MANUAL ON PUMPING TEST ANALYSIS IN FRACTURED ROCK AQUIFERS

BY

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CHAPTER 1

MANUAL ON PUMPING TEST ANALYSIS IN FRACTURED ROCK AQUIFERS

1.1 OBJECTIVES OF THIS THESIS

The main aim of this thesis is to provide a manual on how to perform and analyze a pumping test in fractured-rock aquifers. Somebody with little experience in pumping tests should be able to, with the aid of this manual, go out on site, perform a reliable pumping test and obtain information that can be trusted and used. The contents of this manual will also be presented as a concise field guide in ***Appendix** A*. This guide can be used in the field and for more detail on the different topics the user should refer to the thesis.

This thesis will attempt to assist in analyzing the information gathered during a pumping test. The different methods of analyzing pumping test data will be looked at and in particular the new Flow Characteristic method (FC method) (Van Tonder *et al.*, 1998) will be evaluated against other existing methods.

The thesis will also look at specific issues such as the duration of pumping tests, how to choose a pumping rate for a specific pumping test and different drawdown graphs obtained at different pumping rates.

1.2 PUMPING TESTS

1.2.1 INTRODUCTION

Drilling and developing a borehole is an expensive exercise and in all cases the performance of such a borehole will be of utmost importance to somebody. This can be a farmer using the water for irrigation or even a whole community depending on the borehole for their water supply.

In many urban as well as rural parts of the country the main source of potable water is groundwater. Although only 15 percent of the country's total water consumption are supplied by groundwater resources, very often this is the only water supply to the communities using this resource. In rural areas groundwater supply water to schools, clinics, hospitals as well as small villages.

The policy of the present government is to address the basic needs of all the people in South Africa and in doing this they plan to address the basic water needs of between 12 and 18 million people in approximately 15 000 villages in the rural and remote areas of the country. In doing this, groundwater with its widespread, mostly low yielding occurrence will be widely used and because of this it became a national asset of strategic importance (Braune and Reynders, 1998). This resulted in legislation being passed to change the status of ownership of water in South Africa, including that of groundwater.

It is estimated that some 90 percent of local groundwater occur in secondary aquifers consisting primary of shallow zones of weathering and fracturing. A lack of understanding of the occurrence, movement and recharge of groundwater led to this resource not being utilized sustainable. The consequent failure of boreholes in some instances has unfortunately promoted the belief that groundwater is an unreliable source of water supply and that it should be replaced by the more reliable surface water supply. Because of this it is going to be a very difficult and uphill task to re-establish groundwater as a reliable water source and to give it its rightful place as a source of reliable water supply.

Contrary to surface water, groundwater is not visible and this makes understanding the art of groundwater resource development and determination that more difficult. The depletion of the country's surface water resources is a matter of great concern and in the not too distant future alternative water resources will have to be found. The obvious alternative is to develop the groundwater resources, which will put tremendous strain on this resource. Proper control over the development as well as the management of the groundwater resources will thus be very important in future. The new water law in the country states that all water belongs to the government and abstraction can only take place after a permit had been issued. This lays the foundation for the control over the development and management of the groundwater resources.

Due to the above, pump testing of boreholes will in future become even more important. In performing a pumping test we can determine the possible long-term sustainable yield of a specific borehole as well as the strain that the abstraction from the borehole will place on the aquifer. Performing accurate pumping tests can therefore not be over emphasized. Analyzing this pump test data correctly is also of utmost importance.

In the past incorrect methods were used to predict the possible long-term sustainable yield and in some cases analyzing pumping tests yielded incorrect parameters for the borehole as well as the aquifer. Important information such as the effect of boundary conditions as well as recharge was left out in the determination of the possible sustainable yield. This resulted in the borehole drying up after some time and this led to groundwater being branded as an unreliable water resource.

1.2.2 PURPOSE OF A PUMPING TEST AND THE ANALYSIS OF A PUMPING TEST

The efficient operation and utilization of a borehole requires insight into the productivity (yield potential) of the borehole as well as the aquifer from which the borehole draws its water. A pumping test provides a means of identifying potential constraints on the performance of a borehole and on the exploitation of the groundwater resources. If these constraints are not taken into account it may lead to the uneconomical operation of the borehole and it may even lead to the over-exploitation of the groundwater resource. In South Africa pumping tests are mainly done to determine the possible long-term sustainable yield of the borehole. The water from the borehole will be used to supply potable water to a community or it will be used to irrigate crops.

Analyzing the pump test data will assist in determining parameters of the aquifer. Parameter values such as hydraulic conductivity, transmissivity as well as storativity of both the fracture and matrix can be determined for the double porosity systems that is typical for most parts of the country. In order to obtain some of these parameter values the data obtained from observation boreholes in the vicinity of the pumping borehole must also be analyzed.

In order to achieve the objectives of a pumping test the contractor should supply data that is a true reflection of the behavior of the borehole at a certain pumping or abstraction rate. There is a basic set of rules which applies when a pumping test is performed and in order to obtain pumping test data that will be acceptable, the pumping test should be done according to this set of rules. The interpretation of the pump test data should also be done responsibly. If an incorrect method is used in analyzing the data it will definitely yield incorrect results. If the Theis equation, derived by making certain assumptions such as homogeneity and infinite areal extent, is used to interpret the data, it will yield an incorrect answer. Excluding parameters such as boundary conditions will provide an incorrect estimation of the long-term sustainable yield for a specific borehole.

1.2.3 INITIAL INFORMATION

Before the actual pumping test is done there are several initial actions that should take place. If these steps are not performed properly there might be uncertainties that eventually might result in claims being put in against the different parties involved. The pumping test contractor may even run the risk of not receiving his or her money for work done.

1.2.3.1 CONTRACTUAL MATTERS

Whether a pumping test is to be done for a private person, the government or any local authority, it is of utmost importance that the person doing the test must enter into a proper contract with the other party. Normally the representative of the party or the party itself that requires the pumping test put out a tender and the pumping test contractor will tender to do the work for a certain price. In a tender the scope of the work to be done must be described in detail. In some cases the pumping test contractor will be asked to give a quotation to perform a pumping test and in this quotation the work that will be done must be stated in detail.

