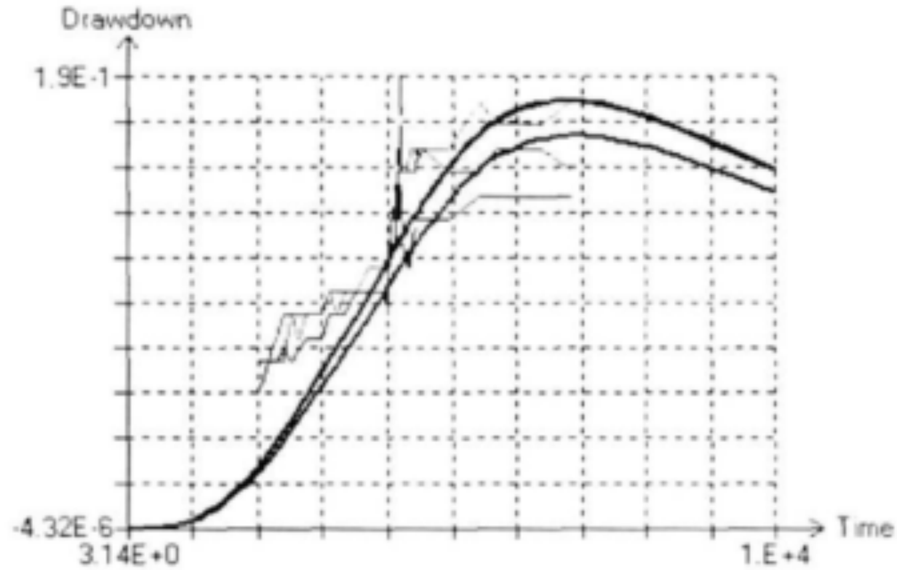
Piezometer below

UO28b
UO29b

25a



T matrix	4.37E-04
T fracture	4.09E-01
S matrix above	4.86E-04
S fracture	2.45E-05
S matrix below	5.20E-04
Leakage m above	1.64E-07
Leakage to fractur	6.56E-07
Leakage m below	3.35E-07
Leakage to fractur	1.34E-06

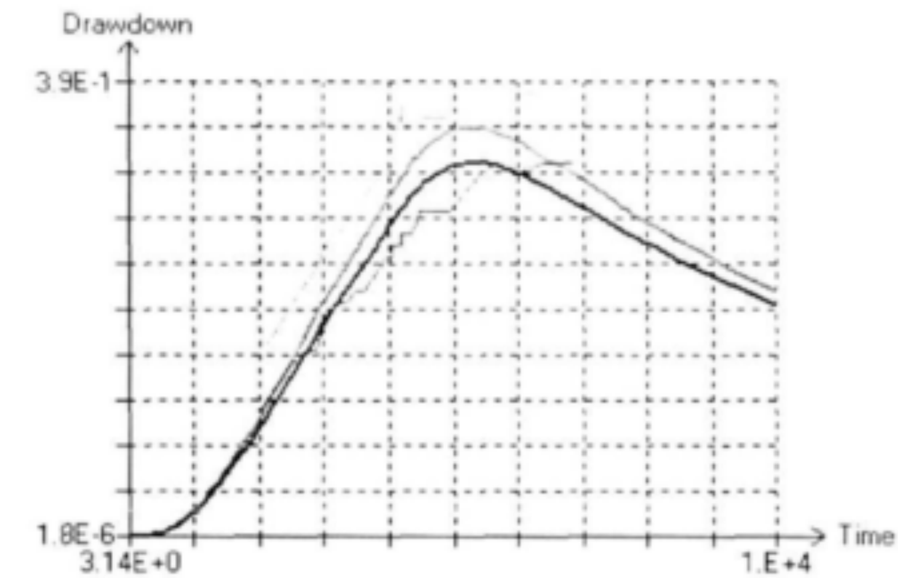


Piezometer above

UO27a

UO29a

UO28a

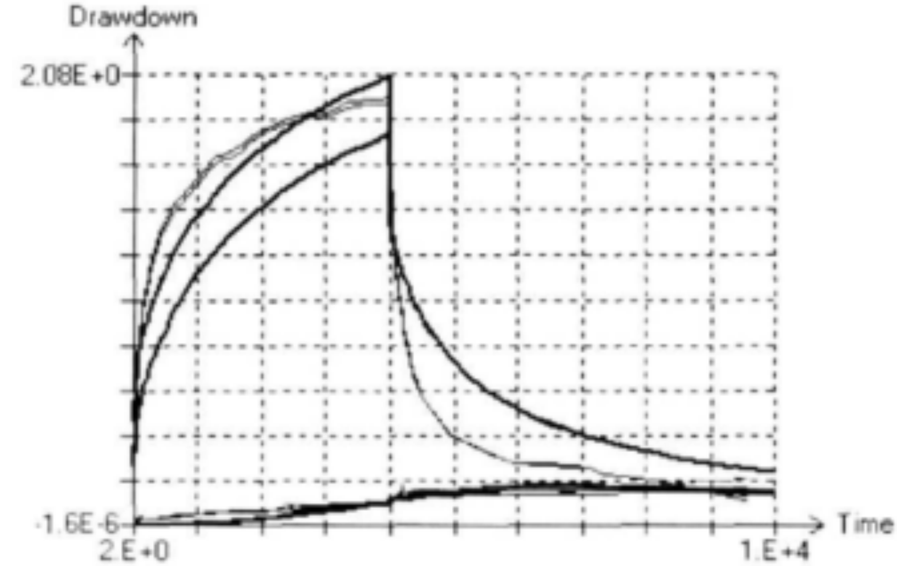


Piezometer below

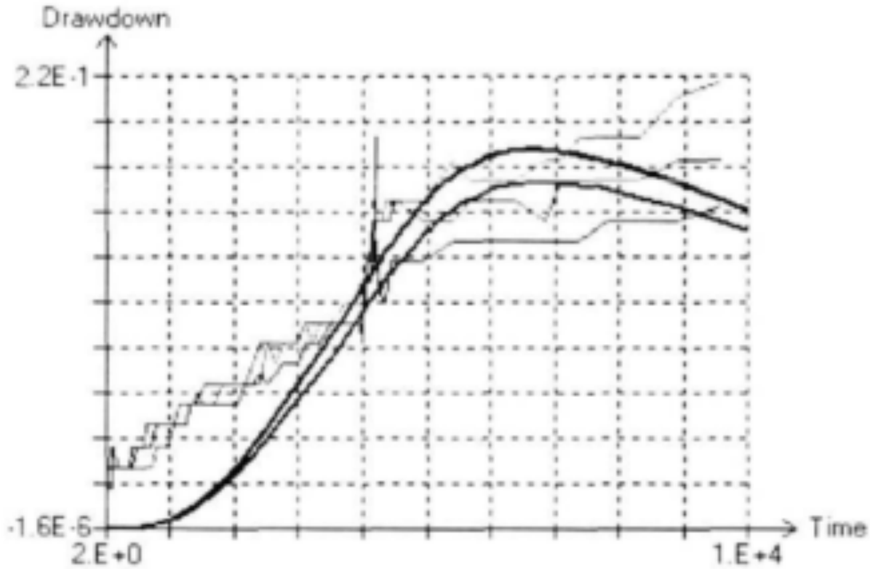
UO28b

UO29b

26a



T matrix	4.42E-04
T fracture	1.00E-01
S matrix above	4.98E-04
S fracture	3.70E-06
S matrix below	5.47E-04
Leakage m above	1.69E-07
Leakage to fractur	6.77E-07
Leakage m below	3.45E-07
Leakage to fractur	1.38E-06

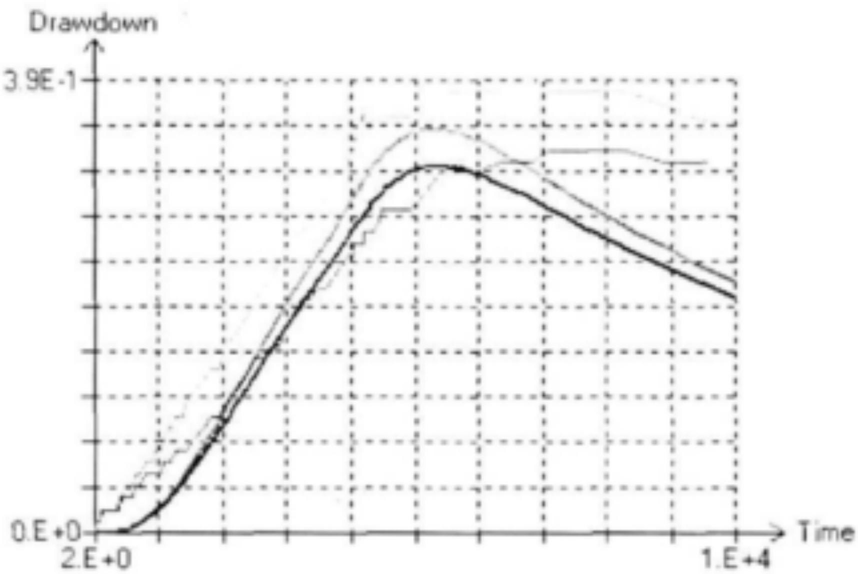


Piezometer above

UO27a

UO29a

UO28a

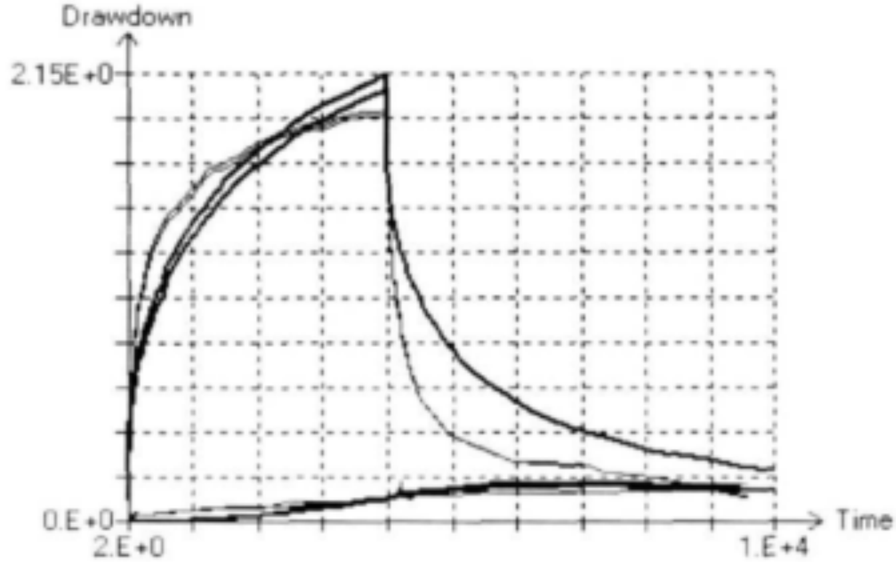


Piezometer below

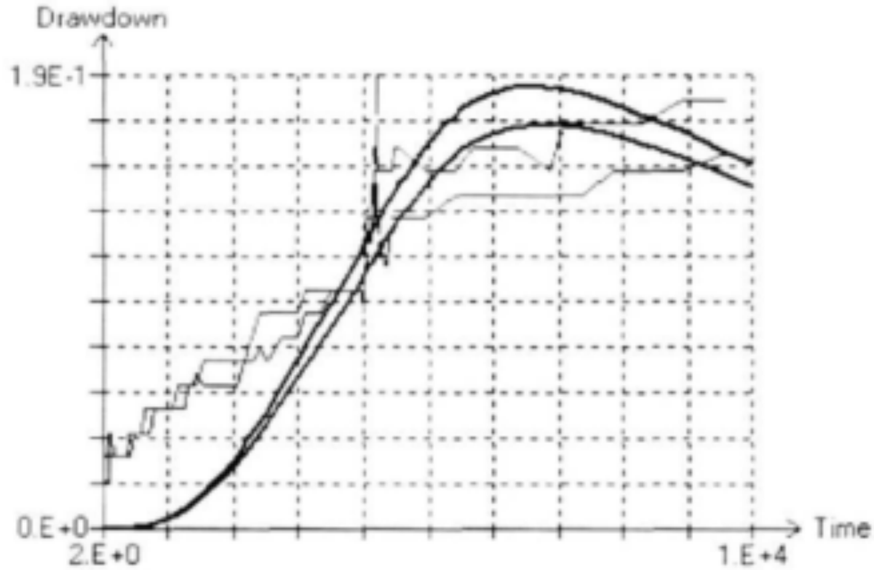
UO28b

UO29b

27

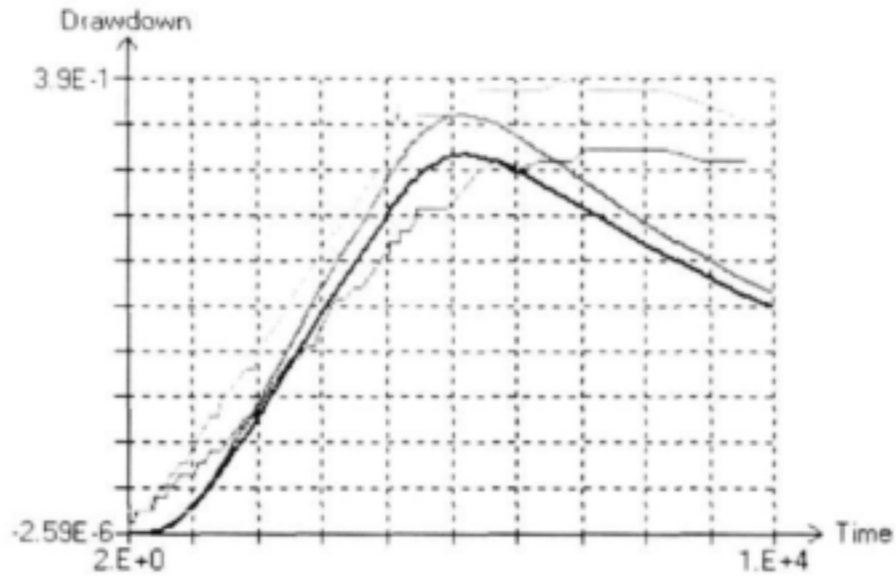


T matrix	5.15E-04
T fracture	3.91E-01
S matrix above	4.89E-04
S fracture	1.65E-05
S matrix below	4.83E-04
Leakage m above	1.68E-07
Leakage to fractur	6.71E-07
Leakage m below	3.19E-07
Leakage to fractur	1.27E-06



Piezometer above

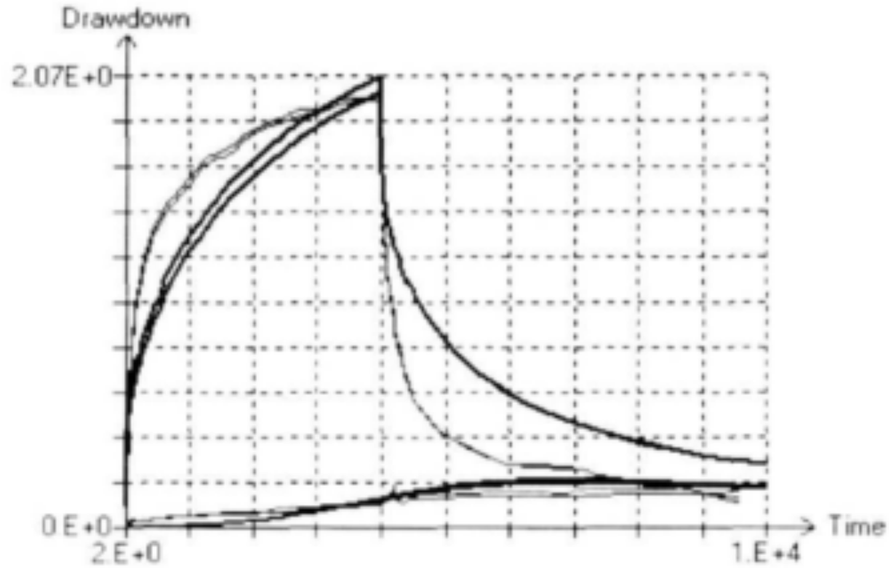
UO29a
UO28a



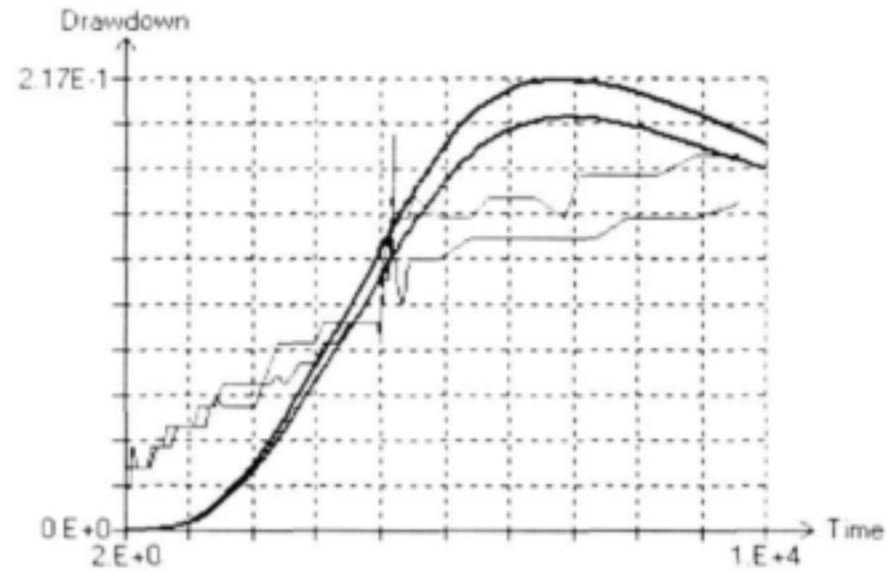
Piezometer below

UO28b
UO29b

27a

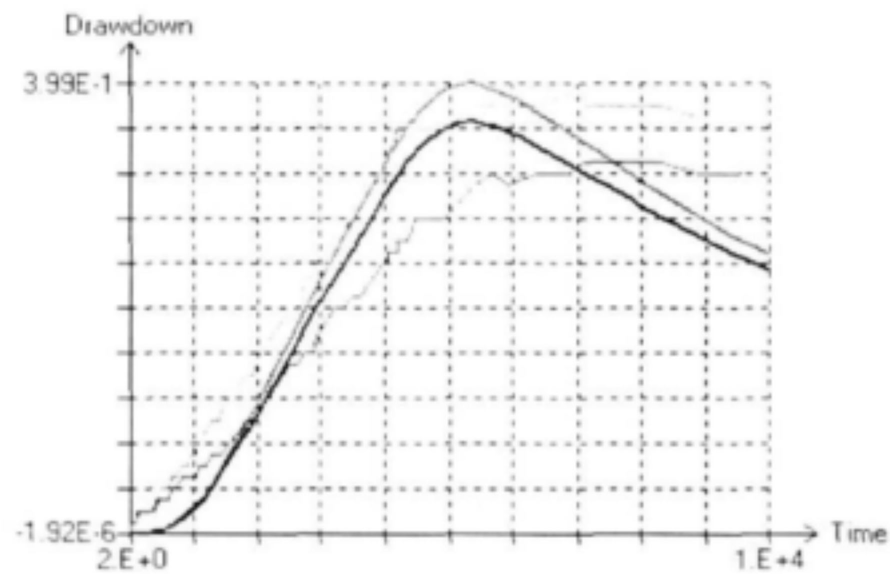


T matrix	3.68E-04
T fracture	3.91E-01
S matrix above	4.89E-04
S fracture	1.65E-05
S matrix below	4.83E-04
Leakage m above	1.68E-07
Leakage to fractur	6.71E-07
Leakage m below	3.19E-07
Leakage to fractur	1.27E-06



Piezometer above

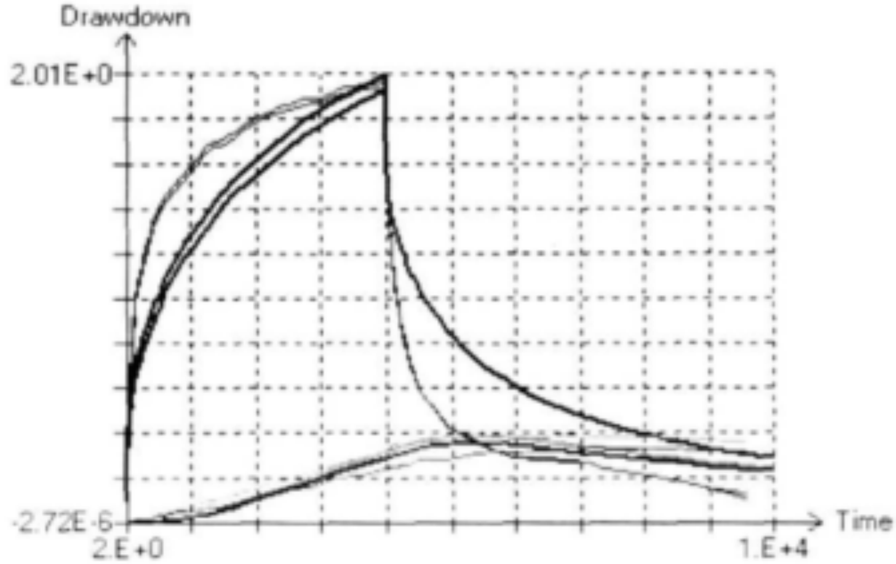
UO29a
UO28a



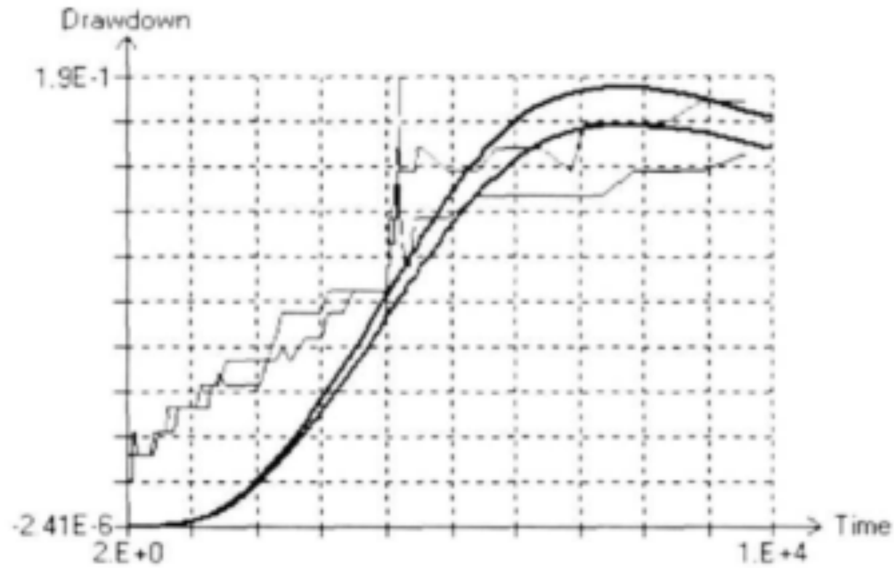
Piezometer below

UO28b
UO29b

27b

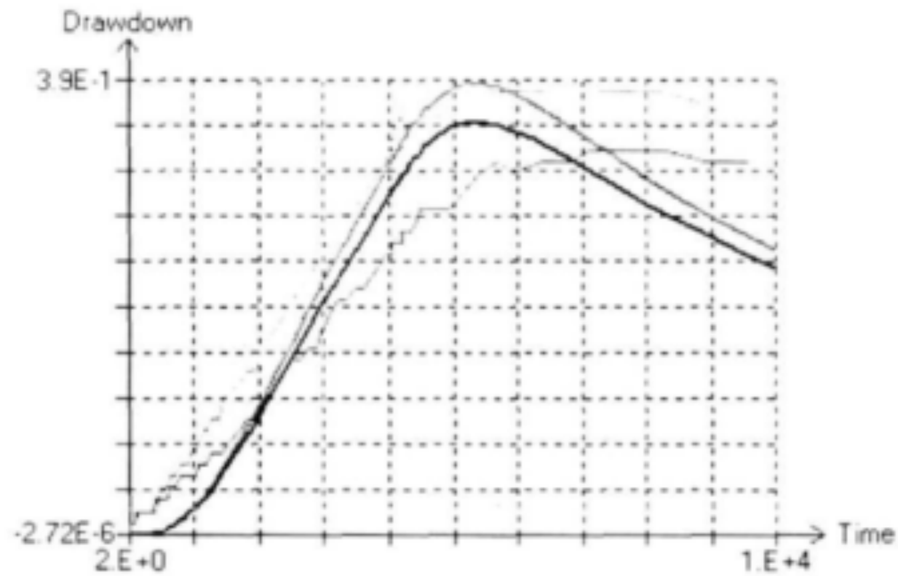


T matrix	3.68E-04
T fracture	3.91E-01
S matrix above	6.00E-04
S fracture	1.65E-05
S matrix below	4.83E-04
Leakage m above	1.68E-07
Leakage to fractur	6.71E-07
Leakage m below	3.19E-07
Leakage to fractur	1.27E-06



Piezometer above

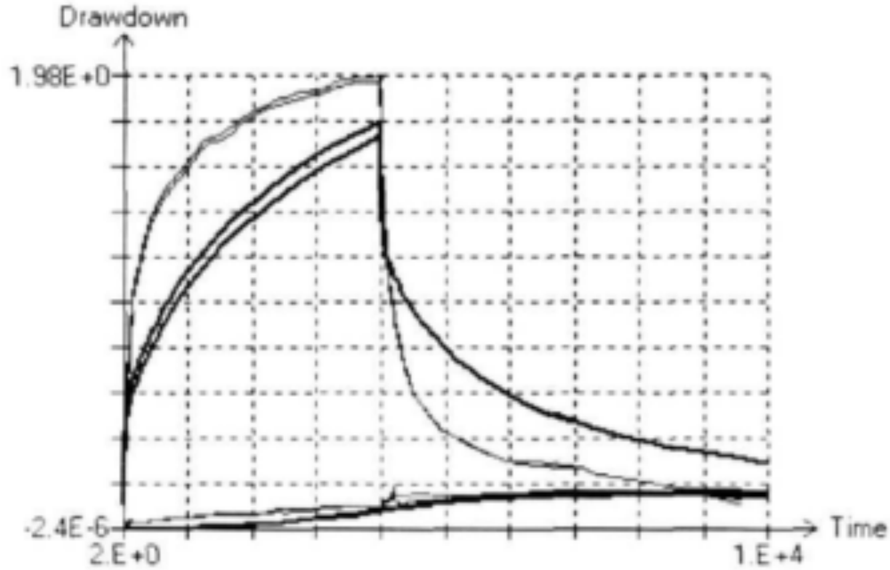
UO29a
UO28a



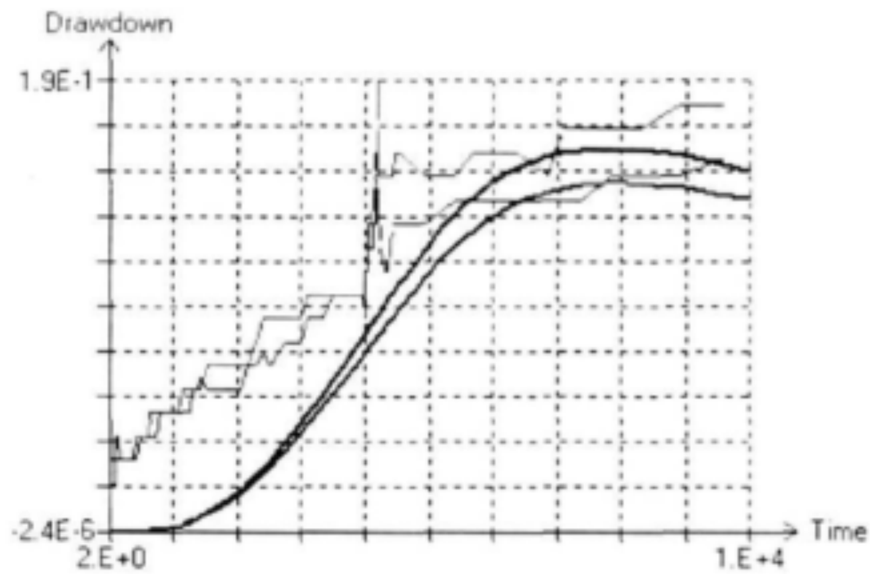
Piezometer below

UO28b
UO29b

27c

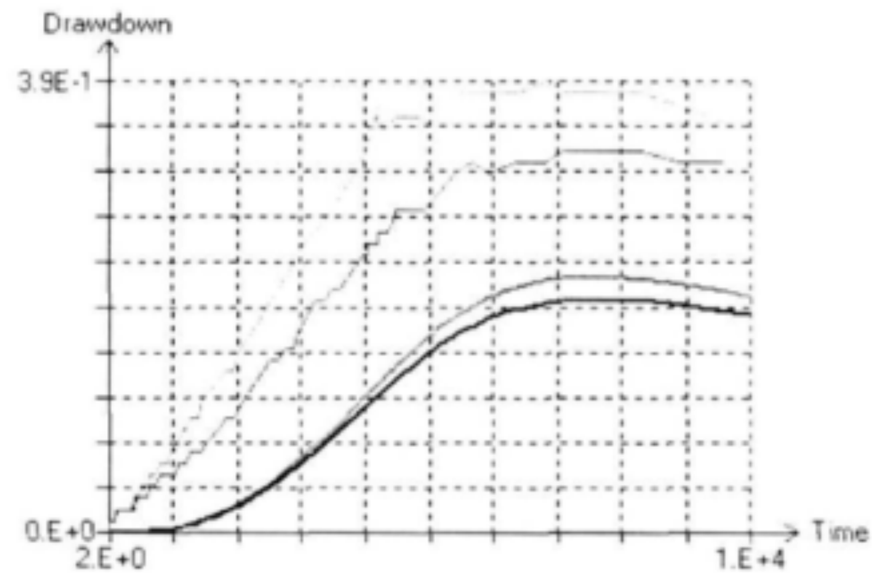


T matrix	3.68E-04
T fracture	3.91E-01
S matrix above	6.00E-04
S fracture	1.65E-05
S matrix below	1.00E-03
Leakage m above	1.68E-07
Leakage to fractur	6.71E-07
Leakage m below	3.19E-07
Leakage to fractur	1.27E-06



Piezometer above

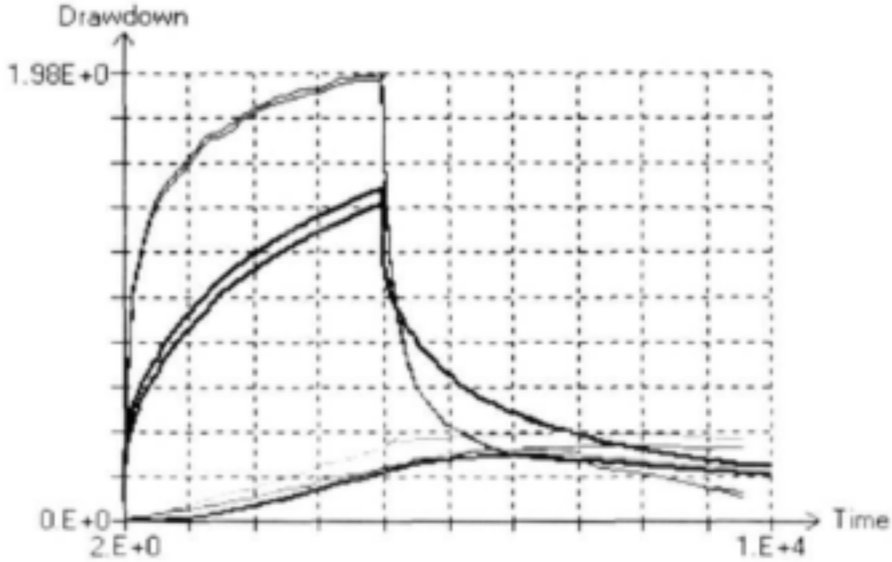
UO29a
UO28a



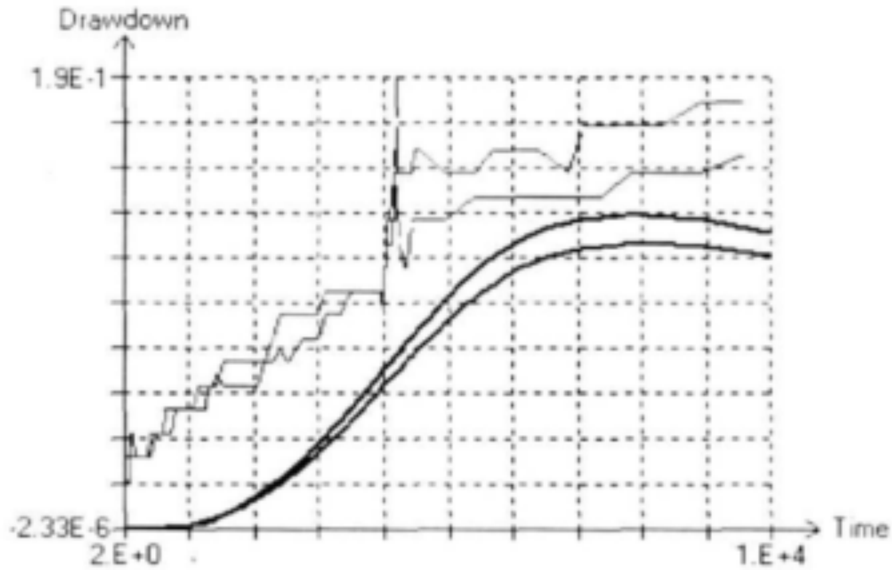
Piezometer below

UO28b
UO29b

27d

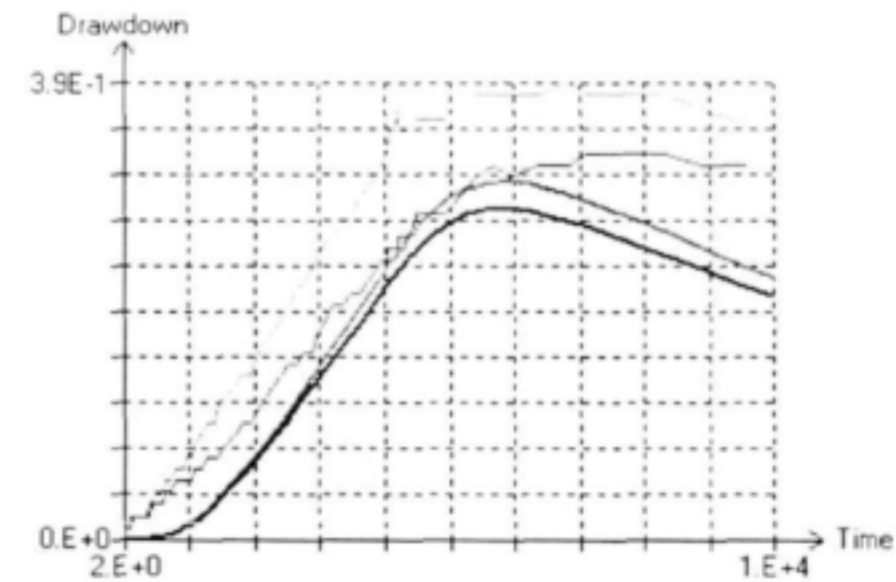


T matrix	3.68E-04
T fracture	3.91E-01
S matrix above	6.00E-04
S fracture	1.65E-05
S matrix below	1.00E-03
Leakage m above	1.68E-07
Leakage to fractur	6.71E-07
Leakage m below	6.00E-07
Leakage to fractur	2.40E-06



Piezometer above

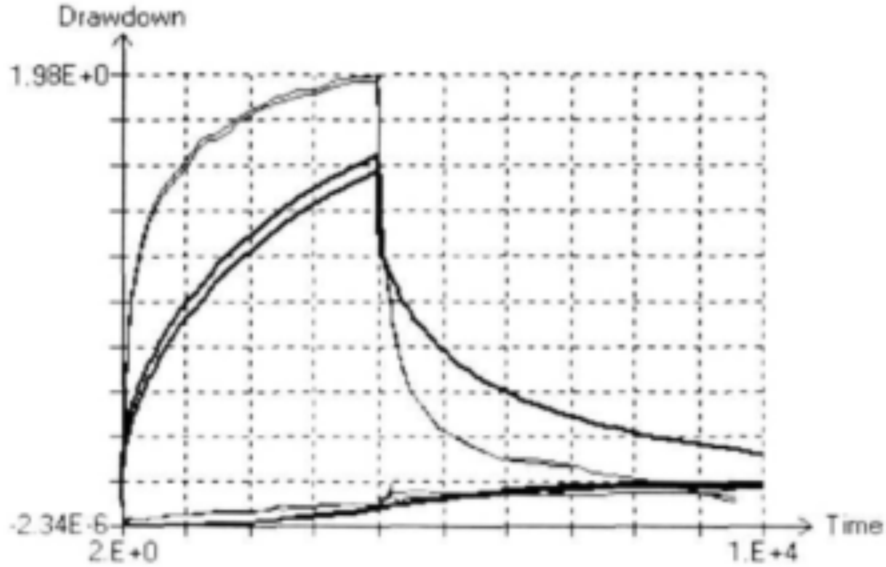
UO29a
UO28a



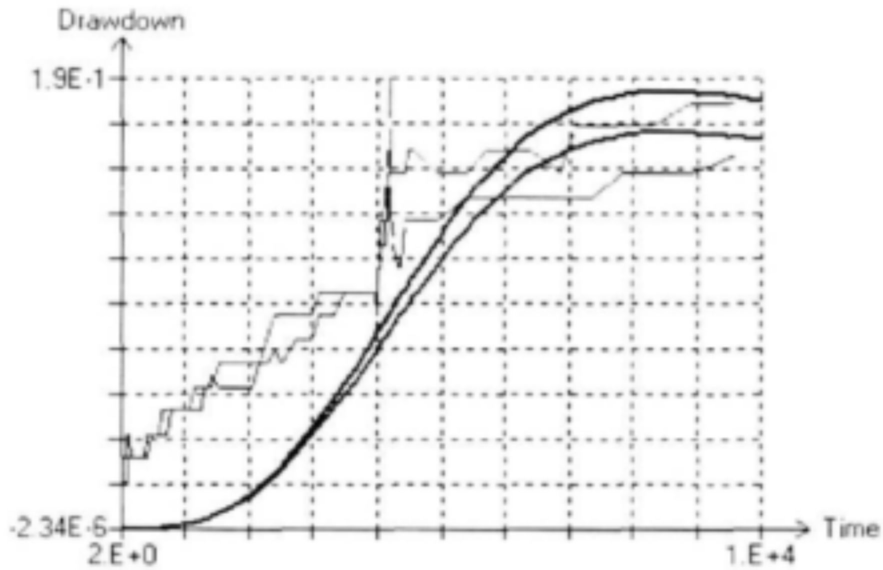
Piezometer below

UO28b
UO29b

27e

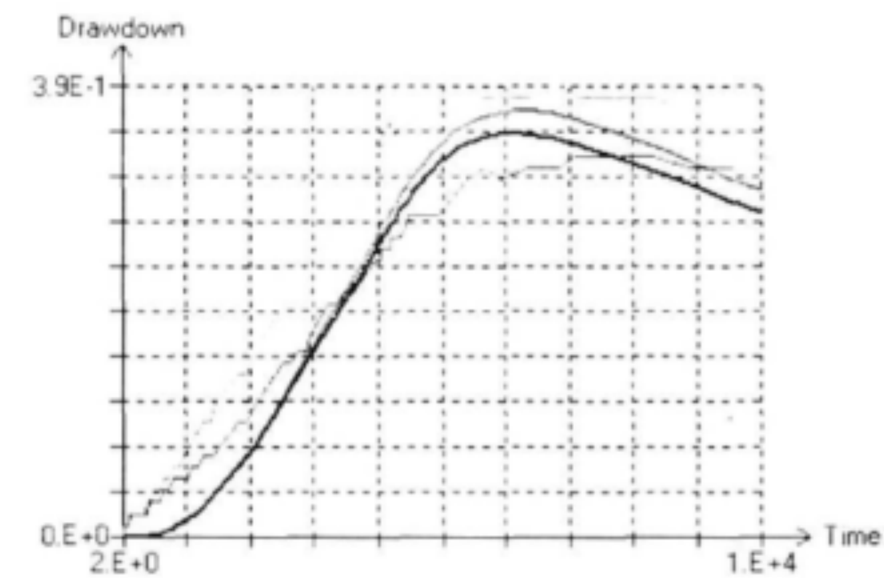


T matrix	2.00E-04
T fracture	3.91E-01
S matrix above	6.00E-04
S fracture	1.65E-05
S matrix below	1.00E-03
Leakage m above	1.68E-07
Leakage to fractur	6.71E-07
Leakage m below	6.00E-07
Leakage to fractur	2.40E-06



Piezometer above

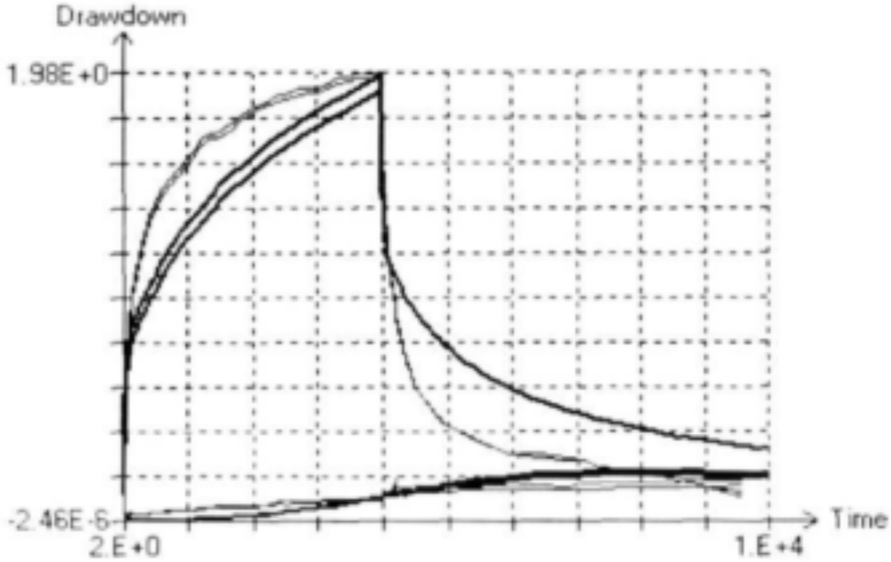
UO29a
UO28a



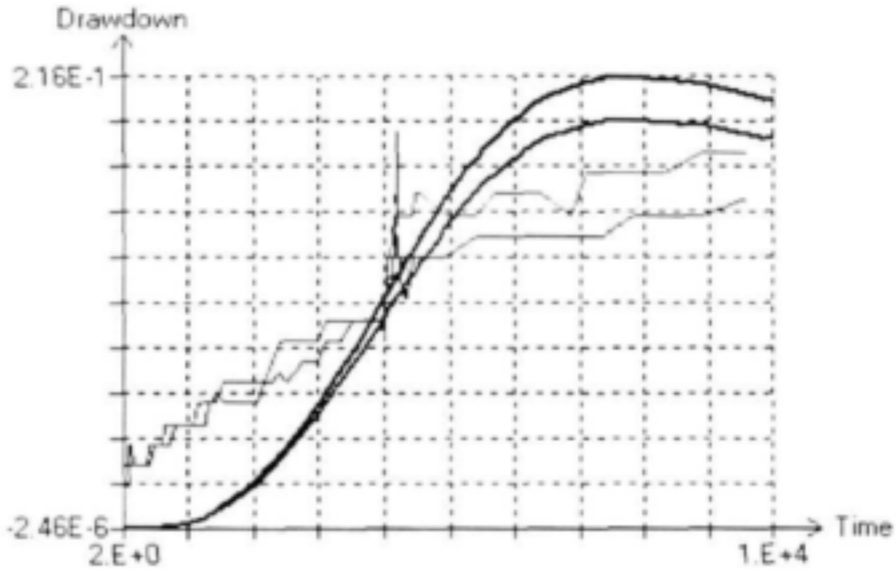
Piezometer below

UO28b
UO29b

27f



T matrix	2.00E-04
T fracture	3.91E-01
S matrix above	6.00E-04
S fracture	1.65E-05
S matrix below	1.00E-03
Leakage m above	1.68E-07
Leakage to fractur	6.71E-07
Leakage m below	6.00E-07
Leakage to fractur	6.71E-07