In both the above instances the pumping test can only be performed after a letter of appointment had been issued. A verbal agreement is very dangerous and it might lead to serious misunderstandings that might even result in differences being settled in court.

1.2.3.2 LOCATION OF BOREHOLE

If the borehole to be tested and other observation boreholes are numbered, these numbers should be obtained from the person or authority that requires the pumping test. These numbers are normally listed in the tender and they should also be listed in the quotation handed in by the pumping test contractor.

When putting out a tender for a pumping test, it is good practice to include a map of the location and position of the borehole to be tested as well as possible observation boreholes. This will eliminate any possible misunderstandings that might occur.

The coordinates of the borehole that are to be tested as well as possible observation wells should be obtained in writing. A Global Positioning System (GPS) can then be used to locate the borehole where the pumping test will be performed as well as the positions of observation boreholes.

A good practice is also to request the party that requires the pumping test or his representative to physically go and point out the exact location of the borehole to be tested and possible observation boreholes. This takes the form of a site meeting and during such a site meeting all uncertainties can be cleared up. The positions can then be verified and mutually marked on 1 : 50 000 maps. With this strategy any uncertainties as far as the positions of the boreholes can be cleared.

1.2.3.3 BOREHOLE FITTED WITH PUMP

It is very important to establish whether the borehole that is to be pump tested is fitted with a pump. If this is the case it must be determined beforehand who would be responsible for the removal as well as the re-installation of the equipment.

The detail about the responsibility for the removal of equipment from the borehole to be tested should be included in the tender or in the quotation handed in. Removal of existing equipment can be a time consuming exercise and proper provision should be made for it in the quotation that is handed in to do the pumping test. In some instances the borehole to be tested is situated inside a building or enclosure and removal of the equipment can only be carried out by removing the roof of the building, making it a very difficult exercise. In most cases a tripod type of frame fitted with a block and tackle or a winch will be the most suitable to remove the equipment.

Care should be taken when removing the equipment not to damage it and after removal information such as serial numbers on the pump, make and model of the pump and any defects present should be written down. The depth at which the pump was situated should also be written down.

After the completion of the pumping test the equipment should be re-installed and the party responsible for doing it should be identified beforehand.

1.2.3.4 BOREHOLE LOGS

When drilling a new borehole the drilling contractor will supply samples of the rock formation being drilled out of the new borehole. This is done by inspecting the rock chips or drill cuttings brought to the surface during drilling. These samples are taken at one-meter intervals and are placed on the ground in the order that they are taken from the newly drilled borehole. The picture below ***(Fig. 1.1)*** shows these samples placed on the ground at a newly drilled borehole.

The samples are then lithologically described by a qualified person according to the prescribed guidelines. The drilling contractor will give a description of the colour of the formation, the relative size of the drill cuttings as well as the possible rock types. This is called a recorded log of the borehole and below is an example of such a log ***(Table 1.1)***.

Figure 1.1: Samples taken from newly drilled borehole.

DEPTH	DESCRIPTION
0.00 – 7.00 meters	Coarse reddish soil (loose, soft)
7.00 – 12.00 meters	Coarse and fine redbrown soil (loose, soft)
12.00 – 24.00 meters	Fine yellow brown sand (loose)
24.00 – 28.00 meters	White calcrete (medium)
28.00 – 35.00 meters	Bluish green shale (fine, solid)

Table 1.1: Recorded borehole log

This information is combined in a schematic layout and it is known as the log of the borehole. A typical log of a borehole is shown below (***Fig. 1.2***).

For large areas of South Africa detailed geological maps had been produced and these maps can assist in understanding the local geology of a specific area. These maps can also be used to compare the borehole logs to the geological map of the area.

The borehole logs supply important information such as possible fracture positions and water bearing formations. It is therefor very important to gather as much as possible information about the geology of the area. If no geological map or borehole log exists, the geology of the area around the borehole will have to be interpreted.

Interpreting the geology of the area however requires extensive knowledge and experience.