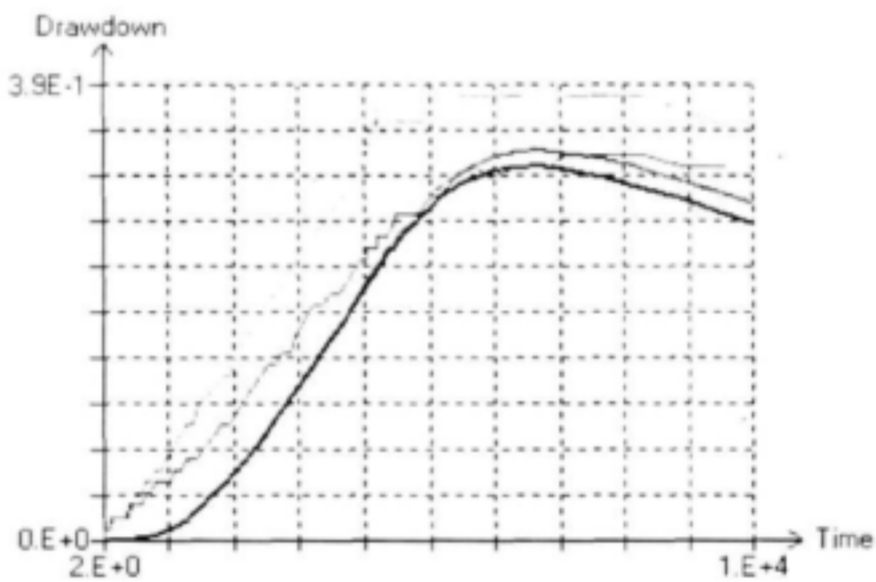


Piezometer above

UO27a

UO29a

UO28a

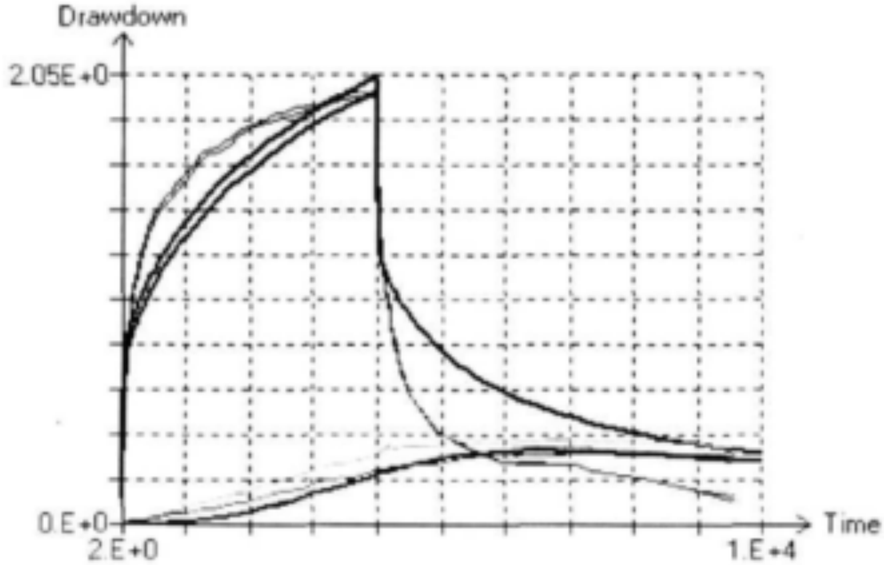


Piezometer below

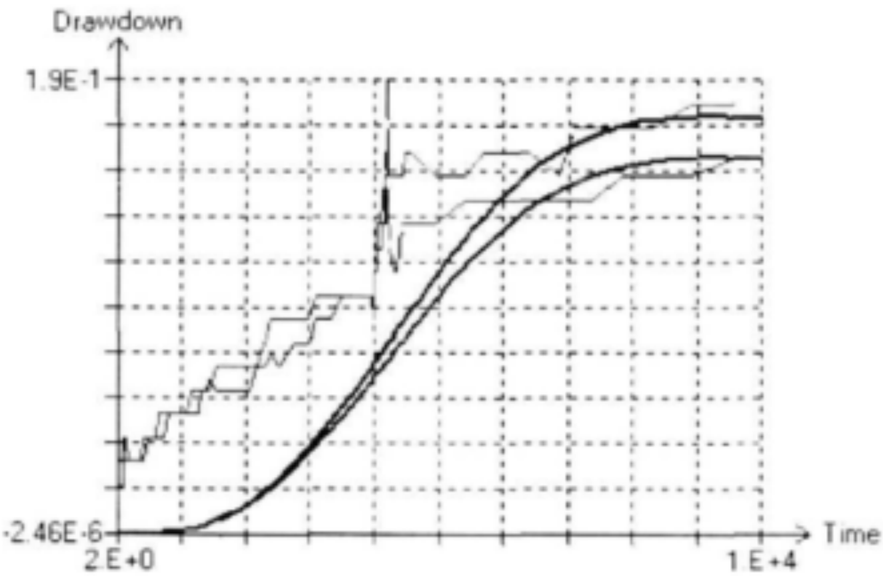
UO28b

UO29b

27g

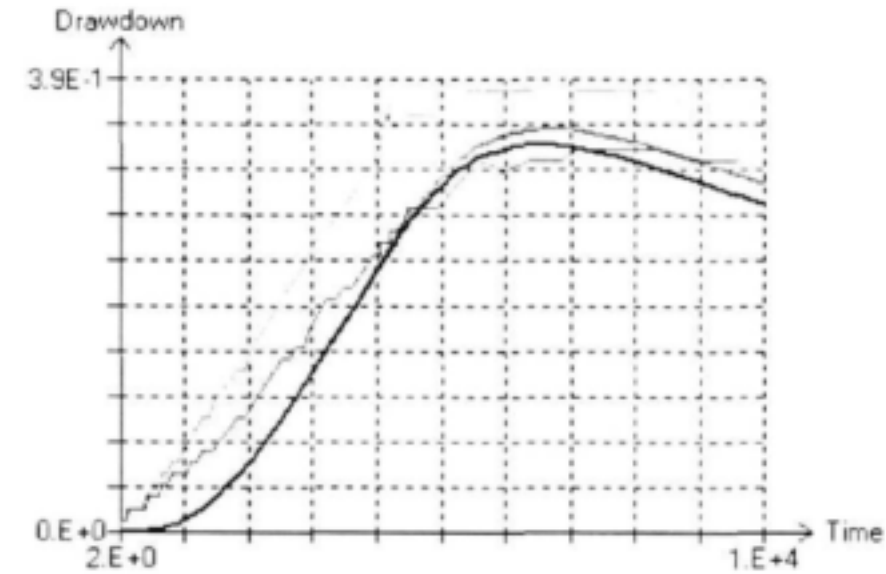


T matrix	2.00E-04
T fracture	3.91E-01
S matrix above	6.00E-04
S fracture	1.65E-05
S matrix below	1.00E-03
Leakage m above	1.30E-07
Leakage to fractur	5.20E-07
Leakage m below	6.00E-07
Leakage to fractur	6.71E-07



Piezometer above

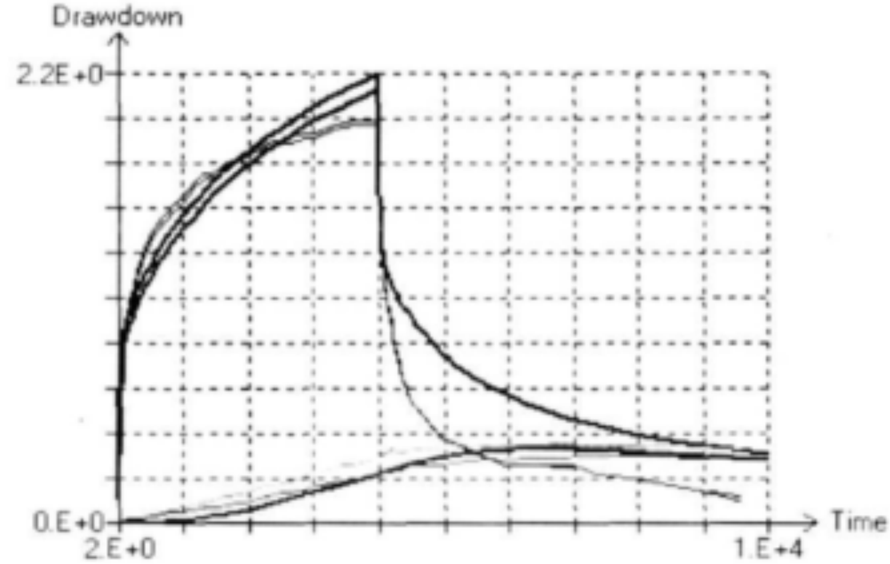
UO29a
UO28a



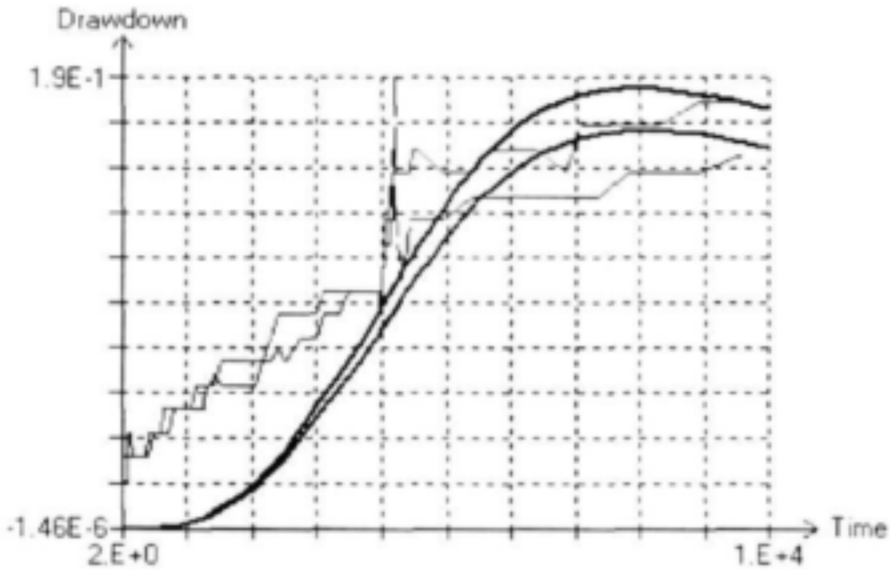
Piezometer below

UO28b
UO29b

27h

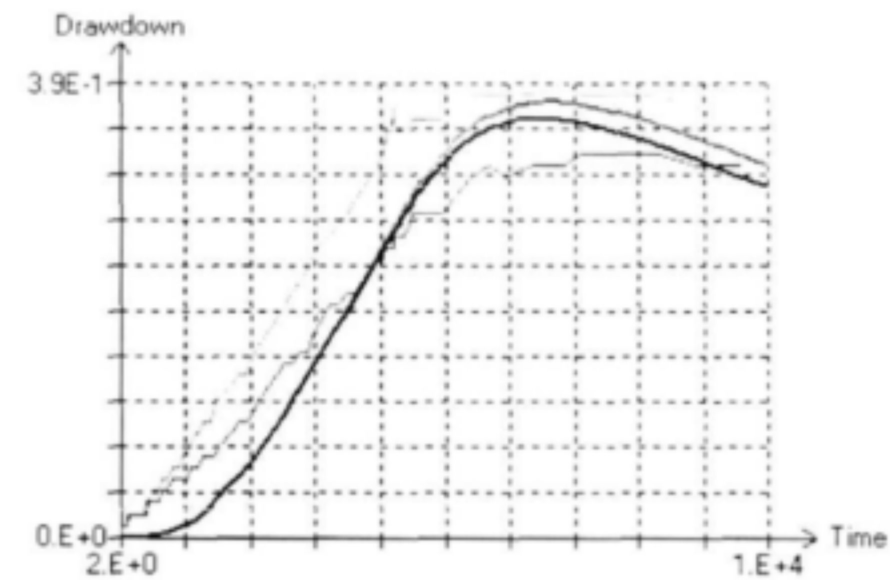


T matrix	2.00E-04
T fracture	3.91E-01
S matrix above	4.00E-04
S fracture	1.65E-05
S matrix below	1.00E-03
Leakage m above	1.00E-07
Leakage to fractur	4.00E-07
Leakage m below	6.00E-07
Leakage to fractur	6.71E-07



Piezometer above

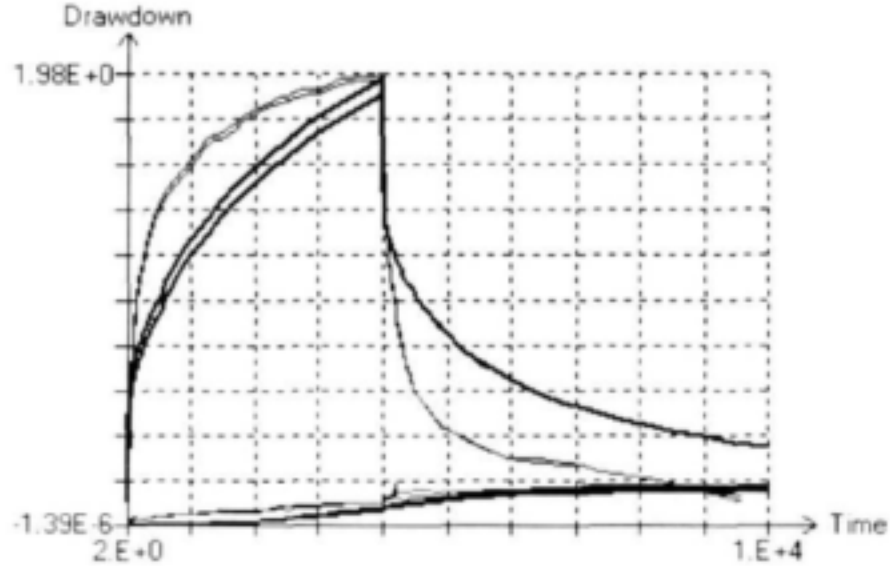
UO29a
UO28a



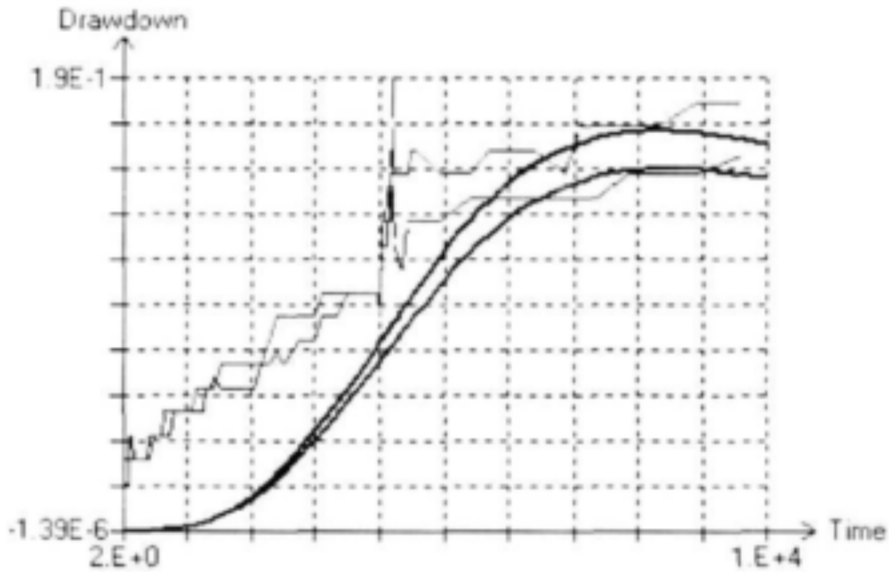
Piezometer below

UO28b
UO29b

27i

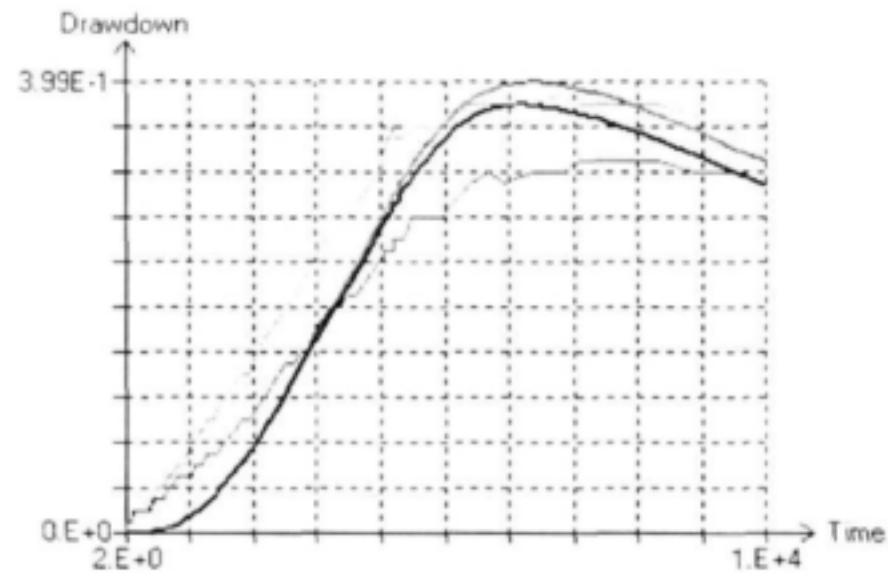


T matrix	2.00E-04
T fracture	3.91E-01
S matrix above	4.00E-04
S fracture	1.65E-05
S matrix below	1.00E-03
Leakage m above	1.00E-07
Leakage to fractur	4.00E-07
Leakage m below	6.00E-07
Leakage to fractur	1.27E-06



Piezometer above

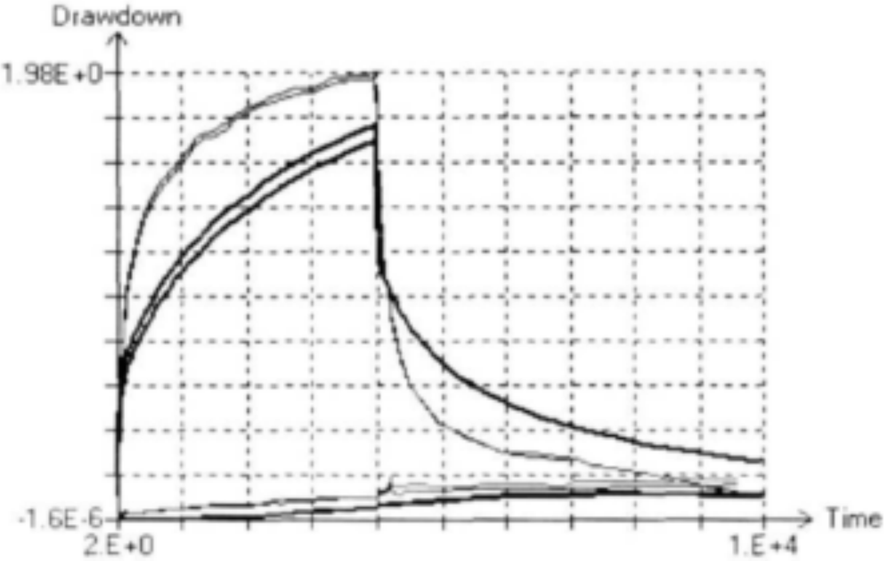
UO29a
UO28a



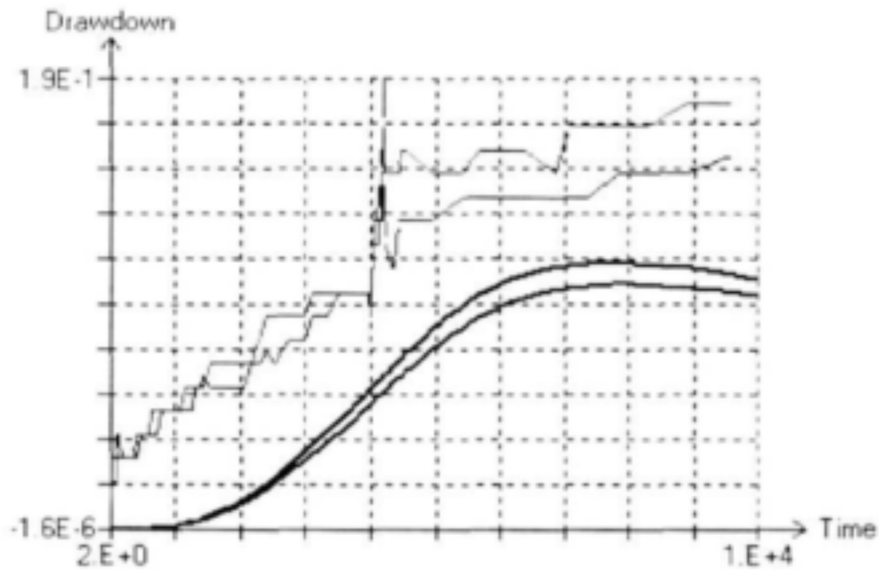
Piezometer below

UO28b
UO29b

27j

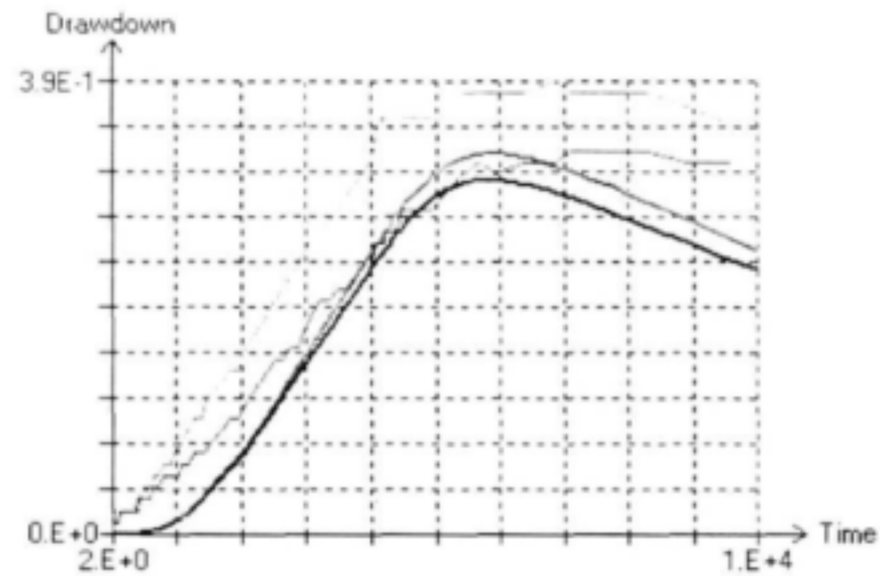


T matrix	3.68E-04
T fracture	3.91E-01
S matrix above	4.00E-04
S fracture	1.65E-05
S matrix below	1.00E-03
Leakage m above	1.00E-07
Leakage to fractur	4.00E-07
Leakage m below	6.00E-07
Leakage to fractur	1.27E-06



Piezometer above

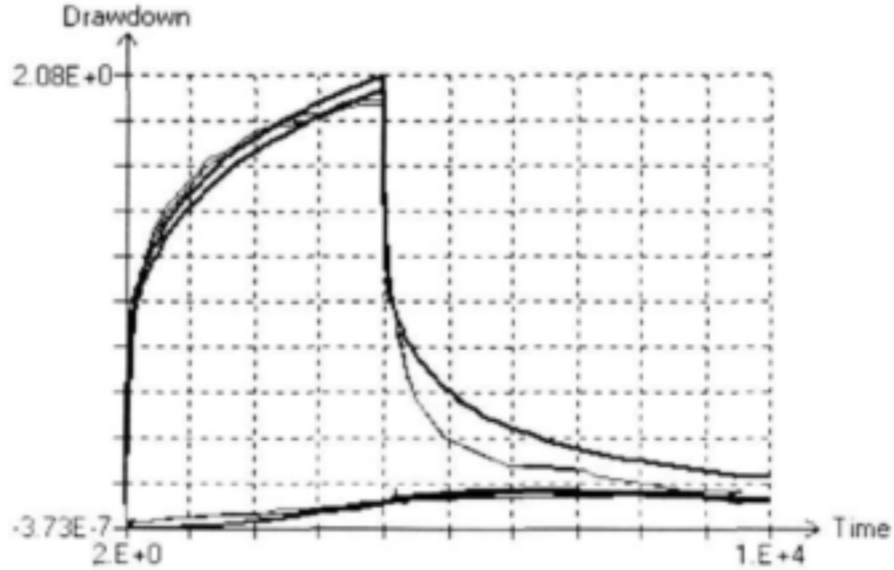
UO29a
UO28a



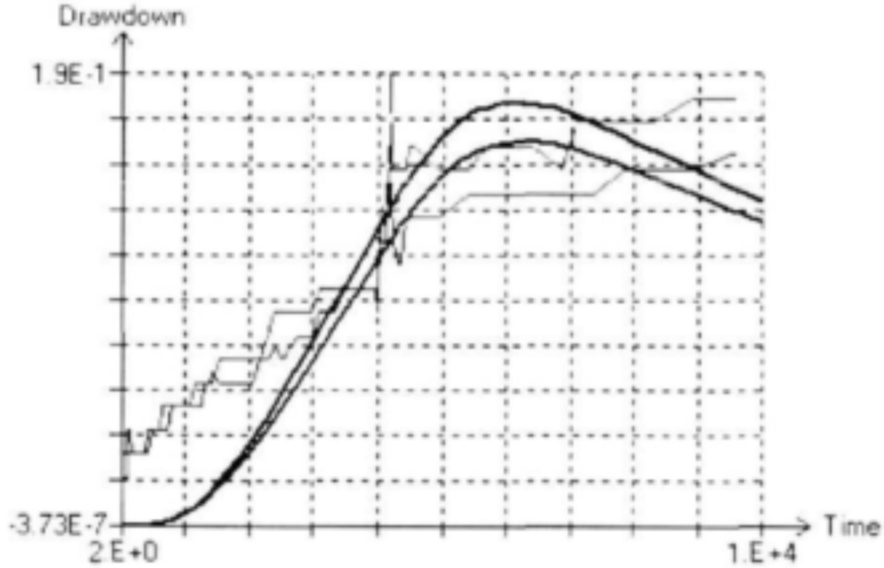
Piezometer below

UO28b
UO29b

Run28

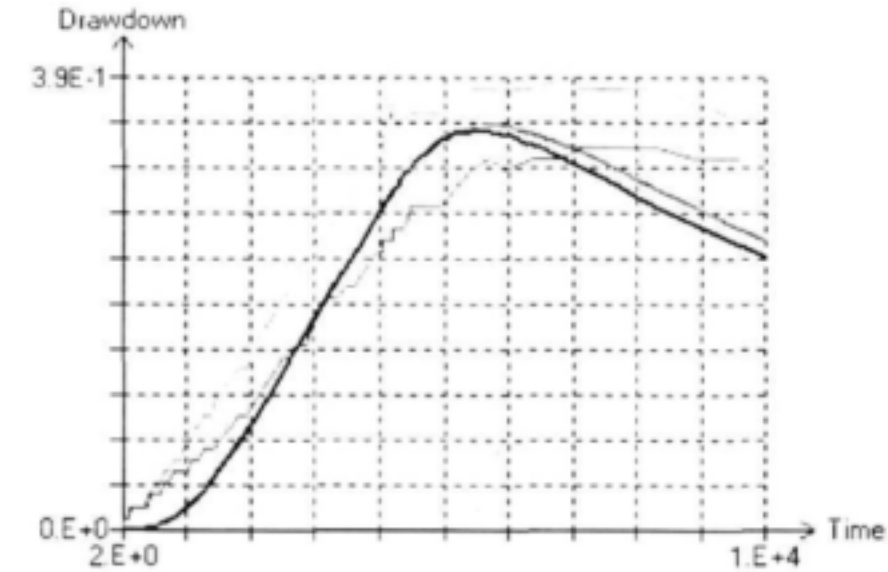


T matrix	3.13E-04
T fracture	4.28E-01
S matrix above	3.19E-04
S fracture	1.71E-05
S matrix below	9.27E-04
Leakage m above	1.07E-07
Leakage to fractur	4.27E-07
Leakage m below	8.24E-07
Leakage to fractur	4.78E-07



Piezometer above

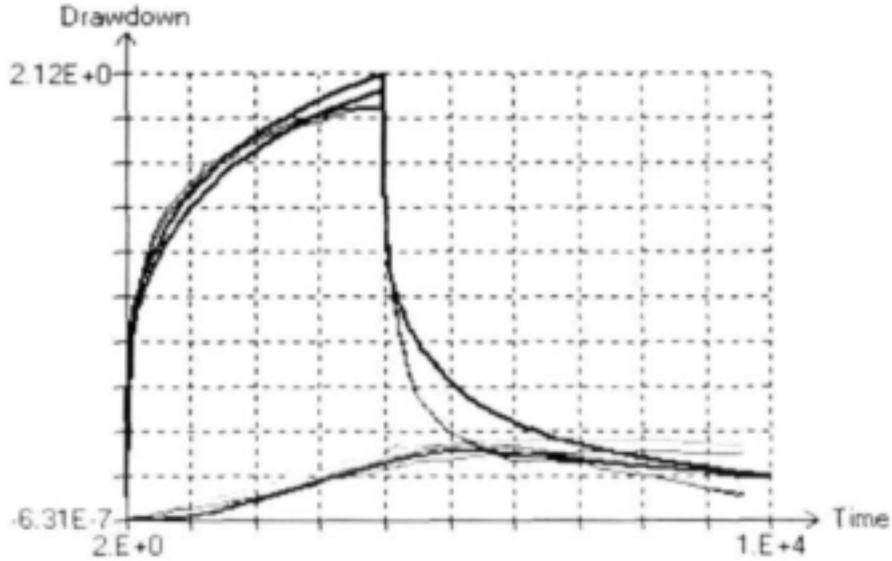
UO29a
UO28a



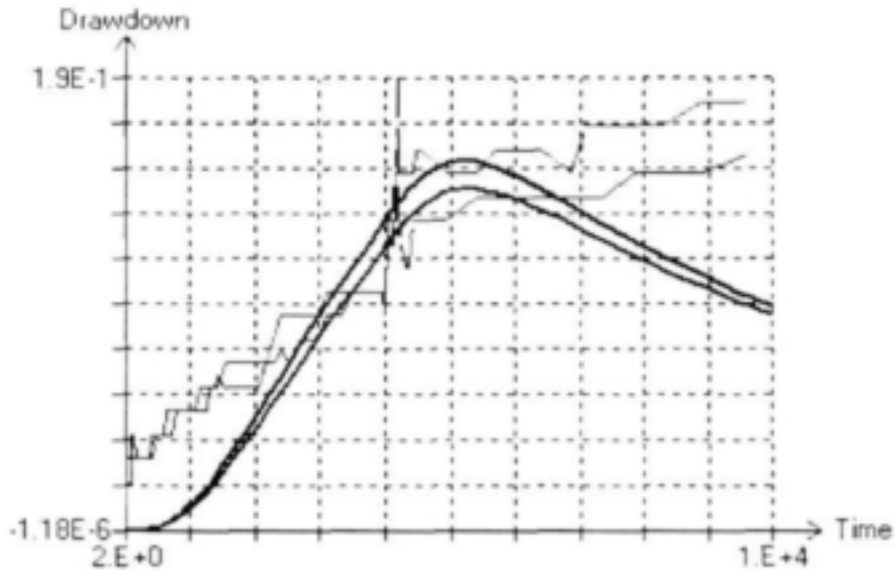
Piezometer below

UO28b
UO29b

Run29

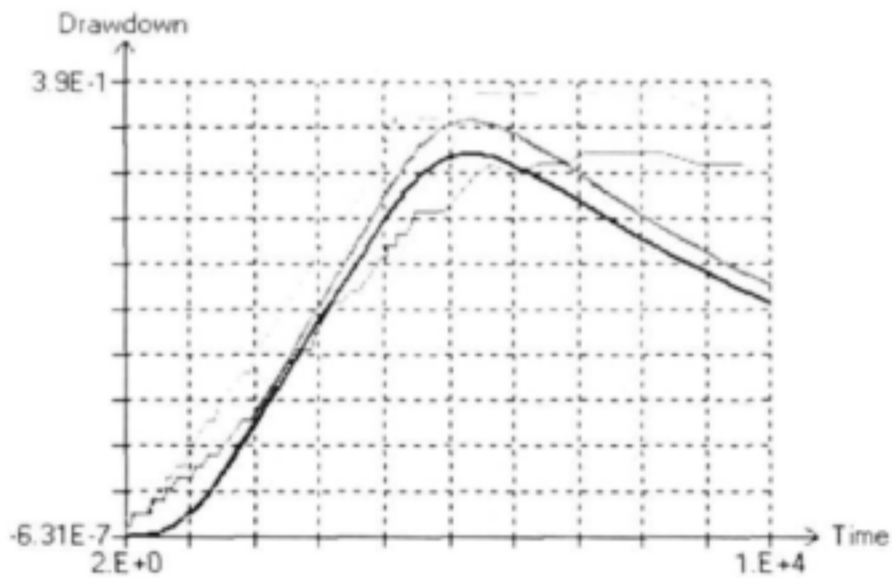


T matrix	5.26E-04
T fracture	3.90E-01
S matrix above	2.06E-04
S fracture	1.75E-05
S matrix below	8.93E-04
Leakage m above	9.94E-08
Leakage to fractur	3.98E-07
Leakage m below	6.63E-07
Leakage to fractur	8.17E-07



Piezometer above

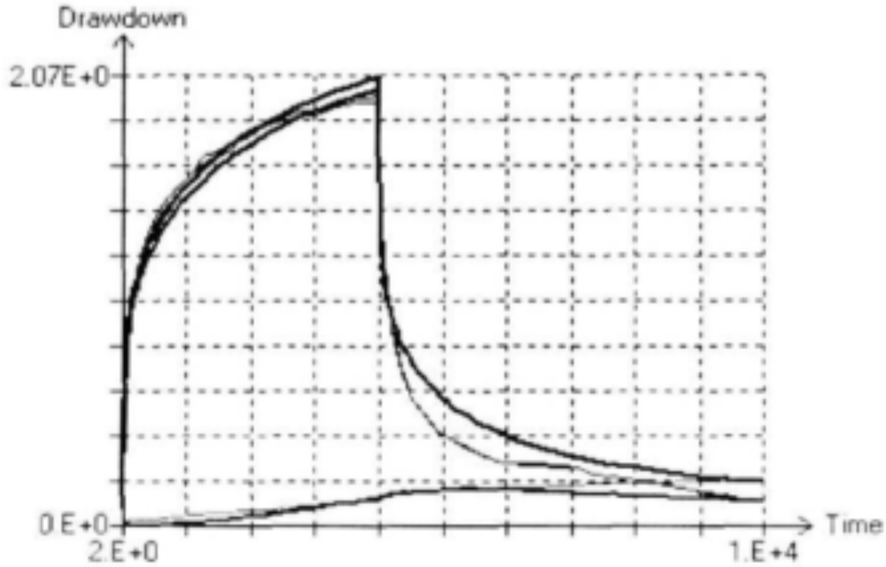
UO29a
UO28a



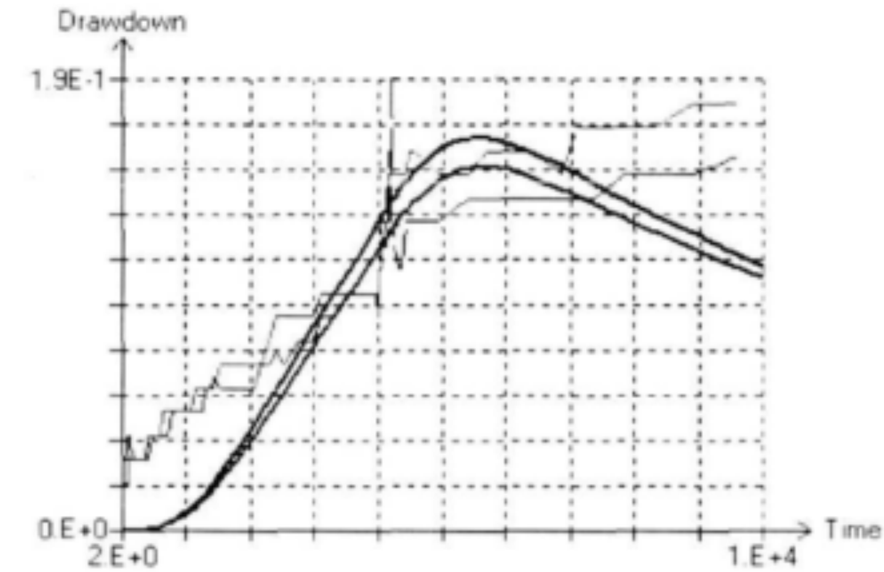
Piezometer below

UO28b
UO29b

Run31

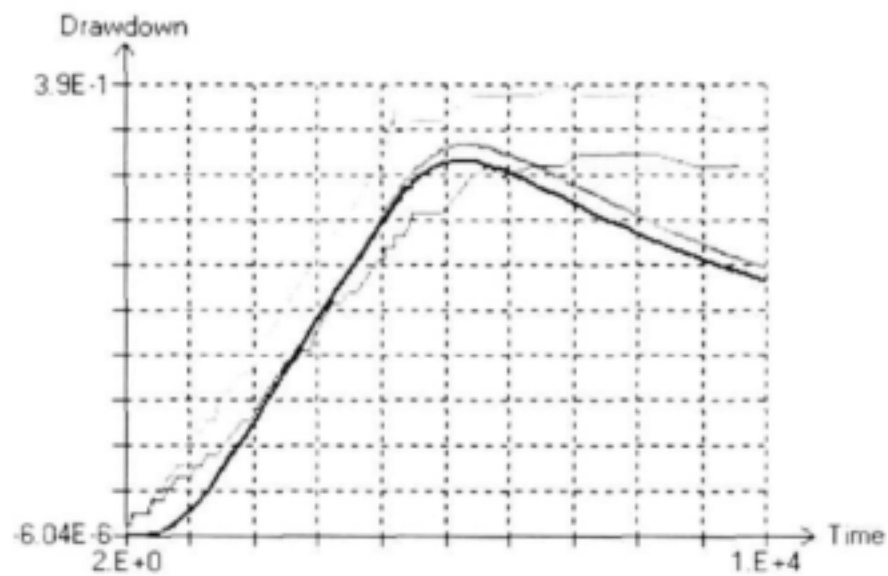


T matrix	2.11E-04
T fracture	5.40E-01
S matrix above	2.94E-04
S fracture	2.11E-05
S matrix below	7.81E-04
Leakage m above	1.14E-07
Leakage to fractur	4.56E-07
Leakage m below	7.67E-07
Leakage to fractur	3.74E-07



Piezometer above

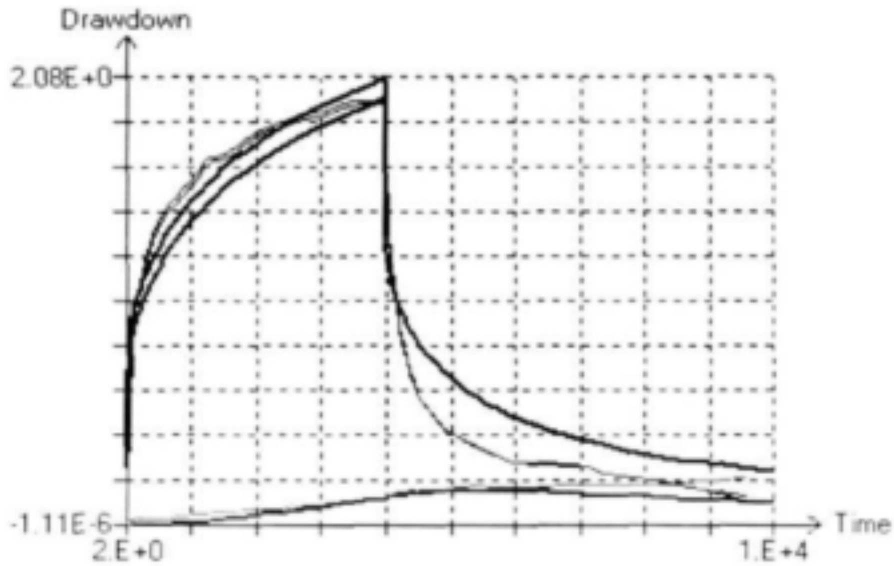
UO29a
UO28a



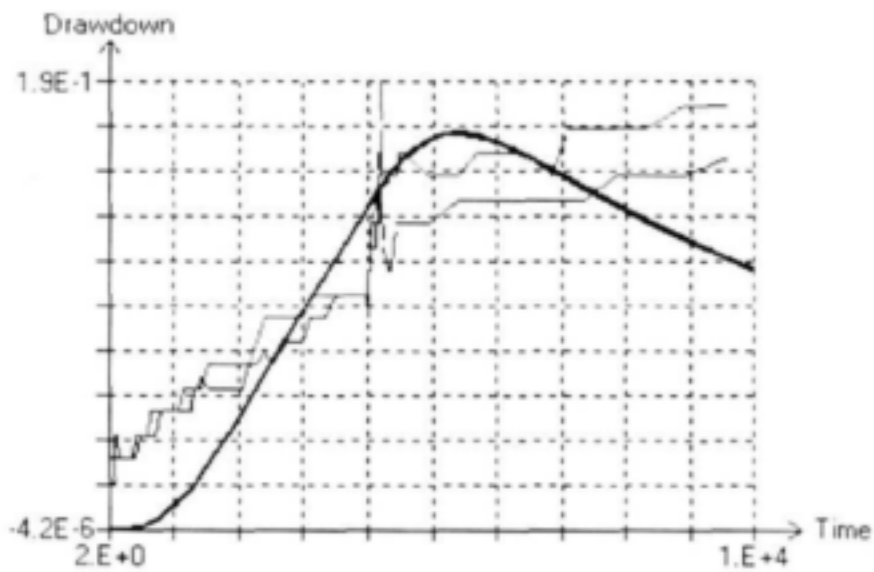
Piezometer below

UO28b
UO29b

Run32

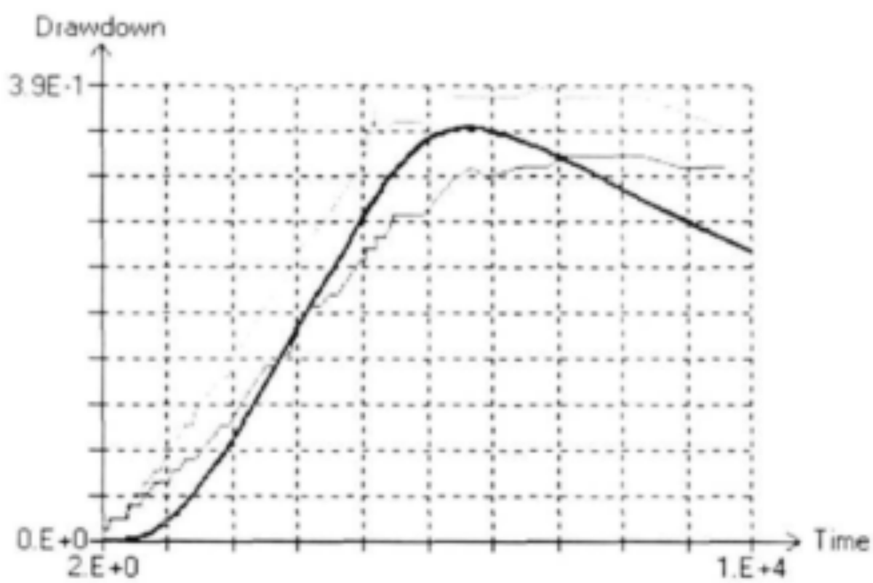


T matrix	3.69E-04
T fracture	3.61E-01
S matrix above	4.23E-04
S fracture	1.11E-05
S matrix below	1.99E-03
Leakage m above	1.81E-07
Leakage to fractur	7.26E-07
Leakage m below	1.27E-06
Leakage to fractur	1.55E-06