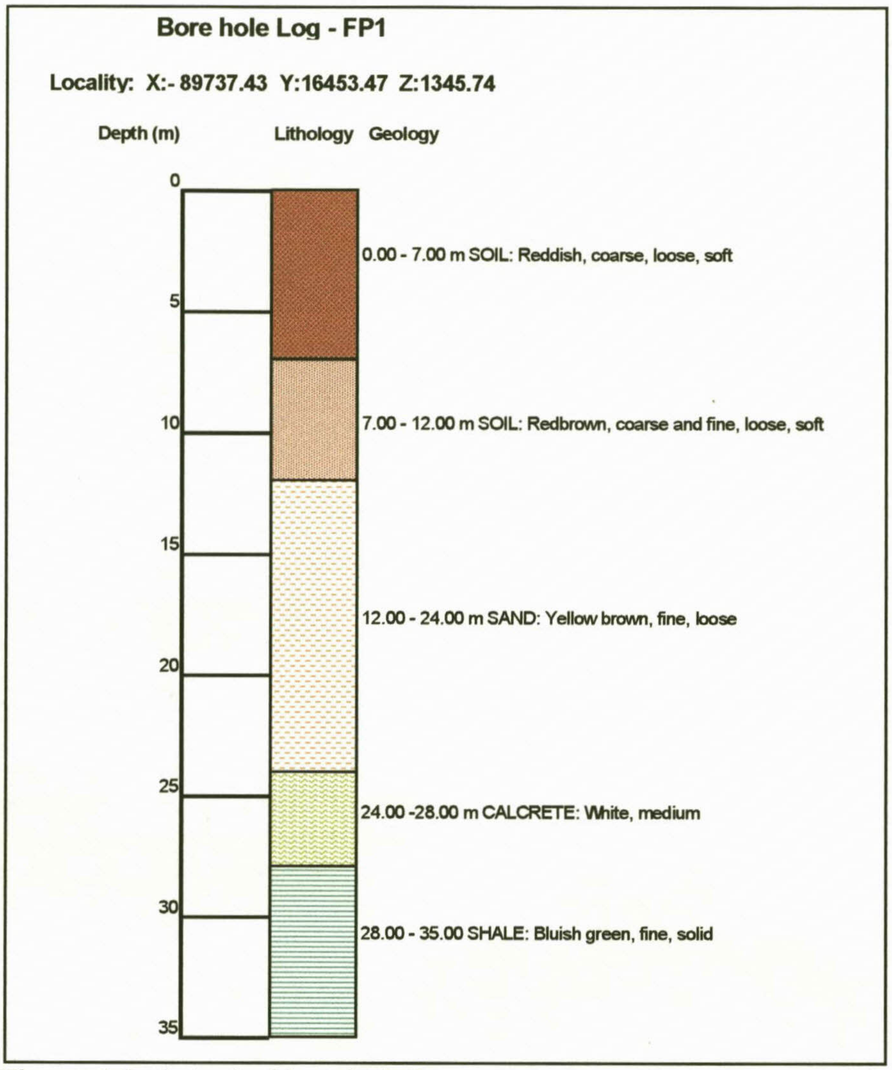


Figure 1.2: A typical borehole log.

1.2.3.5 EXISTING PUMPING TESTS

It is important to gather as much as possible information about the borehole being tested. In many instances pumping tests had already been done at these boreholes and these tests can yield very important information.

The science of Geohydrology is continuously being developed and therefor the existing pumping tests can be re-evaluated with the aid of the latest technology and methods available. A very good example of such new technology that became available only recently is the Flow Characteristic Method (FC Method) developed by Van Tonder *et al.* (1998).

Information such as the rest water level compared with the present water level that can give an indication of whether the groundwater level has fallen or risen. An example of a major drop in the rest water level is in the Molopo area where the water, up till a few years ago formed a natural lake above the ground. Agricultural development in the area led to an increase in the abstraction of the groundwater. This caused the water level in the aquifer to drop to a level of 23 meters below the surface (personal communication with Department of Water Affairs and Forestry pesonnel).

The yield of the borehole can be compared against the existing pumping tests and this can give an indication of whether the groundwater resource had been over exposed.

1.2.3.6 AVAILIBILITY OF POSSIBLE OBSERVATION BOREHOLES

It is also good practice to obtain information about possible observation boreholes in the vicinity of the borehole to be pump tested. Normally the representative of the party that requires the pumping test will supply this information. Details about observation boreholes should be included in the contract.

If no observation boreholes are specified in the contract it is very important that the person doing the pumping test should try and identify possible observation boreholes close to the borehole that is to be tested. People staying in the area will know about boreholes that exist in the vicinity.

The importance of an observation borehole can not be over emphasized. With the aid of observation boreholes the parameters obtained for a borehole can be verified. Parameters such as storativity, which is distance dependent, can also be tested and verified.

1.2.3.7 MAPS AND AERIAL PHOTOGRAPHS OF AREA

It is very important to get hold of maps of the area in which the pumping test is to be performed. Information such as access roads, height above mean sea level, contour information, possible observation boreholes as well as property boundaries could be identified on these maps. Possible aquifer boundaries could also be sighted from these maps.

Aerial photographs could also yield valuable information such as development of the land and growth of trees in the area. Rocky outcrops on aerial photographs could indicate possible dykes. Excessive tree growth in a definite line, away from a river, might indicate shallow groundwater, and this will only be visible on aerial photographs.

CHAPTER 2

EQUIPMENT REQUIRED TO DO A PUMPING TEST

2.1 INTRODUCTION

Normally boreholes that are to be pump tested are situated in remote areas away from towns or businesses. This means that is very difficult to go out and buy any spares or equipment that was left at home. To ensure that all the equipment is taken along it is good practice to draw up a list of equipment that is used during a pumping test. An example of such a list is included in ***Appendix B.*** The equipment required during a pumping test will now be described in detail below.

2.1.1 POWER SUPPLY TO THE PUMP

In some cases, especially new boreholes, the borehole to be tested is not fitted with electrical power and this means that the test contractor will have to supply his own power. A power source, normally a generator, powerful enough to supply power to the pump for a long enough period of time must be used. If a generator is to be used as a power source, enough fuel should be taken along to keep the generator going for the duration of the pumping test.

At some of the boreholes electrical power will be available, but this can either be single phase (220 volts) or three phases (380 volts). Not knowing what kind of electricity is available can cause serious damage to equipment. If electricity is to be used, a long enough lead cable should be taken along to supply the electricity from the power source to the pump.

The type of power that is to be used is not that important. However, the power source should be reliable and it should be able to supply sufficient power to the pump for the duration of the pumping test. A pumping test normally runs through the night and therefore it will be a bonus if the power source could also supply power to flood lights that are to be used.

2.1.2 PUMP SELECTION

There are mainly two types of pumps used to perform pumping tests. They are mono and submersible pumps, available in different shapes and sizes on the market. Because of this, pump selection is a study topic on its own. It is however important to note that the pump that is to be used for the pumping test should be capable of operating continuously at a constant discharge for a period of at least 72 hours.

According to the South African Bureau of Standards code of practice on the Development, Maintenance and Management of Groundwater Resources (SABS 0299-4:1998 Part 4: Test-pumping of water boreholes) the quality of the pump should be such that the variation in discharge must be less than 5 % for a constant rate pumping test. If the variation exceeds this limit, the pumping test should be stopped and after recovery the test should be restarted, using suitable equipment.

Normally a positive displacement type pump (mono pump) is used when performing pumping tests. This type of pump can be divided into two components, the actual pump situated inside the borehole and the power supply situated outside the borehole. With a mono pump the discharge rate can be changed by varying the speed or revolutions of the power supply. This can be done by with the aid of a gearbox or by regulating the fuel throttle. No valve can be used to increase or decrease the pumping rate of a mono pump. The main advantage of a mono pump is the constant rate at which it can pump or discharge water for a long period of time as well as the large volumes of water that it can pump.

It may be acceptable under certain circumstances to use a submersible pump (negative displacement pump) for testing purposes. In the case of a submersible pump both the pump and power supply is situated under the water inside the borehole. When a submersible pump is to be used, it is very important that the unit be fitted with a non-return valve at the bottom of the pump column. This prevents any return flows after the pump was shut down and the recovery period has started. A submersible pump can not deliver very large volumes of water, compared to mono pumps. The discharge from a submersible pump is increased and decreased by using a valve in the delivery piping. It is difficult to maintain a constant discharge rate over a long period of time with a submersible pump.

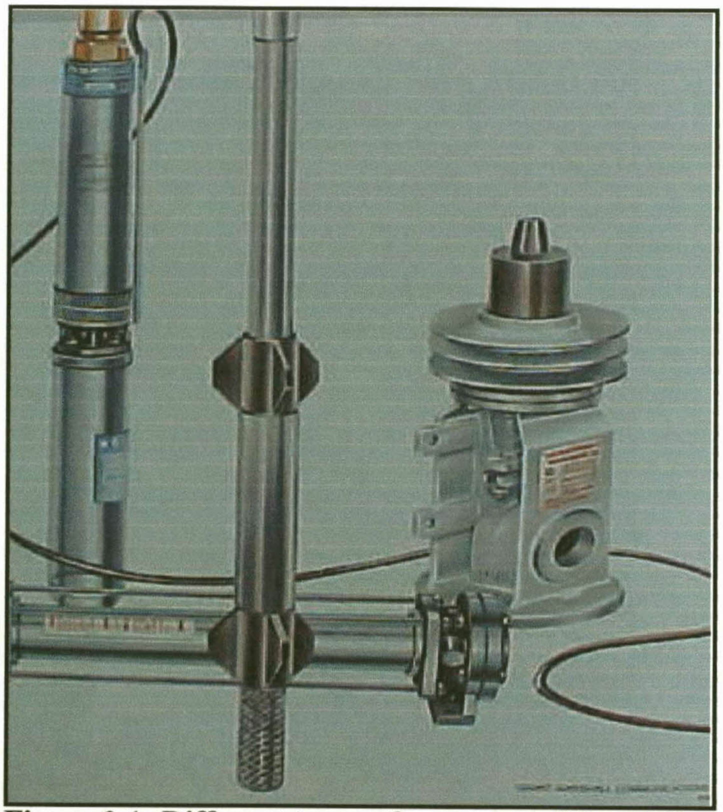


Figure 2.1: Different types of pumps used for testing

In the figure above ***(Fig. 2.1)*** on the left a submersible pump is showed. In the center is a mono pump with its discharge head on the right.

The pump used for a pumping test must be capable of delivering water at a rate in excess of the expected maximum yield of the borehole to be tested. The capacity of the pump and the rate of discharge should be high enough to produce good measurable drawdowns in observation boreholes as far away as 200 meters from the pumping borehole, depending on the aquifer conditions. In many cases some of the pump testing contractors carry more than one pump, each capable of pumping a different rate, depending on the requirements.

2.1.3 EQUIPMENT TO REMOVE EXISTING PUMPING EQUIPMENT

The responsibility for the removal of existing pumping equipment should be sorted out in the scope of the work to be done, or in the contract, or in the tender. This is very important because in many cases this can be a very difficult and time-consuming task. Provision for the removal and the re-installation of existing equipment should be made in the tender, taking into account the risks attached to this exercise. Some of the boreholes that are to be tested are inside little enclosures, making the removal of equipment a very difficult task.

In some cases it is almost impossible to get equipment out of existing boreholes because of tree roots growing into the boreholes or borehole sides falling in. Sometimes bees build their hives inside boreholes and this also clog up the upper part of the borehole. Disconnecting rusted delivery pipes as the equipment is removed from the borehole is no easy task, sometimes even completely impossible.

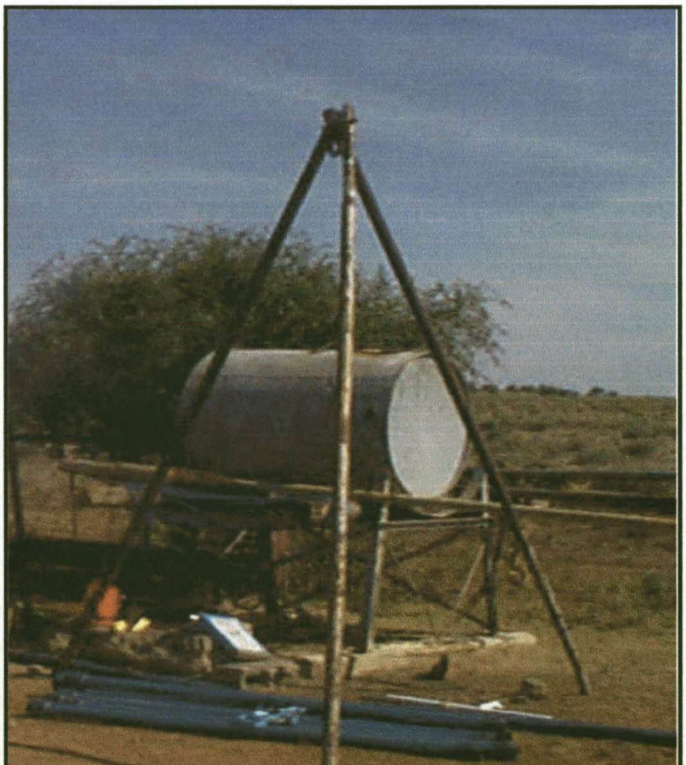


Figure 2.2: Tripod to remove equipment

A possible method of removing existing equipment is to make use of a tripod type of frame ***(Fig. 2.2)*** and a block and tackle or winch. The same frame and hoist gear can be used to install and remove pump-testing equipment in the borehole. In some extreme cases existing equipment can be pulled from the borehole with the aid of a vehicle, but this is not recommended.