Piezometer above

UO29a
UO28a

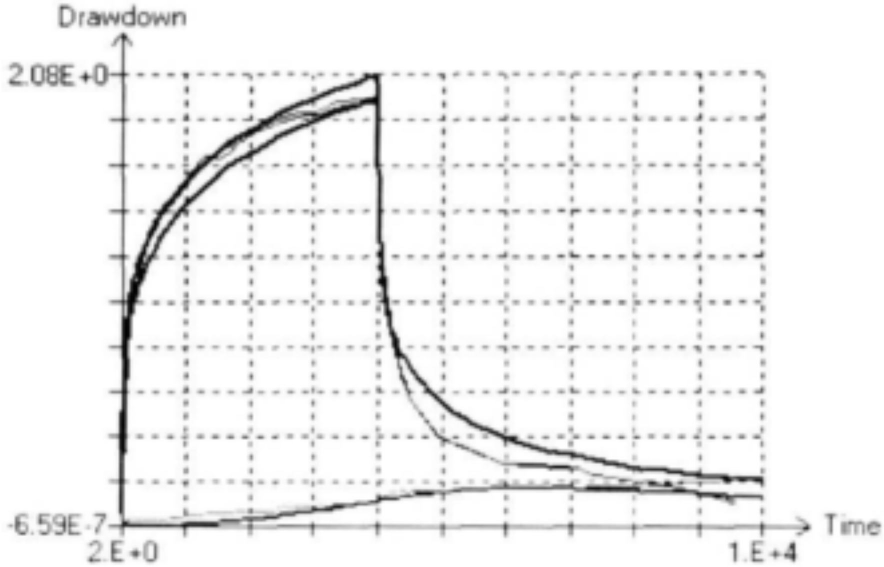


Piezometer below

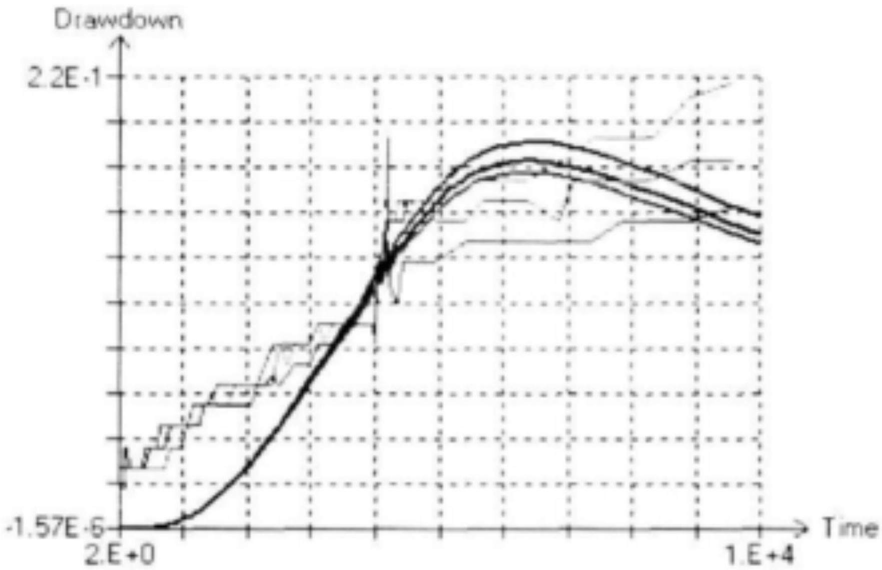
UO28b

UO29b

33a

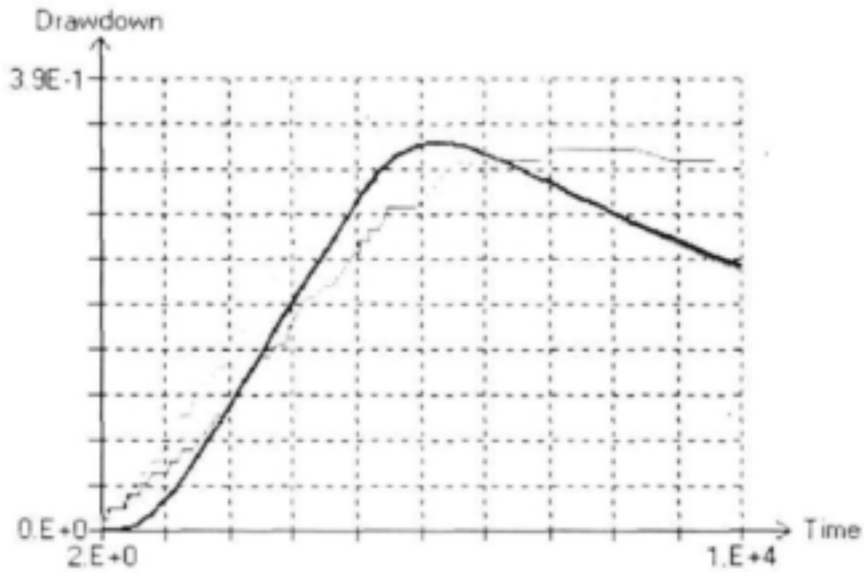


T matrix	2.13E-04
T fracture	3.66E-01
S matrix above	2.00E-04
S fracture	2.37E-05
S matrix below	5.63E-04
Leakage m above	6.44E-08
Leakage to fractur	2.58E-07
Leakage m below	7.98E-07
Leakage to fractur	2.30E-07



Piezometer above

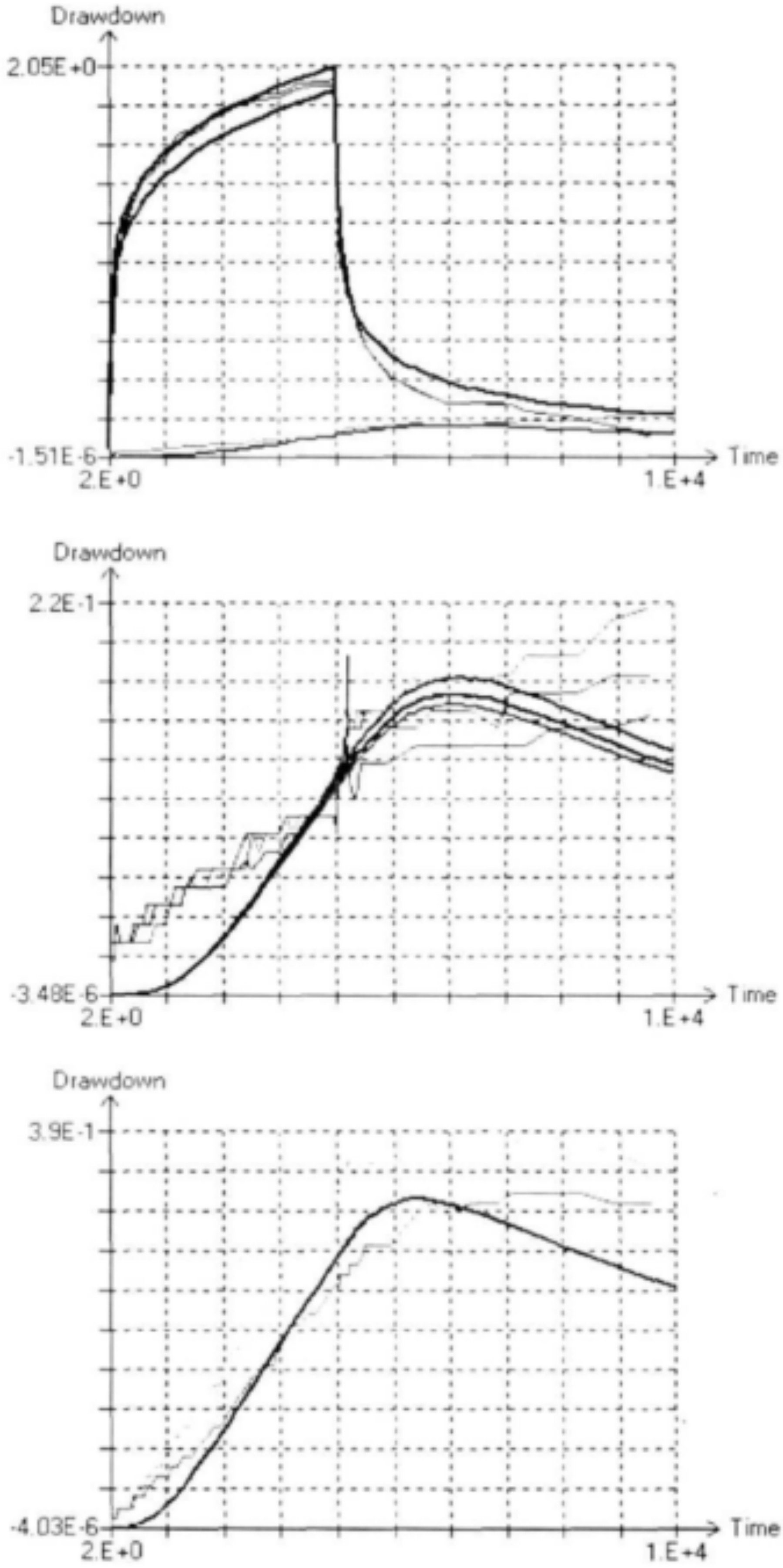
UO27a
UO29a
UO28a



Piezometer below

UO28b
UO29b

33b



T matrix	1.73E-04
T fracture	2.00E-01
S matrix above	1.36E-04
S fracture	2.73E-05
S matrix below	6.95E-04
Leakage m above	4.71E-08
Leakage to fractur	1.88E-07
Leakage m below	8.54E-07
Leakage to fractur	2.91E-07

Piezometer above

UO27a
UO29a
UO28a

Piezometer below

UO28b
UO29b

Campus Model UO5-Test, July 2000	Parameter and results of PEST calibration runs					
	Parameter No.	**Run 6a**	**Run 7a**	**Run 7b**	**Run 9a**	**Run 6b**
Calibration Method		PEST	PEST	PEST	PEST	PEST
calibrated Parameters		all	P matrix	P matrix	all	P matrix
used Observations		fracture	piezometer	piezometer	all, weight	piezometer
T matrix	11	4.55E-04	1.10E-03	1.10E-03	1.63E-03	4.55E-04
T matrix (0.5m)	10	2.27E-04	5.49E-04	5.51E-04	8.14E-04	2.27E-04
T matrix (0.2m)	12	9.10E-05	2.20E-04	2.20E-04	3.26E-04	9.10E-05
T fracture	2	4.30E-01	4.50E-01	4.30E-01	7.40E-01	4.30E-01
S matrix above	7	2.25E-05	4.86E-04	5.03E-04	2.87E-04	3.92E-04
S matrix above (0.5m)	3	1.13E-05	2.43E-04	2.52E-04	1.44E-04	1.96E-04
S matrix above (0.2m)	6	4.50E-06	9.73E-05	1.01E-04	5.74E-05	7.84E-05
S fracture	4	2.76E-05	5.11E-05	2.76E-05	2.14E-05	2.76E-05
S matrix below	17	2.25E-05	4.86E-04	5.03E-04	2.87E-04	4.85E-04
S matrix below (0.5m)	20	1.13E-05	2.43E-04	2.52E-04	1.44E-04	2.42E-04
Leakage matrix ab (1-1)	1	7.04E-07	1.68E-07	1.68E-07	1.24E-07	7.58E-08
Leakage matrix ab (1-.5)	8	9.38E-07	2.24E-07	2.24E-07	1.65E-07	1.01E-07
Leakage matrix ab (.5-.5)	9	1.41E-06	3.36E-07	3.36E-07	2.48E-07	1.52E-07
Leakage matrix ab (.5-.2)	5	2.02E-06	4.82E-07	4.82E-07	3.55E-07	2.18E-07
Leakage fracture above	13	2.82E-06	6.71E-07	6.71E-07	4.95E-07	3.03E-07
Leakage matrix be (1-1)	14	7.04E-07	1.68E-07	1.68E-07	1.24E-07	3.16E-07
Leakage matrix be (1-.5)	18	9.38E-07	2.24E-07	2.24E-07	1.65E-07	4.22E-07
Leakage matrix be (.5-.5)	19	1.41E-06	3.36E-07	3.36E-07	2.48E-07	6.33E-07
Leakage matrix be (.5-.2)	15	2.02E-06	4.82E-07	4.82E-07	3.55E-07	9.08E-07
Leakage fracture below	16	2.82E-06	6.71E-07	6.71E-07	4.95E-07	1.27E-06
T matrix aquifer (m2/d)		13.1	31.6	31.7	46.9	13.1
K horizontal matrix (m/d)		0.66	1.58	1.59	2.34	0.66
T fracture (m2/d)		619.1	648.0	619.1	1065.9	619.1
K horizontal fracture (m/d)		3095.3	3240.0	3095.3	5329.4	3095.3
K vertical matrix above (m/d)		1.01E-03	2.42E-04	2.42E-04	1.78E-04	1.09E-04
K vertical matrix below (m/d)		1.01E-03	2.42E-04	2.42E-04	1.78E-04	4.56E-04
Fracture Skin						
S matrix above		2.25E-04	4.86E-03	5.03E-03	2.87E-03	3.92E-03
S fracture		2.76E-05	5.11E-05	2.76E-05	2.14E-05	2.76E-05
S matrix below		2.25E-04	4.86E-03	5.03E-03	2.87E-03	4.85E-03
S matrix total		4.50E-04	9.73E-03	1.01E-02	5.74E-03	8.77E-03
	MIN / MAX					
phi	1.296	**1.296**	333.6	333.2	335.6	72.76
correlation coefficient	0.9972	**0.9972**	0.6363	0.6356	0.6919	0.9157
number of residuals		720	960	960	1280	1000
mean value of weighted res.	-1.60E-03	**-1.60E-03**	0.2173	0.2284	0.1507	5.57E-02
maximum weighted residual	0.1106	**0.1106**	1.615	1.625	1.773	0.7883
minimum weighted residual	-0.3098	**-0.3098**	-1.424	-1.364	-1.417	-0.4838
standard variance of w.res.	1.81E-03	**1.81E-03**	0.3486	0.3482	0.2632	7.31E-02
standard error of w.res.	4.26E-02	**4.26E-02**	0.5904	0.5901	0.5131	2.70E-01
maximum weighting factor		1	10	10	10	10
Comment		no observ. in matrix used	T, S fract. fixed fixed values from Run6	T, S fract. fixed fixed values from Run6a		T, S fract. + T matrix fixed

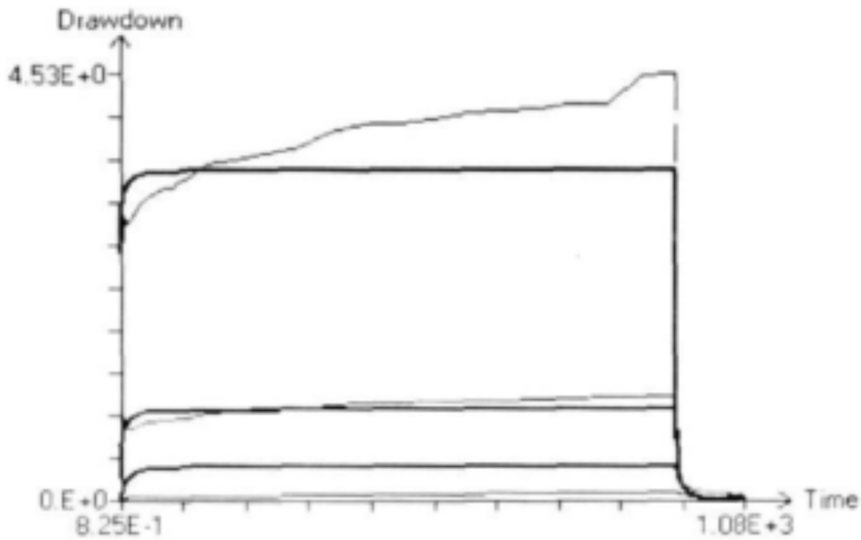
Campus Model UO5-Test, July 2000	**Parameter and results of PEST calibration runs**					
	Run 6c	**Run 6d**	**Run 6e**	**Run 6f**	**Run 21/22**	**Run 22a**
Calibration Method	PEST	PEST	PEST	PEST	PEST	PEST
calibrated Parameters	P matrix	P1, P14	P3, P17	P1,3,14,17	all	all
used Observations	piezometer	matrix	matrix	matrix	all	all
T matrix	4.55E-04	4.55E-04	4.55E-04	4.55E-04	8.63E-04	2.70E-04
T matrix (0.5m)	2.27E-04	2.27E-04	2.27E-04	2.27E-04	4.32E-04	1.35E-04
T matrix (0.2m)	9.10E-05	9.10E-05	9.10E-05	9.10E-05	1.73E-04	5.40E-05
T fracture	4.30E-01	4.30E-01	4.30E-01	4.30E-01	6.09E-01	2.15E-01
S matrix above	3.10E-04	3.10E-04	3.40E-04	3.25E-04	2.20E-04	1.00E-03
S matrix above (0.5m)	1.55E-04	1.55E-04	1.70E-04	1.62E-04	1.10E-04	5.00E-04
S matrix above (0.2m)	6.20E-05	6.20E-05	6.79E-05	6.49E-05	4.40E-05	2.00E-04
S fracture	2.76E-05	2.76E-05	2.76E-05	2.76E-05	3.99E-06	1.74E-05
S matrix below	7.66E-04	7.66E-04	6.40E-04	5.82E-04	3.05E-04	5.00E-04
S matrix below (0.5m)	3.83E-04	3.83E-04	3.20E-04	2.91E-04	1.52E-04	2.50E-04
Leakage matrix ab (1-1)	8.15E-08	7.04E-08	7.04E-08	1.21E-07	1.17E-07	2.69E-07
Leakage matrix ab (1-.5)	1.09E-07	9.38E-08	9.38E-08	1.61E-07	1.56E-07	3.59E-07
Leakage matrix ab (.5-.5)	1.63E-07	1.41E-07	1.41E-07	2.41E-07	2.34E-07	5.39E-07
Leakage matrix ab (.5-.2)	2.34E-07	2.02E-07	2.02E-07	3.46E-07	3.36E-07	7.73E-07
Leakage fracture above	2.24E-07	2.24E-07	2.24E-07	2.24E-07	4.68E-07	1.08E-06
Leakage matrix be (1-1)	6.51E-07	3.61E-07	3.61E-07	5.20E-07	2.66E-07	2.85E-07
Leakage matrix be (1-.5)	8.67E-07	4.82E-07	4.82E-07	6.93E-07	3.54E-07	3.80E-07
Leakage matrix be (.5-.5)	1.30E-06	7.23E-07	7.23E-07	1.04E-06	5.32E-07	5.69E-07
Leakage matrix be (.5-.2)	1.87E-06	1.04E-06	1.04E-06	1.49E-06	7.63E-07	8.17E-07
Leakage fracture below	4.57E-07	4.57E-07	4.57E-07	4.57E-07	1.06E-06	1.14E-06
T matrix aquifer (m2/d)	13.1	13.1	13.1	13.1	24.9	7.8
K horizontal matrix (m/d)	0.66	0.66	0.66	0.66	1.24	0.39
T fracture (m2/d)	619.1	619.1	619.1	619.1	876.2	310.0
K horizontal fracture (m/d)	3095.3	3095.3	3095.3	3095.3	4381.2	1550.2
K vertical matrix above (m/d)	1.17E-04	1.01E-04	1.01E-04	1.74E-04	1.69E-04	3.88E-04
K vertical matrix below (m/d)	9.37E-04	5.20E-04	5.20E-04	7.48E-04	3.83E-04	4.10E-04
Fracture Skin	x	x	x	x		
S matrix above	3.10E-03	3.10E-03	3.40E-03	3.25E-03	2.20E-03	1.00E-02
S fracture	2.76E-05	2.76E-05	2.76E-05	2.76E-05	3.99E-06	1.74E-05
S matrix below	7.66E-03	7.66E-03	6.40E-03	5.82E-03	3.05E-03	5.00E-03
S matrix total	1.08E-02	1.08E-02	9.80E-03	9.07E-03	5.25E-03	1.50E-02
phi	118.7	98.95	132	116.5	63.67	133
correlation coefficient	0.8695	0.9345	0.9308	0.9291	0.9241	0.8477
number of residuals	800	400	400	500	1120	1120
mean value of weighted res.	0.1749	0.3555	0.4509	0.2887	1.84E-02	0.105
maximum weighted residual	0.9004	0.8798	1.107	0.8681	1.312	0.8461
minimum weighted residual	-0.3728	-0.3649	-0.4861	-0.4289	-0.5212	-0.6423
standard variance of w.res.	0.1494	0.2486	0.3317	0.2348	5.72E-02	0.1195
standard error of w.res.	0.365	0.4986	0.5759	0.4845	0.2392	0.3457
maximum weighting factor	10	10	10	10	10	10
Comment	T, S fract. + T matrix fixed Leakance to fracture is not tied	only matrix observation Leakance to fracture is not tied	only matrix observation Leakance to fracture is not tied	only matrix observation Leakance to fracture is not tied	Matrix above and below diff. without UO23a, b	Change of bounds + initial values

Campus Model UO5-Test, July 2000	Parameter and results of PEST calibration runs					
	Run 23/24	Run 25	Run 25a	Run 26	Run 28	Run 29
Calibration Method	PEST	PEST	PEST	PEST	PEST	PEST
calibrated Parameters	all	all	all	P2, P4	all	all
used Observations	piezometer	piezometer	piezometer	piezometer	all	all
T matrix	4.42E-04	4.34E-04	4.37E-04	4.42E-04	3.13E-04	5.26E-04
T matrix (0.5m)	2.21E-04	2.17E-04	2.19E-04	2.21E-04	1.57E-04	2.63E-04
T matrix (0.2m)	8.83E-05	8.67E-05	8.74E-05	8.83E-05	6.27E-05	1.05E-04
T fracture	4.20E-01	4.16E-01	4.09E-01	3.25E-01	4.28E-01	3.90E-01
S matrix above	4.98E-04	4.86E-04	4.86E-04	4.98E-04	3.19E-04	2.06E-04
S matrix above (0.5m)	2.49E-04	2.43E-04	2.43E-04	2.49E-04	1.60E-04	1.03E-04
S matrix above (0.2m)	9.96E-05	9.72E-05	9.73E-05	9.96E-05	6.38E-05	4.11E-05
S fracture	2.58E-05	2.46E-05	2.45E-05	1.86E-05	1.71E-05	1.75E-05
S matrix below	5.47E-04	5.25E-04	5.20E-04	5.47E-04	9.27E-04	8.93E-04
S matrix below (0.5m)	2.74E-04	2.62E-04	2.60E-04	2.74E-04	4.64E-04	4.46E-04
Leakage matrix ab (1-1)	1.69E-07	1.65E-07	1.64E-07	1.69E-07	1.07E-07	9.94E-08
Leakage matrix ab (1-.5)	2.26E-07	2.20E-07	2.18E-07	2.26E-07	1.42E-07	1.33E-07
Leakage matrix ab (.5-.5)	3.38E-07	3.30E-07	3.28E-07	3.38E-07	2.13E-07	1.99E-07
Leakage matrix ab (.5-.2)	4.86E-07	4.74E-07	4.71E-07	4.86E-07	3.06E-07	2.86E-07
Leakage fracture above	6.77E-07	6.61E-07	6.56E-07	6.77E-07	4.27E-07	3.98E-07
Leakage matrix be (1-1)	3.45E-07	3.35E-07	3.35E-07	3.45E-07	8.24E-07	6.63E-07
Leakage matrix be (1-.5)	4.60E-07	4.46E-07	4.47E-07	4.60E-07	1.10E-06	8.84E-07
Leakage matrix be (.5-.5)	6.90E-07	6.70E-07	6.70E-07	6.90E-07	1.65E-06	1.33E-06
Leakage matrix be (.5-.2)	9.91E-07	9.61E-07	9.62E-07	9.91E-07	2.37E-06	1.90E-06
Leakage fracture below	1.38E-06	1.34E-06	1.34E-06	1.38E-06	4.78E-07	8.17E-07
T matrix aquifer (m2/d)	12.7	12.5	12.6	12.7	9.0	15.2
K horizontal matrix (m/d)	0.64	0.62	0.63	0.64	0.45	0.76
T fracture (m2/d)	605.5	599.6	588.5	467.3	615.9	560.9
K horizontal fracture (m/d)	3027.4	2998.1	2942.4	2336.4	3079.7	2804.4
K vertical matrix above (m/d)	2.44E-04	2.38E-04	2.36E-04	2.44E-04	1.54E-04	1.43E-04
K vertical matrix below (m/d)	4.97E-04	4.82E-04	4.82E-04	4.97E-04	1.19E-03	9.55E-04
Fracture Skin					x	x
S matrix above	4.98E-03	4.86E-03	4.86E-03	4.98E-03	3.19E-03	2.06E-03
S fracture	2.58E-05	2.46E-05	2.45E-05	1.86E-05	1.71E-05	1.75E-05
S matrix below	5.47E-03	5.25E-03	5.20E-03	5.47E-03	9.27E-03	8.93E-03
S matrix total	1.05E-02	1.01E-02	1.01E-02	1.05E-02	1.25E-02	1.10E-02
phi	77.02	74.37	157.1	74.88	34.66	36.25
correlation coefficient	0.9141	0.9145	0.8244	0.9158	0.9504	0.9466
number of residuals	1000	1000	1000	1000	800	800
mean value of weighted res.	9.63E-02	7.20E-02	0.1626	9.24E-02	2.95E-02	3.15E-02
maximum weighted residual	0.8053	0.7824	0.8464	0.8068	0.585	0.8946
minimum weighted residual	-0.4444	-0.4809	-0.4549	-0.4413	-0.3871	-0.3973
standard variance of w.res.	7.76E-02	7.49E-02	0.1582	7.50E-02	4.38E-02	4.58E-02
standard error of w.res.	0.2785	0.2737	0.3977	0.2739	0.2092	0.2139
maximum weighting factor	10	10	10	10	10	10
Comment	Change of initial values	Change of initial values	Number of observation is reduced	Matrix parameter fixed	Initial values from 27i Leakance to fracture is not tied	Initial values from mean (Run 6 - 26) Leakance to fracture is not tied

Campus Model UO5-Test, July 2000	Parameter and results of PEST calibration runs			
	Run 31	Run 32	Run 33a	Run 33b
Calibration Method	PEST	PEST	PEST	PEST
calibrated Parameters	all	all	all	all
used Observations	all	all	all	all
T matrix	4.22E-04	3.69E-04	2.13E-04	1.73E-04
T matrix (0.5m)	2.11E-04	1.85E-04	1.06E-04	8.63E-05
T matrix (0.2m)	8.44E-05	7.39E-05	4.25E-05	3.45E-05
T fracture	5.40E-01	3.61E-01	3.66E-01	2.00E-01
S matrix above	2.94E-04	4.23E-04	2.00E-04	1.36E-04
S matrix above (0.5m)	1.47E-04	2.12E-04	1.00E-04	6.82E-05
S matrix above (0.2m)	5.87E-05	8.47E-05	4.00E-05	2.73E-05
S fracture	2.11E-05	1.11E-05	2.37E-05	2.73E-05
S matrix below	7.81E-04	1.99E-03	5.63E-04	6.95E-04
S matrix below (0.5m)	3.91E-04	9.93E-04	2.81E-04	3.47E-04
Leakage matrix ab (1-1)	1.14E-07	1.81E-07	6.44E-08	4.71E-08
Leakage matrix ab (1-.5)	1.52E-07	2.42E-07	8.58E-08	6.28E-08
Leakage matrix ab (.5-.5)	2.28E-07	3.63E-07	1.29E-07	9.42E-08
Leakage matrix ab (.5-.2)	3.27E-07	5.21E-07	1.85E-07	1.35E-07
Leakage fracture above	4.56E-07	7.26E-07	2.58E-07	1.88E-07
Leakage matrix be (1-1)	7.67E-07	1.27E-06	7.98E-07	8.54E-07
Leakage matrix be (1-.5)	1.02E-06	1.69E-06	1.06E-06	1.14E-06
Leakage matrix be (.5-.5)	1.53E-06	2.54E-06	1.60E-06	1.71E-06
Leakage matrix be (.5-.2)	2.20E-06	3.64E-06	2.29E-06	2.45E-06
Leakage fracture below	3.74E-07	1.55E-06	2.30E-07	2.91E-07
T matrix aquifer (m2/d)	12.2	10.6	6.1	5.0
K horizontal matrix (m/d)	0.61	0.53	0.31	0.25
T fracture (m2/d)	778.0	519.1	526.3	288.0
K horizontal fracture (m/d)	3890.0	2595.6	2631.6	1440.0
K vertical matrix above (m/d)	1.64E-04	2.61E-04	9.27E-05	6.78E-05
K vertical matrix below (m/d)	1.10E-03	1.83E-03	1.15E-03	1.23E-03
Fracture Skin	x	x	x	x
S matrix above	2.94E-03	4.23E-03	2.00E-03	1.36E-03
S fracture	2.11E-05	1.11E-05	2.37E-05	2.73E-05
S matrix below	3.91E-03	1.99E-02	5.63E-03	6.95E-03
S matrix total	6.84E-03	2.41E-02	7.63E-03	8.31E-03
phi	40.82	52.71	38.01	35.82
correlation coefficient	0.9538	0.9349	0.959	0.9614
number of residuals	1000	1000	1000	1000
mean value of weighted res.	1.79E-02	3.07E-02	4.91E-02	4.74E-02
maximum weighted residual	0.9924	1.118	0.8307	0.9306
minimum weighted residual	-0.4762	-0.4136	-0.3727	-0.3709
standard variance of w.res.	4.11E-02	5.31E-02	3.83E-02	3.61E-02
standard error of w.res.	0.2028	0.2305	0.1957	0.19
maximum weighting factor	10	10	10	10
Comment	Matr below reduced to 5m thick Leakance to fracture is not tied	Area of fracture is halfed Leakance to fracture is not tied	Area of fracture is doubled Leakance to fracture is not tied	Change of Boundaries

Campus Model UO5-Test, July 2000	Parameter and results of PEST calibration runs				
	MIN	MAX	Factor (Max/Min)	Average	Geomean
Calibration Method calibrated Parameters used Observations					
T matrix	2.70E-04	8.63E-04	3.2	4.6166E-04	4.4609E-04
T matrix (0.5m)	1.35E-04	4.32E-04	3.2	2.3083E-04	2.2304E-04
T matrix (0.2m)	5.40E-05	1.73E-04	3.2	9.2333E-05	8.9218E-05
T fracture	2.15E-01	6.09E-01	2.8	4.1235E-01	4.0319E-01
S matrix above	2.06E-04	1.00E-03	4.9	4.1460E-04	3.8062E-04
S matrix above (0.5m)	1.03E-04	5.00E-04	4.9	2.0730E-04	1.9031E-04
S matrix above (0.2m)	4.11E-05	2.00E-04	4.9	8.2920E-05	7.6124E-05
S fracture	3.99E-06	2.76E-05	6.9	2.2112E-05	2.0249E-05
S matrix below	3.05E-04	9.27E-04	3.0	6.1565E-04	5.9183E-04
S matrix below (0.5m)	1.52E-04	4.64E-04	3.0	3.0783E-04	2.9592E-04
Leakage matrix ab (1-1)	7.04E-08	2.69E-07	3.8	1.2911E-07	1.1896E-07
Leakage matrix ab (1-.5)	9.38E-08	3.59E-07	3.8	1.7211E-07	1.5857E-07
Leakage matrix ab (.5-.5)	1.41E-07	5.39E-07	3.8	2.5823E-07	2.3792E-07
Leakage matrix ab (.5-.2)	2.02E-07	7.73E-07	3.8	3.7068E-07	3.4153E-07
Leakage fracture above	2.24E-07	1.08E-06	4.8	4.7981E-07	4.2064E-07
Leakage matrix be (1-1)	2.66E-07	8.24E-07	3.1	4.3134E-07	4.0433E-07
Leakage matrix be (1-.5)	3.54E-07	1.10E-06	3.1	5.7498E-07	5.3898E-07
Leakage matrix be (.5-.5)	5.32E-07	1.65E-06	3.1	8.6268E-07	8.0867E-07
Leakage matrix be (.5-.2)	7.63E-07	2.37E-06	3.1	1.2384E-06	1.1608E-06
Leakage fracture below	4.57E-07	1.38E-06	3.0	9.2532E-07	8.3013E-07
T matrix aquifer (m2/d)	7.78	24.86	3.2	13.30	12.85
K horizontal matrix (m/d)	0.39	1.24	3.2	0.66	0.64
T fracture (m2/d)	310.0	876.2	2.8	593.79	580.60
K horizontal fracture (m/d)	1550.2	4381.2	2.8	2968.93	2902.98
K vertical matrix above (m/d)	1.01E-04	3.88E-04	3.8	1.8592E-04	1.7130E-04
K vertical matrix below (m/d)	3.83E-04	1.19E-03	3.1	6.2113E-04	5.8224E-04
Fracture Skin					
S matrix above	2.06E-03	1.00E-02	4.9	4.1460E-03	3.8062E-03
S fracture	3.99E-06	2.76E-05	6.9	2.2112E-05	2.0249E-05
S matrix below	3.05E-03	9.27E-03	3.0	6.1565E-03	5.9183E-03
S matrix total	5.25E-03	1.50E-02	2.9	1.0303E-02	1.0060E-02
phi					
correlation coefficient					
number of residuals					
mean value of weighted res.					
maximum weighted residual					
minimum weighted residual					
standard variance of w.res.					
standard error of w.res.					
maximum weighting factor					
Comment					

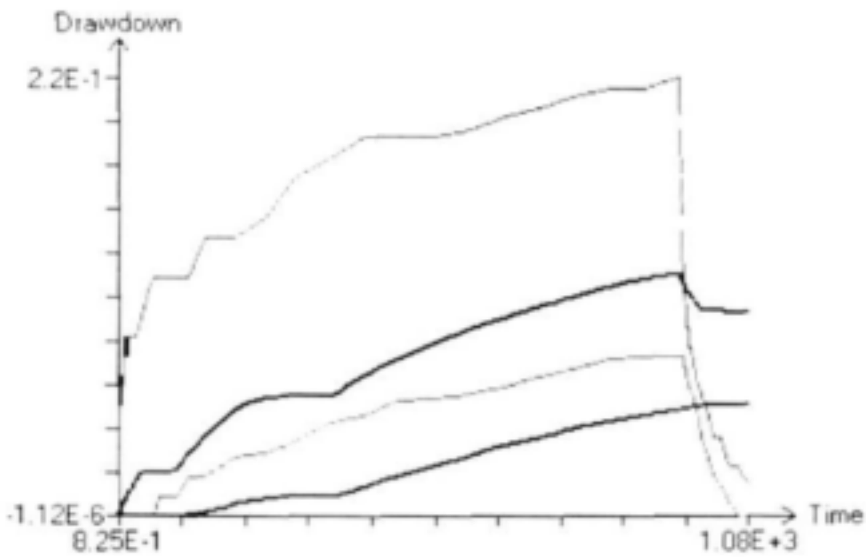
Run 2



Khd (Dolerite)	1.17E-01
Khf (Fracture)	2.10E-03
Khm (Mudstone)	1.64E-03
Khy (Dyke)	2.00E-05
Sd (Dolerite, 5m)	7.97E-03
Sf (Fracture, 5m)	2.03E-06
Sm (Matrix, 25m)	5.77E-05

Boreholes:	M1
	M2
	M5

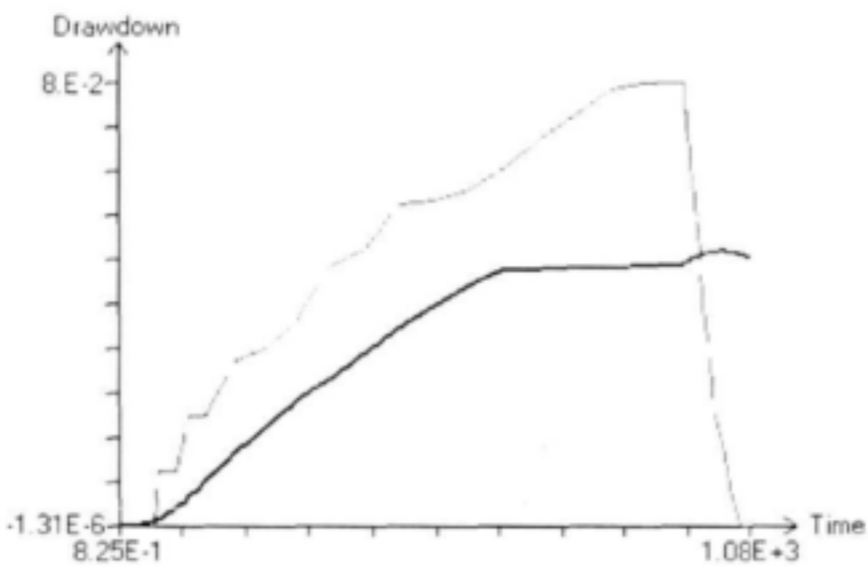
Run 3a



Khd (Dolerite)	3.66E-02
Khf (Fracture)	2.12E-02
Khm (Mudstone)	3.02E-04
Khy (Dyke)	1.00E-06
Sd (Dolerite, 5m)	1.10E-02
Sf (Fracture, 5m)	1.89E-05
Sm (Matrix, 25m)	3.55E-05

Boreholes:	M3
	M6

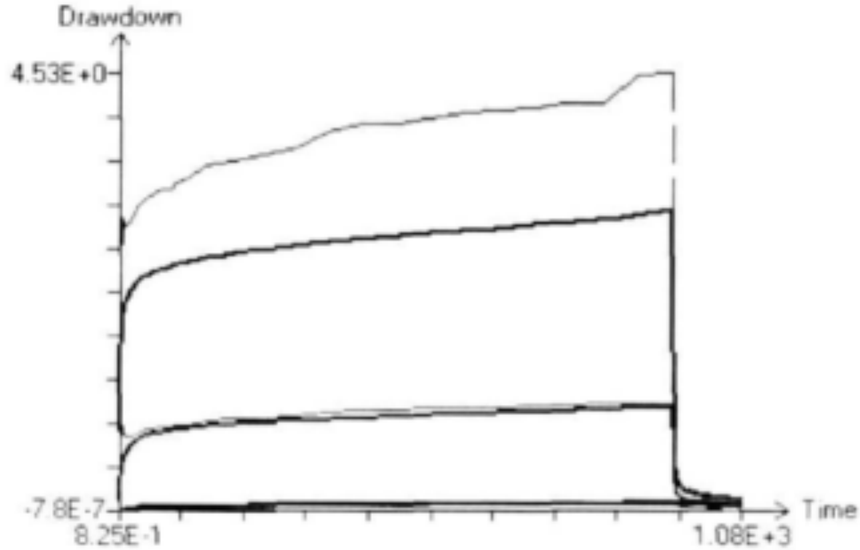
Run 3b



Khd (Dolerite)	5.25E-02
Khf (Fracture)	4.23E-02
Khm (Mudstone)	1.56E-04
Khy (Dyke)	1.00E-06
Sd (Dolerite, 5m)	3.01E-03
Sf (Fracture, 5m)	1.77E-07
Sm (Matrix, 25m)	7.96E-04

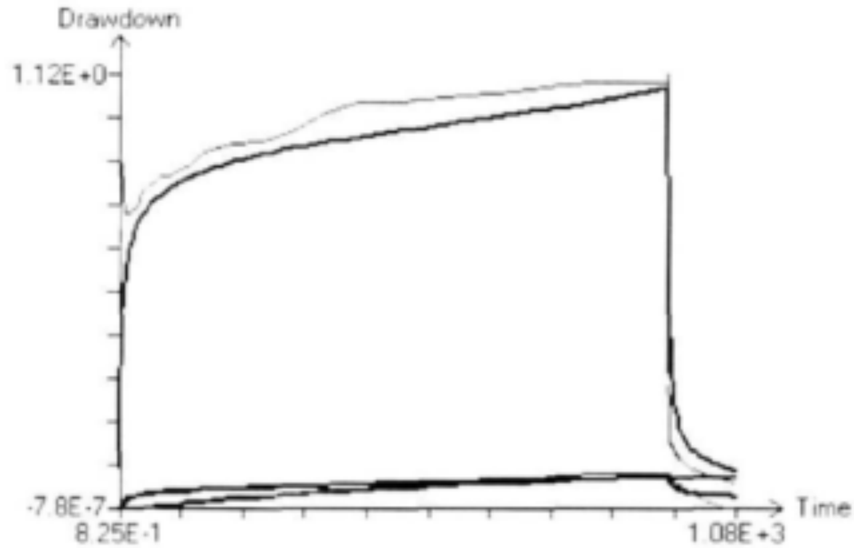
Boreholes:	M6

Run 10

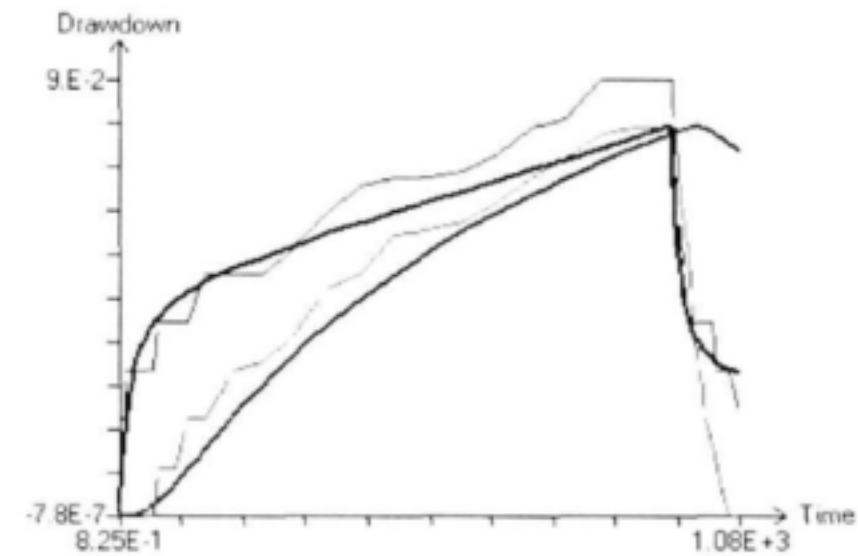


Khd (Dolerite)	5.30E-02
Khf (Fracture)	2.80E-03
Khm (Mudstone)	8.00E-06
Khy (Dyke)	1.00E-06
Ssd (Dolerite)	1.30E-03
Ssf (Fracture)	5.00E-05
Ssm (Mudstone)	1.20E-04