2.1.4 EQUIPMENT TO DETERMINE DEPTH OF BOREHOLE

It is important to determine the depth of the borehole in order to determine the depth at which to install the pump used in testing the borehole. When performing a pumping test the pump should be placed as deep as possible inside the borehole, but without any interference of silt or debris lying at the bottom of the borehole.

A normal 50 or 100 meter measuring tape can be used to determine the depth of the borehole. A weight should be attached to the tape and then it can be lowered into the borehole. When the tape starts picking up slack, the weight has reached the bottom of the borehole and a reading on the tape will indicate the depth of the borehole.

Another method of determining the depth of the borehole is to drop a bailer down the borehole and marking the cable when it starts picking up slack. The distance from the bottom of the bailer to the mark on the cable can be measured and this will indicate the depth of the borehole. This method is preferred because it will clearly indicate any obstruction in the borehole and while the bailer is inside the borehole, any silt or loose material can be removed. This will limit any interference from the loose material during the pumping test.

2.1.5 SLUG TEST EQUIPMENT

A slug test (Vivier and Van Tonder, 1995) is a quick and easy method that can be used to predict the yield of the borehole by measuring the rate of recovery of the water level after a sudden change. This test is performed by suddenly raising or lowering the static water level in the borehole with the aid of a closed cylinder ***(Fig. 2.3 below)***.

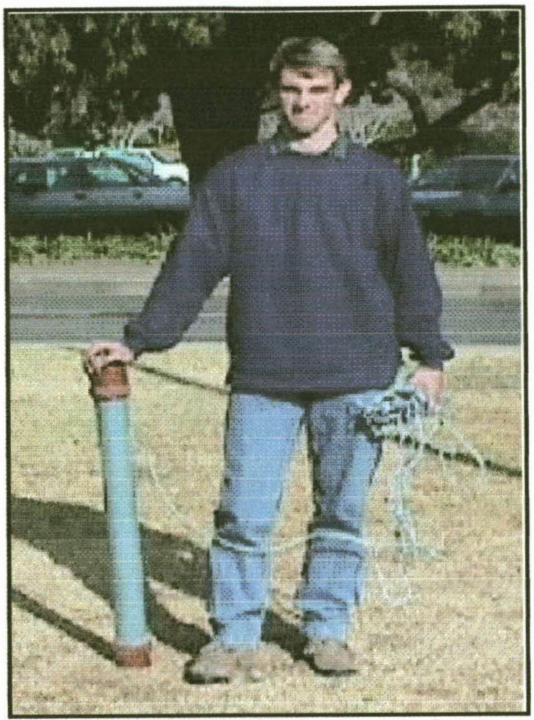


Figure 2.3: Slug with known volume to do slug test

The cylinder replaces its own volume of water in the borehole, thus increasing the pressure in the borehole. The equilibrium in the water level is changed and it will recover or stabilize to its initial water level. By measuring the rate of recovery or recession time (time taken to recover) of the water level, the borehole's transmissivity or hydraulic conductivity can be measured.

To perform this test a closed cylinder with a known volume, tied to a length of rope should be used. Instrumentation to measure the rate of recession of the water level inside the borehole is also required. For this purpose a data logger can be used. The borehole diameter must be 165 millimeter in order to use this method. The recession time to recover to at least 90 % of its initial value is used in a formula to determine the yield of the borehole. The formula:

$$y = 117155.08166\, t^{0.824126} \tag{2.1}$$

where t = recession time in seconds

will give the possible yield of the borehole in l/h (Vivier *et al.*,1995).

The graph below ***(Fig. 2.4)*** was drawn up from results obtained by testing 32 boreholes. The graph shows that a straight line is obtained, using log-log scale. If the recession time for the borehole is entered on the x-axis, the possible yield can be read off on the y-axis.

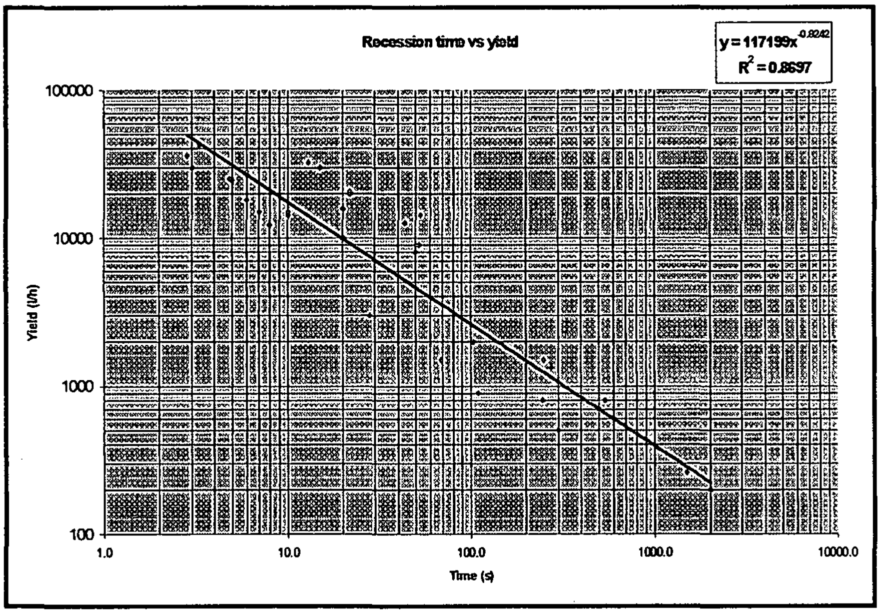


Figure 2.4: Correlation between recession time and borehole yields

If a slug test indicates that the potential yield of a borehole will be less than 0.3 l/s, then performing any additional tests should be reconsidered. If the potential yield is more than 0.3 l/s, the contractor should proceed with other tests such as stepped drawdown, multi rate or constant rate pumping tests.