Boreholes:	M1
	M2
	M5



Boreholes:	M2
	M5
	M6



Boreholes:	M5
	M6

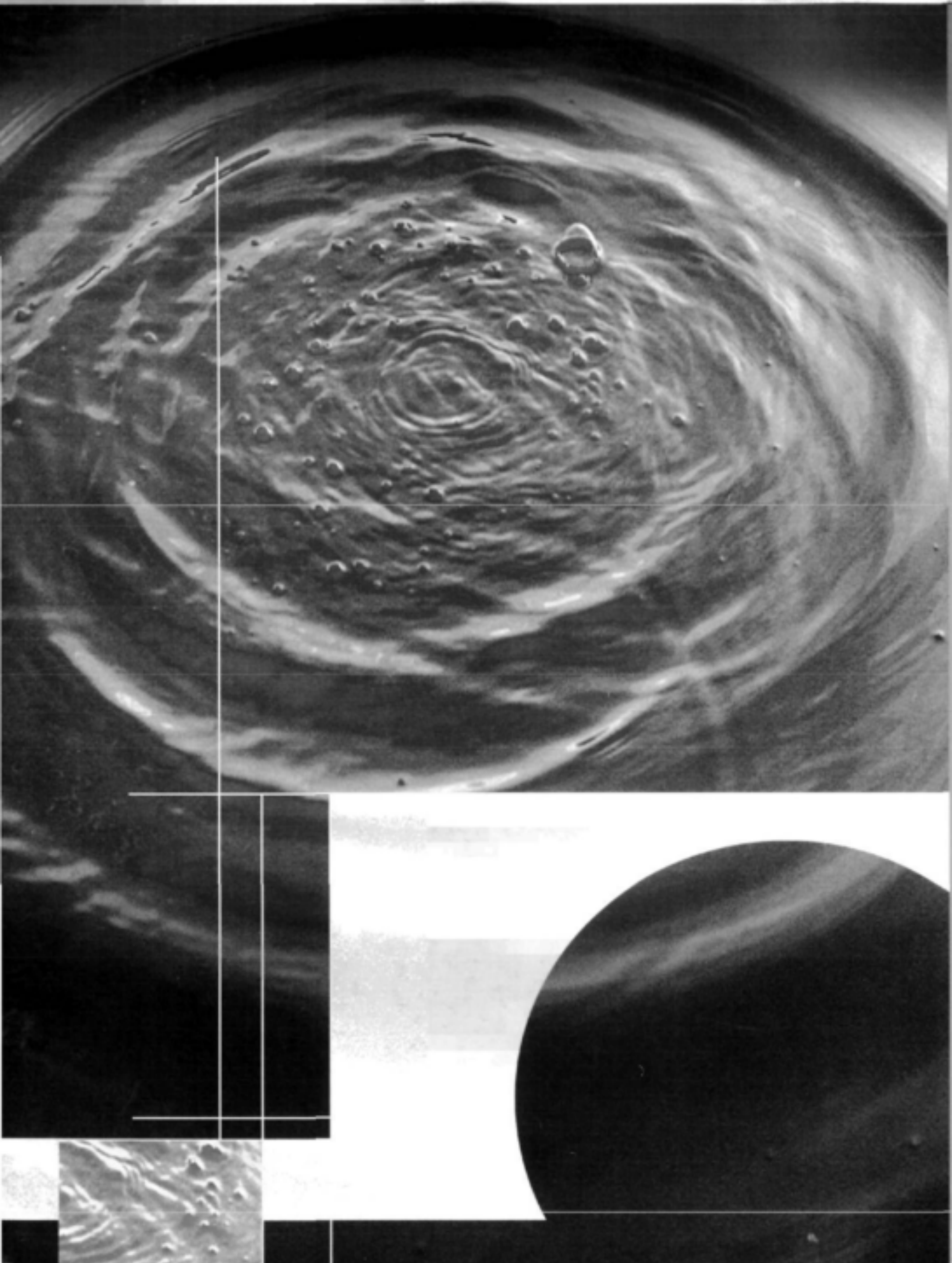
Meadhurst-Model		**Parameter and results of PEST calibration runs**					
		P No.	**Initial Value**	**Run 2**	**Run 3a**	**Run 3b**	**Run 10**
Calibration Method				PEST	PEST	PEST	PEST
calibrated Parameters				K and S	Dol., Mud.	K and S	all
used Observations				M1, M2	M3, M6	M6	M2,M5,M6
K dolerite	m/min	1	**3.40E-03**	1.17E-01	3.66E-02	5.25E-02	5.30E-02
K fracture	m/min	2	**6.00E-04**	2.10E-03	2.12E-02	4.23E-02	2.80E-03
K fracture (5m)	m/min	3	**6.00E-04**	2.10E-03	2.12E-02	4.23E-02	2.80E-03
K matrix	m/min	4	**2.76E-04**	1.64E-03	3.02E-04	1.56E-04	8.00E-06
S dolerite (5m) / Ss (Run 10)		5	**4.00E-04**	7.97E-03	1.10E-02	3.01E-03	1.30E-03
S fracture (5m) / Ss (Run 10)		6	**3.00E-06**	2.03E-06	1.89E-05	1.77E-07	5.00E-05
S fracture (25m) / Ss (Run 10)		7	**1.50E-05**	1.02E-05	9.43E-05	8.87E-07	5.00E-05
S matrix (25m) / Ss (Run 10)		8	**1.00E-04**	5.77E-05	3.55E-05	7.96E-04	1.20E-04
Leakage dolerite - matrix	1/min	9	**2.20E-07**	1.31E-06	2.42E-07	1.25E-07	6.40E-09
Leakage fracture (2-2)	1/min	10	**4.00E-05**	1.40E-04	1.41E-03	2.82E-03	1.87E-04
Leakage Dyke (2-5)	1/min	11	**1.33E-09**	1.33E-09	1.33E-09	1.33E-09	1.33E-09
K Dyke (2m)	m/min	12	**2.00E-05**	2.00E-05	1.00E-06	1.00E-06	1.00E-06
K Dyke (5m)	m/min	13	**2.00E-05**	2.00E-05	1.00E-06	1.00E-06	1.00E-06
T Dolerite	m2/d		**24.5**	843.10	263.28	378.00	381.60
T Dyke	m2/d		**0.9**	0.9	0.04	0.04	0.04
T Fracture	m2/d		**25.9**	90.85	915.93	1827.36	120.96
T Mudstone	m2/d		**9.9**	59.13	10.88	5.63	0.29
K horizontal dolerite	m/d		**4.9**	168.62	52.66	75.60	76.32
K horizontal fracture	m/d		**0.9**	3.03	30.53	60.91	4.03
K horizontal mudstone	m/d		**3.97E-01**	2.37E+00	4.35E-01	2.25E-01	1.15E-02
S Dolerite			**4.00E-04**	7.97E-03	1.10E-02	3.01E-03	6.50E-03
S Fracture			**1.80E-05**	1.22E-05	1.13E-04	1.06E-06	1.50E-03
S Mudstone			**1.00E-04**	5.77E-05	3.55E-05	7.96E-04	3.00E-03
Ss Dolerite	1/m		**8.00E-05**	1.59E-03	2.20E-03	6.03E-04	1.30E-03
Ss Fracture	1/m		**6.00E-07**	4.06E-07	3.77E-06	3.55E-08	5.00E-05
Ss Mudstone	1/m		**4.00E-06**	2.31E-06	1.42E-06	3.19E-05	1.20E-04
Thickness Dolerite	m		**5**	5	5	5	5
Thickness Mudstone	m		**25**	25	25	25	25
			MIN / MAX				
phi			19.11	**19.11**	250.9	75.88	103.9
correlation coefficient			0.9736	**0.9736**	0.5356	0.7394	0.8964
number of residuals				150	150	75	225
mean value of weighted res. (abs)			2.47E-02	**2.47E-02**	4.80E-01	2.11E-01	0.2488
maximum weighted residual			1.197	**1.197**	1.928	1.484	1.713
minimum weighted residual			-0.6803	**-0.6803**	-2.984	-2.567	-2.374
standard variance of w.res.			1.33E-01	**0.1327**	1.742	1.1	0.4744
standard error of w.res.			3.64E-01	**0.3643**	1.32	1.049	0.6888
maximum weighting factor				4	50	50	50
Comment					Khf + Sf are fixed	only M6 is used, Khf + Sf are released	All parameters are released

Appendix F: Data Disc

F.1 **Data of hydraulic Tests, used for numerical modeling**

F.2 **Pre-built model for horizontal bedding-plane fracture**

F.3 **Pre-built model for vertical fracture, situated on a dyke**



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Appendix A: Figures and Maps

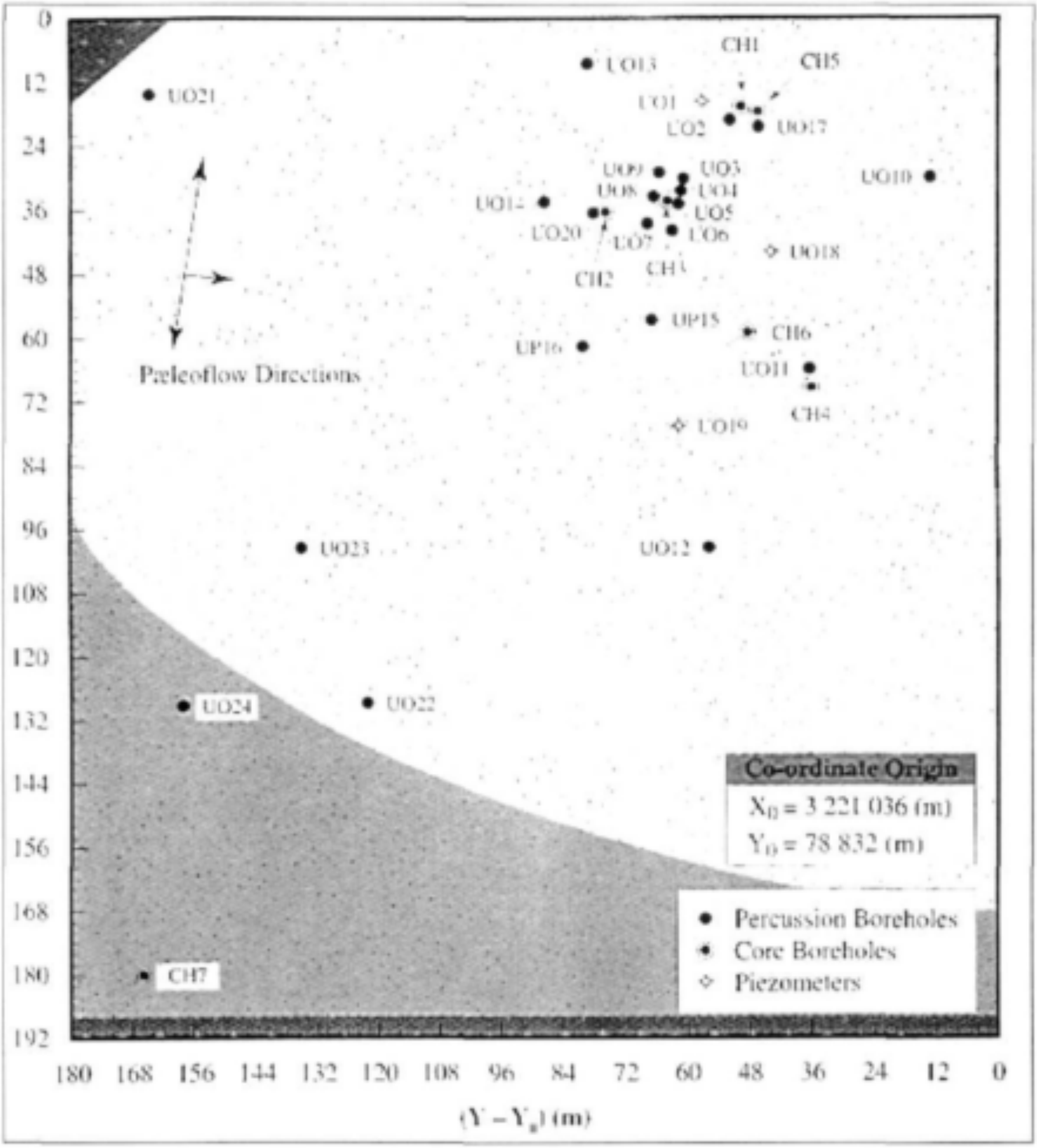


Fig. A.1. Locations of the Boreholes at Campus Test Site (after Botha *et.al.*, 1998)

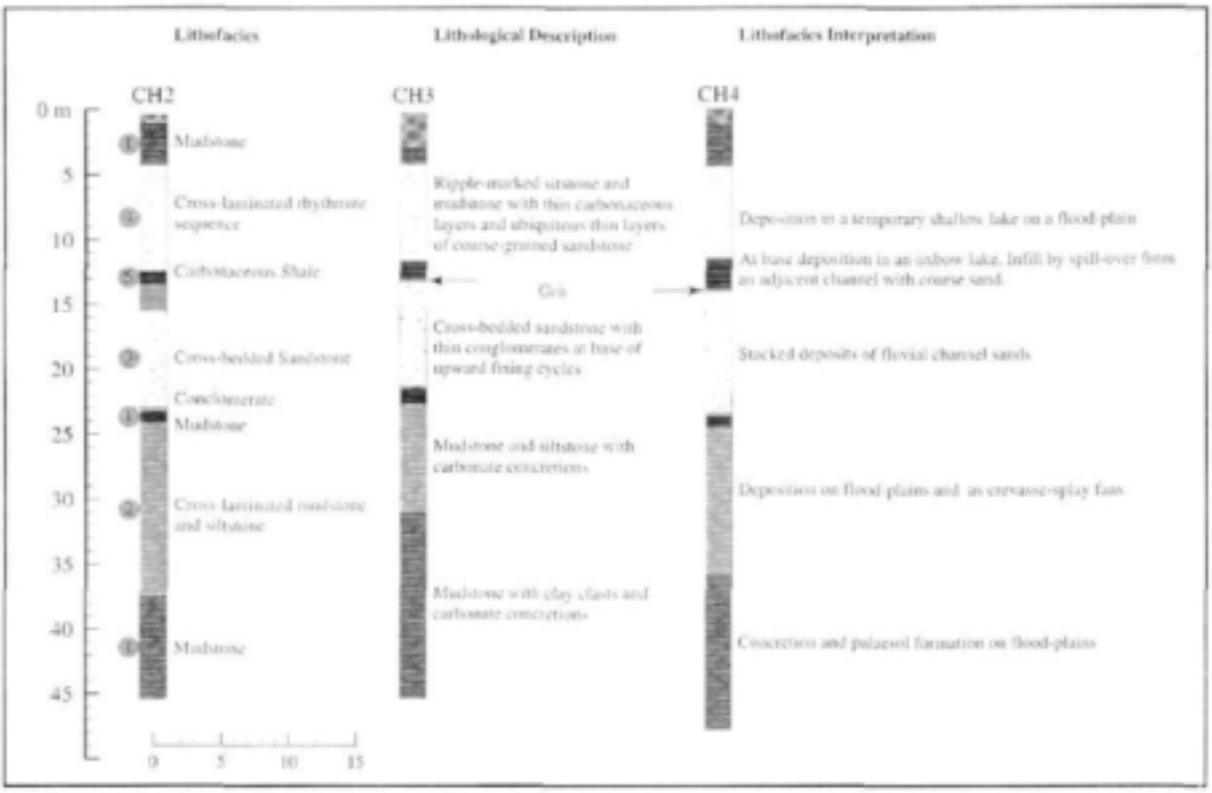


Fig. A.2. Lithology of boreholes on the Campus Site (after Botha *et al.*, 1998)

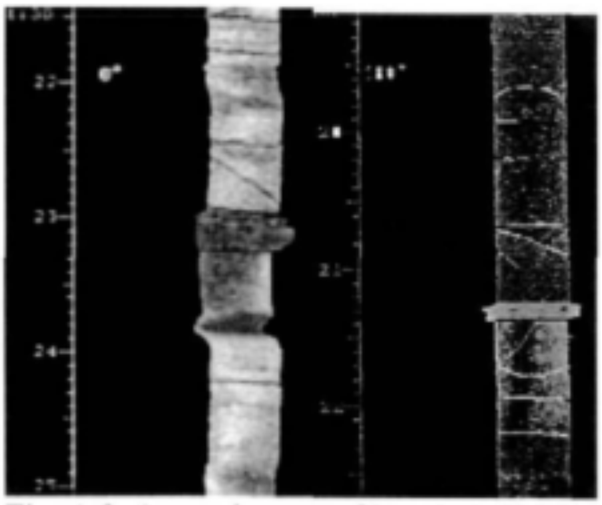


Fig. A.3. Acoustic scan of borehole UO5 and UO23 at a depth of between 20 and 25 m below surface

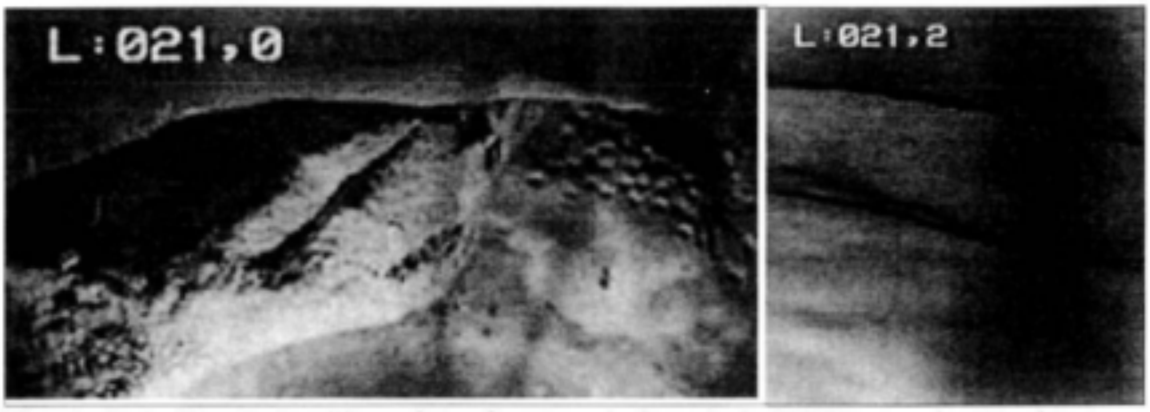


Fig. A.4(a). Borehole video of the fracture in borehole UO23 at a depth of between 21.0 – 21.2 m below surface

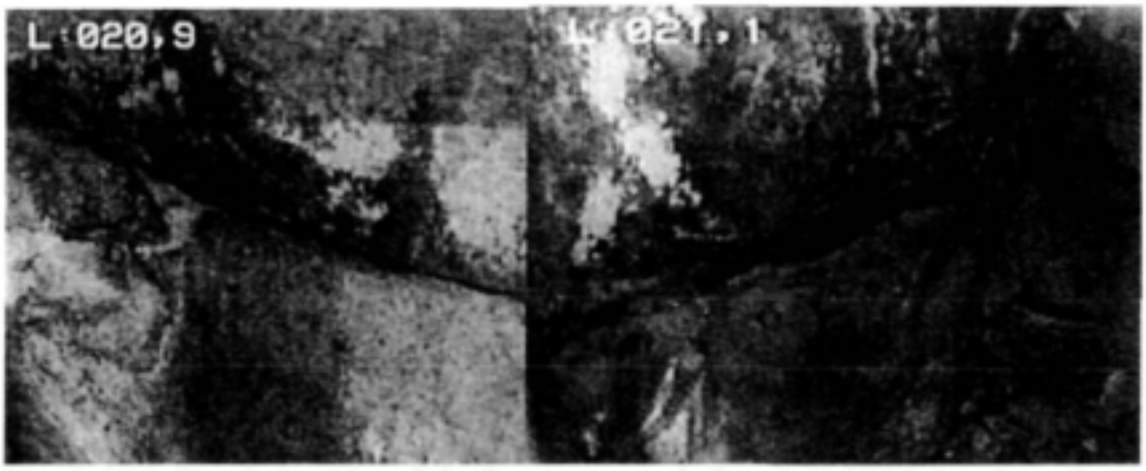


Fig. A.4(b). Borehole video of the fracture zone in borehole UO5 showing a fracture zone thickness of about 200mm.

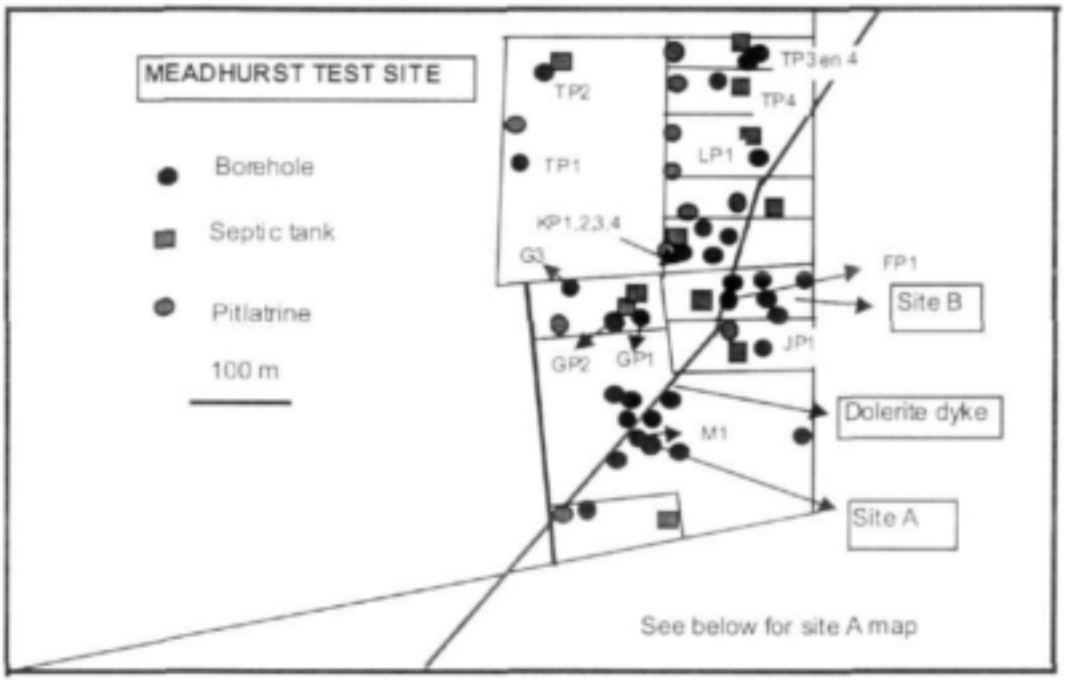


Fig. A.5. Position of boreholes, pitlatrines and septic tanks at Meadhurst test site