2.1.6 WATER LEVEL MEASURING EQUIPMENT

When performing a pumping test, the static water level inside the borehole is lowered and this change in water level is recorded against time. This information is the only insight into the behavior of the borehole as well as the aquifer and it is therefor very important to measure the water levels and time intervals as accurately as possible. Gathering correct and accurate information during the pumping test is of utmost importance. These measurements can be done by hand or with an electronic data logger..

2.1.6.1 HAND READINGS

Hand readings are taken with a dipmeter ***(Fig. 2.5 - right)***, a tape measure or in some case two electric wires with a break in the circuit at the zero point of the device ***(Fig. 2.5 - left)***. As the zero point reaches the water, the water closes the circuit and a light flashes or a buzzer sounds. The distance from the collar of the casing of the borehole to the water level is measured and recorded. The predetermined time intervals are measured with the aid of a stopwatch and also recorded with the depth of the water level. This information is recorded on data sheets drawn up specifically for this purpose. The data sheets will be discussed later in this thesis.

Sometimes the turbulence caused by the pump as well as return flows into the pumping borehole can make water level measurement with a dipmeter very difficult or even impossible. To overcome this problem a plastic conduit tube, normally 16 millimeter diameter, is introduced down the pumping borehole. This conduit is attached to the riser main of the pump at 2 to 3 meter intervals. Water level measurements are then taken inside this conduit tube.

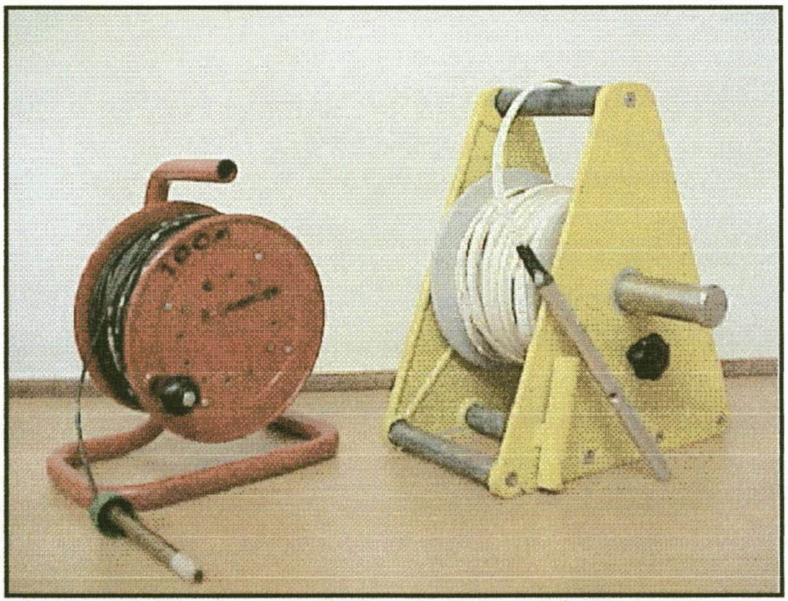


Figure 2.5: Two types of dipmeters used for water level measurement

With the method of hand water level measurement, the ever-present human error can always creep in and cause valuable information to be recorded inaccurately. To overcome this problem, electronic data loggers are used. These data loggers are reliable and they can be set up to take readings at specified time intervals.

2.1.6.2 ELECTRONIC DATA LOGGING EQUIPMENT

There are many types and makes of data loggers available on the market and therefor the specifications of all the different components of the logger should be looked at very carefully. A data logger that satisfies the needs of the pump test contractor as well as the standards set by the industry should be used. The datalogger can be divided into three main components namely, power supply, the pressure probe and the logger itself.

2.1.6.2.1 POWER SUPPLY TO THE DATA LOGGER

The power consumption of data loggers are normally very low and usually a 12-volt battery will be able to supply sufficient power to the equipment for the duration of the pumping test. In some cases, especially during longer pumping tests and where the frequency of data logging are set at small intervals, solar panels ***(Fig. 2.7)*** are used to charge the battery that supplies power to the equipment. When electrical power is available, it can be used in conjunction with a transformer bringing the power down to 12 volt. Normally a power regulator is used to ensure that a good quality of power is supplied to the equipment.

2.1.6.2.2 PRESSURE PROBES

The pressure probe ***(Fig. 2.6)*** used for water level measurement has got diameters that vary between 12 and 42 millimeter and it can therefor be installed in most of the boreholes and piezometers. The pressure probe makes use of a ceramic reference pressure-measuring cell that senses the hydrostatic pressure of the water column via a capacitive pressure diaphragm and this value is converted into an electric signal.

The power required to operate the pressure probe is only 12 volt and the output from the probe can either be 1-5 volt or 4-20 mA. The probe ranges vary from 0-2.5 meters to 0-40 meters, which is sufficient for most boreholes. The accuracy of the probes is better than 1 cm for 10 meters of measurement, which is the acceptable standard in the industry.

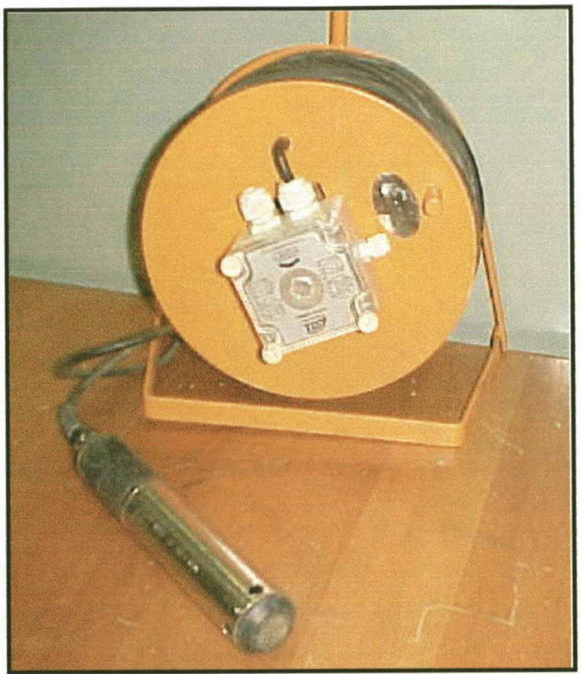


Figure 2.6: Pressure probe and vented cable

2.1.6.2.3 DATA LOGGERS

A multi channel data logger ***(Fig. 2.7)*** is used to convert the electronic signal from the pressure probe to a height. This is the height of the water column above the pressure probe inside the borehole or piezometer. This reading can be taken and stored at specified time intervals. These intervals can range from 5 seconds to once a day (24 hours), depending on the need of the client. The data logger being multi channeled can accommodate up to four pressure probes. Only one data logger can therefor be used to take and store readings at the pumping borehole as well as three observation boreholes in the vicinity.

The data logger is powered by a 12-volt power system and like the pressure probe, a battery and solar panel can be used as the power source. This enables the pumping test operator to use the data logger in remote areas without any power problems.

There is also a function where the readings can be taken at certain time intervals, but the average of a number of specified time intervals will be stored. The logger can also be set up to take a reading only if the reading differs by a preset margin from the previous reading. A ring memory enables the data logger to store large amounts of data and this data is taken from the data logger with the aid of laptop computer and software.

There are various types of data loggers available on the marked, and the type of data logger used does not really matter. It is however important that the data logger must be reliable because valuable data can be lost if the data logger fails during the pumping test.

Figure 2.7: Data logger and power supply

A variation on the pressure probe and data logger combination is the data logger that makes use of an indirect measuring principle (bubble principle). A piston pump inside the instrument generates compressed air that flows through a dedicated line into a bubble chamber inside the borehole at programmable intervals. Depending on the groundwater level above the bubble chamber orifice, an air pressure equal to the hydrostatic pressure is established inside the measuring tube. Assuming a constant liquid density, there is a linear relationship between the water level to be measured and the air pressure inside the measuring tube. The bubble-line pressure and the barometric pressure are measured concurrently by an absolute pressure-measuring cell inside the data logger. The water level is calculated as the difference between the two signals.

2.1.7 INTERVALS OF WATER LEVEL MEASUREMENTS

The water levels inside the pumping borehole as well as the observation boreholes must be measured many times during the pumping tests as well as during the recovery stage of the test. Because the water level drops rapidly during the early times of the pumping test (first two hours), it is important that water level readings should be taken at short intervals. As the pumping test progresses the intervals at which readings are taken can be lengthened. The same principle applies for both hand readings taken with a dipmeter as well as readings taken with the aid of a data logger. When a data logger is used the number of readings taken can be filtered afterwards. It is therefor good practice to take readings at short intervals for the duration of the pumping test and then to filter the readings afterwards. By using this method important events such as fracture positions and boundaries can be pinpointed and logged in detail. Other external pumping activities that might have an effect on the pumping test can also be picked up easily if this method of logging water levels is used. On the chart below ***(Fig. 2.8)*** it can clearly be seen that water was abstracted from another borehole (step 1) close to the pumping test borehole. The time at which the pumping activities were stopped (step 2) can also clearly be seen.

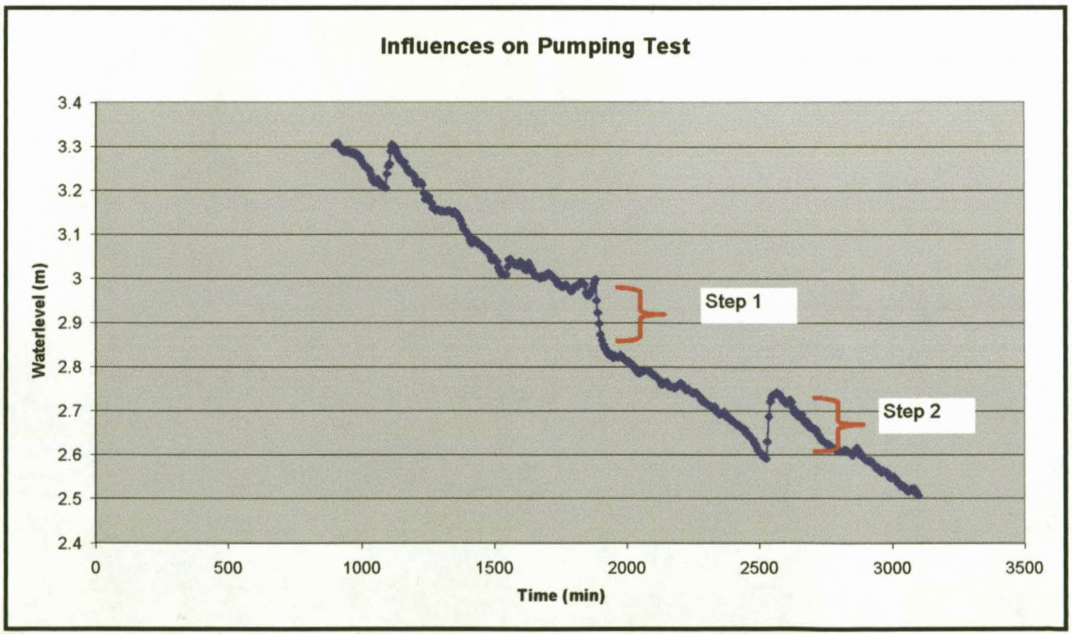


Figure 2.8: The influence from external pumping activities on the drawdown

The intervals at which hand readings should be taken can be seen on the data sheet as described in the next section. It must also be noted that hand readings must be taken at all times, even if a pressure probe and data logger had been installed for the pumping test. The hand readings will verify the readings taken with the aid of the pressure probe and data logger.

2.1.8 DATA LOGGING SHEETS

Everything that happens during a pumping test should be recorded. It is very important that all the information should be kept together. Information recorded on various or on small pieces of paper can easily be lost and this might lead to the pumping test being a failure. A pumping test is an expensive exercise and if it is a failure, a lot of money will be wasted.