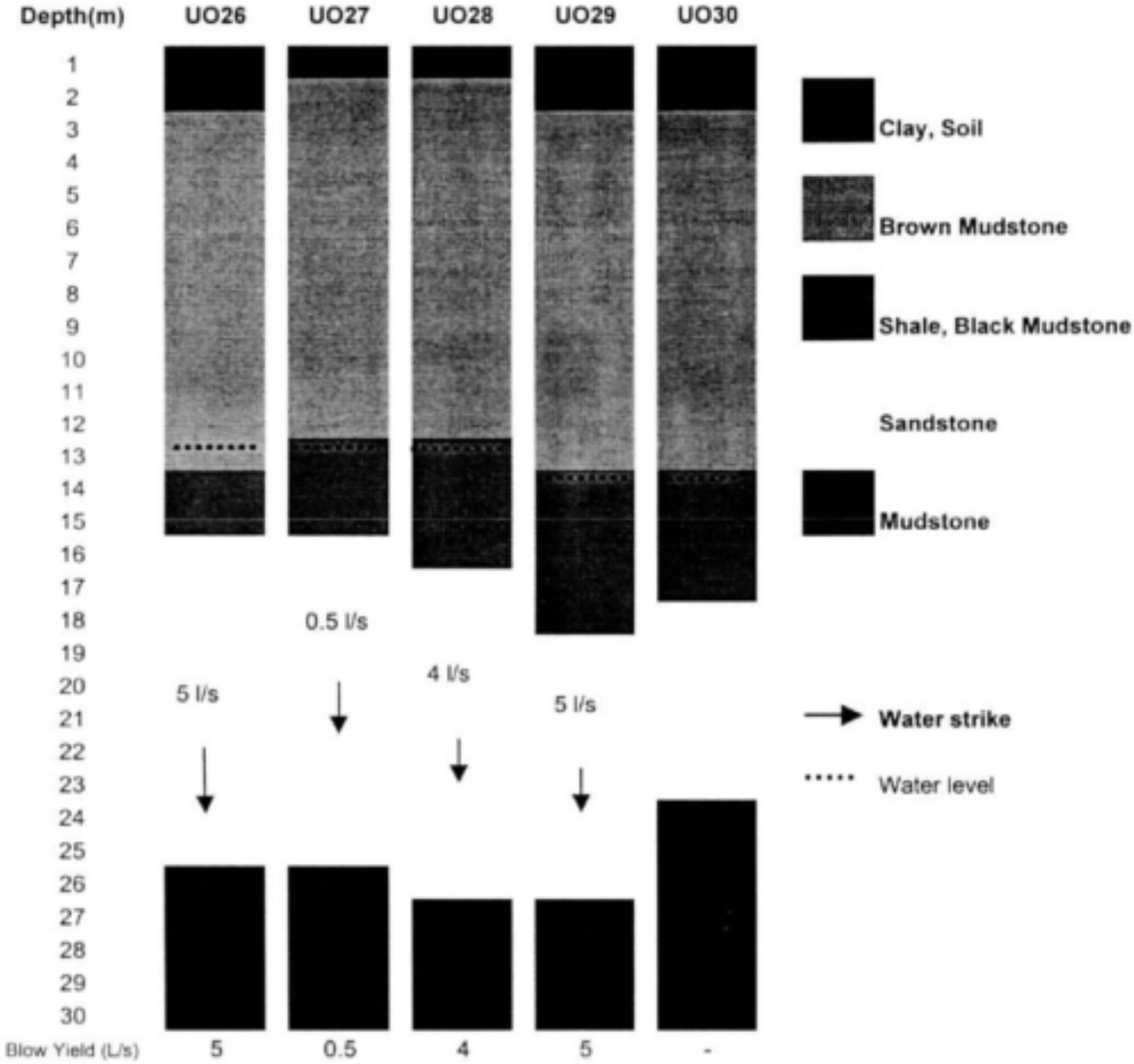
Appendix B: Borehole Logs

B.1 Borehole Logs Campus Test Site

B.2 Borehole Fluid Logs, EC-Profiles Campus Test Site

B.3 Borehole Logs Meadhurst Test Site

Appendix B.1 Borehole Logs Campus Test Site

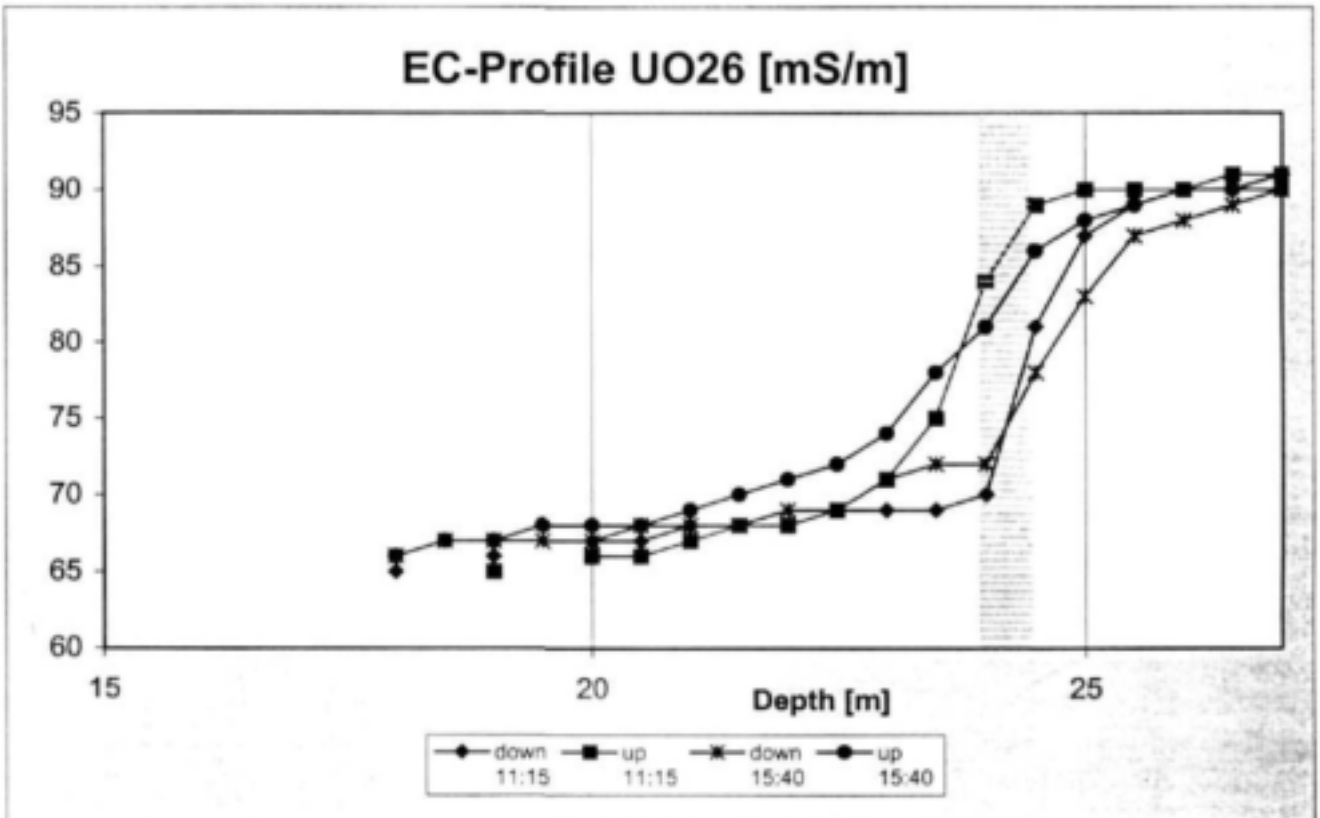


Appendix B.2

EC-Profiles of Borehole UO26 **Date:** **22.05.2000**

Abstraction at UP16 with appr. 3 l/s		Start pumping:	10:20	Stop pumping:	14:05
Injection of 300g NaCl in UO7		Start injection:	10:30	Stop mixing:	11:30

Depth [m]	down 11:15	up 11:15	down 15:40	up 15:40	Estimated Position of Fracture
15					
16					
17					
18	65		66	66	
18.5			67	67	
19	66	65	67	67	
19.5			67	68	
20	67	66	67	68	
20.5	67	66	68	68	
21	68	67	68	69	
21.5	68	68	68	70	
22	68	68	69	71	
22.5	69	69	69	72	
23	69	71	71	74	
23.5	69	75	72	78	
24	70	84	72	81	**about 24 m below surface**
24.5	81	89	78	86	
25	87	90	83	88	
25.5	89	90	87	89	
26	90	90	88	90	
26.5	90	91	89	90	
27	91	91	90	90	

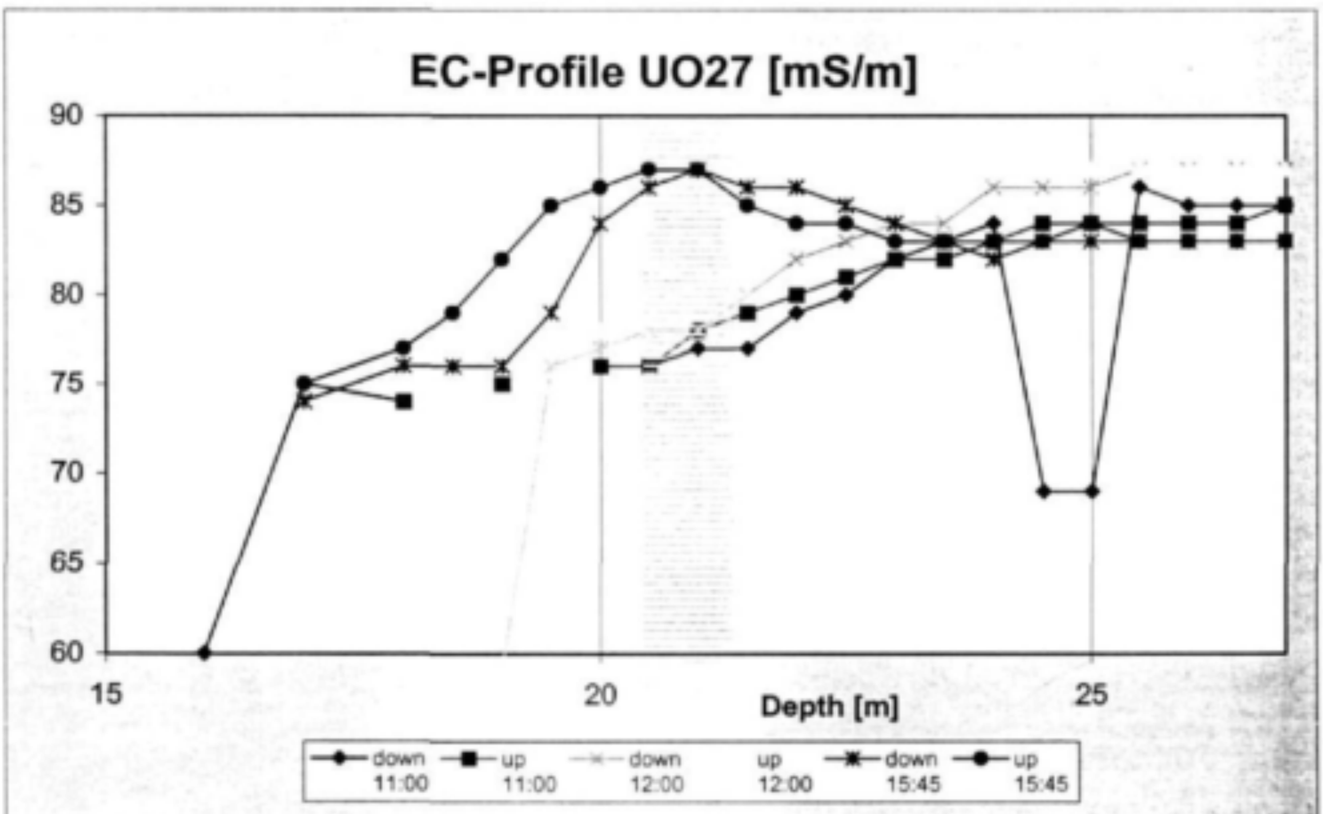


Appendix B.2

EC-Profiles of Borehole UO27 **Date: 22.05.2000**

Abstraction at UP16 with appr. 3 l/s	Start pumping:	10:20	Stop pumping:	14:05
Injection of 300g NaCl in UO7	Start injection:	10:30	Stop mixing:	11:30

Depth [m]	down 11:00	up 11:00	down 12:00	up 12:00	down 15:45	up 15:45	Estimated Position of Fracture
15							
16	60						
17	75				74	75	
18	74	74			76	77	
18.5					76	79	
19	75	75	59	76	76	82	
19.5			76	77	79	85	
20	76	76	77	78	84	86	
20.5	76	76	78	79	86	87	
21	77	78	78	81	87	87	about 21 m below surface
21.5	77	79	80	82	86	85	
22	79	80	82	84	86	84	
22.5	80	81	83	85	85	84	
23	82	82	84	86	84	83	
23.5	83	82	84	86	83	83	
24	84	83	86	87	82	83	
24.5	69	84	86	87	83	83	
25	69	84	86	87	83	84	
25.5	86	84	87	87	83	83	
26	85	84	87	87	83	83	
26.5	85	84	87	87	83	83	
27	85	85	87	87	83	83	

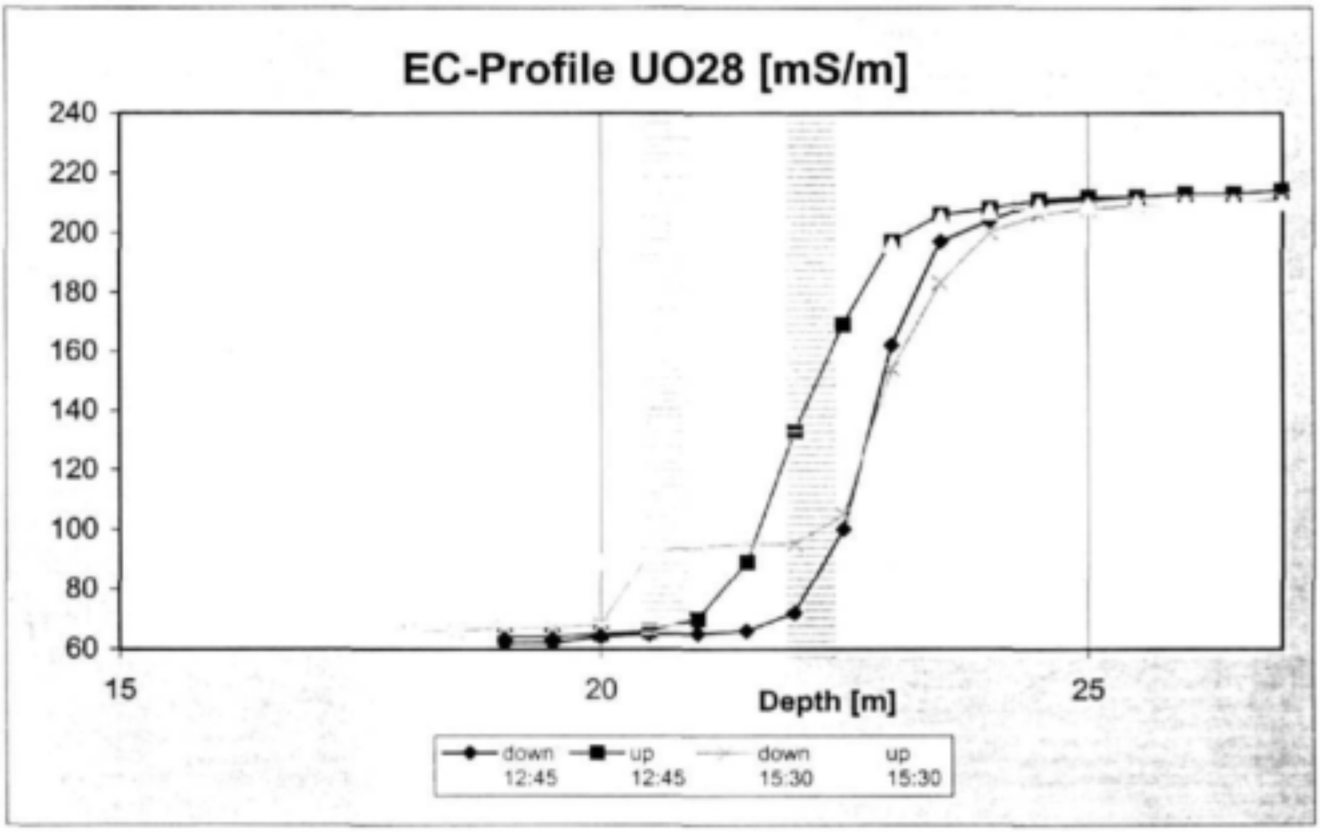


Appendix B.2

EC-Profiles of Borehole UO28 **Date: 22.05.2000**

Abstraction at UP16 with appr. 3 l/s	Start pumping: 10:20	Stop pumping:	14:05
Injection of 350g NaCl in UO14	Start injection: 11:55	Stop mixing:	13:00

Depth [m]	down 12:45	up 12:45	down 15:30	up 15:30	Estimated Position of Fracture
15					
16					
17					
18			66	66	
18.5			66	68	
19	62	64	67	70	
19.5	62	64	67	77	
20	64	65	68	89	
20.5	65	66	92	93	about 20.5 m below surface
21	65	70	94	97	
21.5	66	89	95	102	
22	72	133	95	152	about 22 m below surface
22.5	100	169	105	186	
23	162	197	154	196	
23.5	197	206	183	205	
24	204	208	200	207	
24.5	210	211	206	209	
25	211	212	208	209	
25.5	212	212	209	210	
26	213	213	210	210	
26.5	213	213	210	210	
27	214	214	211	210	



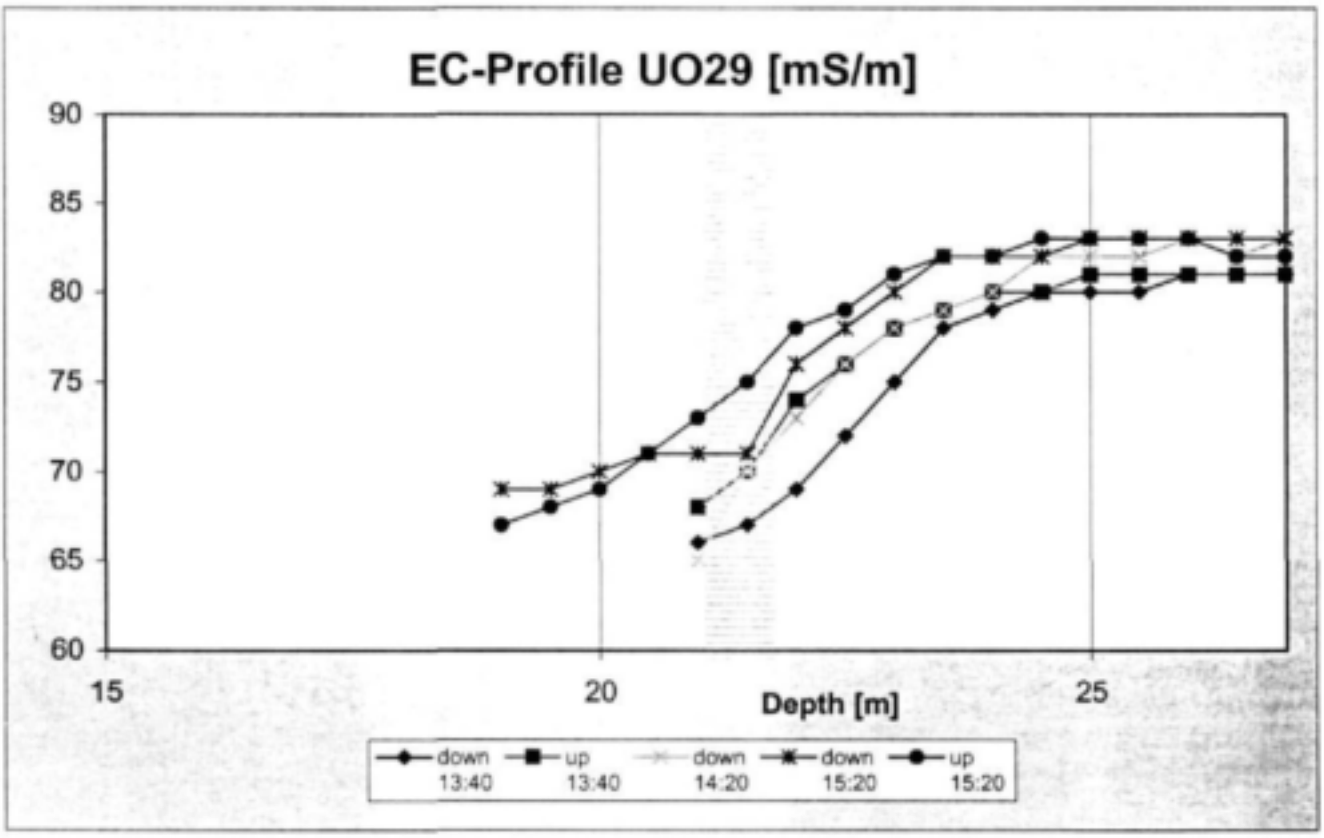
Appendix B.2

EC-Profiles of Borehole UO29

Date: **22.05.2000**

Abstraction at UP16 with appr. 3 l/s	Start pumping: 10:20	Stop pumping:	14:05
Injection of 350g NaCl in UO23	Start injection: 13:10	Stop mixing:	14:30

Depth [m]	down 13:40	up 13:40	down 14:20	down 15:20	up 15:20	Estimated Position of Fracture
15						
16						
17						
18						
18.5						
19				69	67	
19.5				69	68	
20				70	69	
20.5				71	71	
21	66	68	65	71	73	**about 21 m below surface**
21.5	67	70	70	71	75	
22	69	74	73	76	78	
22.5	72	76	76	78	79	
23	75	78	78	80	81	
23.5	78	79	79	82	82	
24	79	80	80	82	82	
24.5	80	80	82	82	83	
25	80	81	82	83	83	
25.5	80	81	82	83	83	
26	81	81	83	83	83	
26.5	81	81	82	83	82	
27	81	81	83	83	82	



Appendix B.2

EC-Profiles of Borehole UO30 **Date: 22.05.2000**

Abstraction at UP16 with appr. 3 l/s	Start pumping: 10:20	Stop pumping:	14:05
Injection of 350g NaCl in UO23	Start injection: 13:10	Stop mixing:	14:30

Depth [m]	down 13:30	up 13:30	down 14:25	down 15:10	up 15:10	Estimated Position of Fracture
15						
16						
17						
18						
18.5						
19						
19.5				58	80	
20				74	82	
20.5				78	83	
21	64	66	69	80	83	**about 21 m below surface**
21.5	65	66	70	84	82	
22	66	66	70	83	77	
22.5	67	67	70	80	75	
23	67	67	70	78	74	
23.5	67	67	70	75	73	
24	67	68	71	74	73	
24.5	68	68	71	73	73	
25	68	69	71	72	73	
25.5	68	70	72	72	73	
26	69	70	72	72	73	
26.5	69	70	72	72	73	
27	70	70	73	73	73