It is therefor a good practice to draw up a form or sheet on which all the relevant information can be recorded. The format of such a data-logging sheet is entirely up to the individual, but it should contain all the relevant information after the pumping test was completed. This sheet should be drawn up beforehand and it should be able to accommodate information such as:

- ☐ Name of pumping test borehole
- ☐ Number of borehole
- ☐ Date of pumping test
- ☐ X coordinate
- ☐ Y coordinate
- ☐ Z coordinate
- ☐ Pumping rate
- ☐ Rest or static water levels
- ☐ Intervals at which readings should be taken
- ☐ Weather conditions
- ☐ Description of possible boundaries
- ☐ External factors that might have an influence on the pumping test.

In some cases a universal form or sheet is drawn up and this sheet can therefor be used to record information on slug tests, calibration tests, constant rate pumping tests, multi rate pumping tests as well as recovery tests. An example of such a data sheet is included in ***Appendix C***.

2.1.9 DISCHARGE OR DELIVERY PIPES TO RELAY WATER FROM THE PUMPING BOREHOLE

As already mentioned, the purpose of a pumping test is to remove water from the pumping borehole as well as from the aquifer. Care should therefor be taken that the water removed from the borehole does not end up back in the aquifer before the pumping test is finished. To ensure that this does not happen, the water must be taken away and discharged at a point far away from the pumping activities.

Discharge piping runs from the delivery side of the pump up the borehole and on the surface it takes water away from the borehole. Sometimes it is very difficult to put a continuos piece of delivery piping down the borehole and to overcome this problem the pipes are broken up into sections. The equal diameter sections of pipes are connected as the pump is lowered into the borehole.

The delivery pipe that runs along the ground normally consists of a large diameter continuos plastic pipe. According to Hobbs and Marais (1997) this pipe should be at least 50 meters long, but preferably 100 meters. It must be free of leaks for the entire length of the pipe. Under certain circumstances, it may be required to discharge the water up to 300 meters away from the borehole being tested.

According to the South African Bureau of Standards code of practice on the Development, Maintenance and Management of Groundwater Resources (SABS 0299-4:1998 Part 4: Test-pumping of water boreholes) the discharge point of the delivery pipe must be so far away that the discharged water does not flow back into the aquifer during the pumping test. It is also specified that in the case of

- a confined aquifer with a thick, impervious confining layer, the water must be discharged at least 10 meter away from the borehole

- ☐ an alluvial gravel subterrain, at least 300 meters, but preferably more than 500 meters away from the borehole and
- ☐ an aquifer of which the surrounding geological structure is not known, at least 1000 meters away from the borehole.

It is recognized that some water leakage will generally occur during a pumping test. This is acceptable provided that such leakage does not interfere with any water level monitoring and the total amount of leakage to the end of the discharge pipeline does not exceed more than one percent of the pumping rate as measured at the end of the pumping test.

2.1.10 EQUIPMENT TO MEASURE DISCHARGE FROM BOREHOLE

For the duration of the pumping test the discharge from the pump should be monitored and measured. Discharge measurement should take place at specified intervals to ensure the pumping rate is constant. There are various methods with which to determine the discharge rate from the borehole (Hobbs and Marais, 1997).

2.1.10.1 VOLUMETRIC METHOD

This is also called the container and stopwatch method. This is a very simple, but effective method to determine the discharge rate from the pump. The time it takes to fill a container of known volume is recorded and with this information the discharge rate can be determined. The container should stand level when it is filled and the stopwatch should be able to measure to an accuracy of one tenth of a second. This method is fairly accurate and it is commonly used. The table below ***(Table 2.1)*** gives some indication of the size of the container to be used with the different discharge rates from the pump.

Discharge rate	**Container size**
Less than 2 l/s	20 liter
2-5 l/s	50 liter
5 – 20 l/s	210 liter
20 – 30 l/s	500 liter
30 – 50 l/s	1000 liter
More than 50 l/s	Use other suitable methods

Table 2.1: Discharge rate versus container size for volumetric measurements

2.1.10.2 FLOW METERS TO MEASURE DISCHARGE RATE

The flowmeter ***(Fig. 2.9)*** is installed in the delivery line from the pump. The flowmeter must be properly calibrated before it is used and its piping must be of similar diameter to that of the discharge pipe.

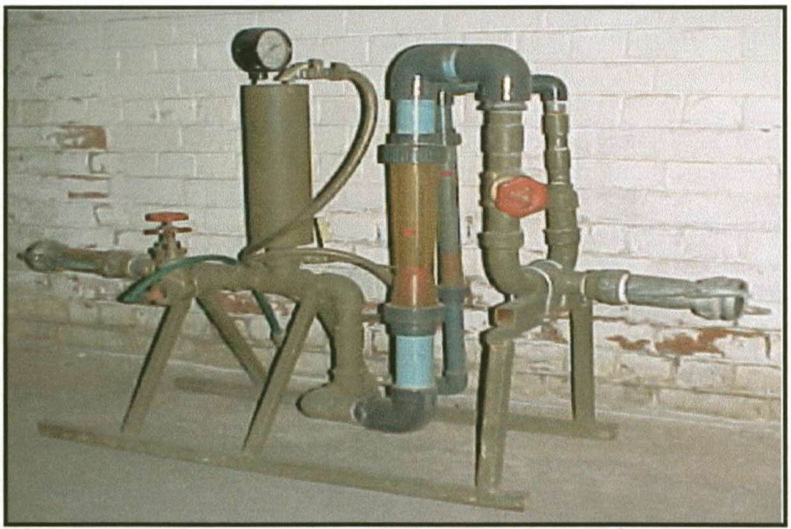


Figure 2.9: Flowmeter to measure discharge from pump

There must be no turbulent flow or entrained air in the discharge pipe before the meter. The discharged water must be free of solid material carried in suspension. Some flowmeters have got two valves for discharge setting, a coarse and a fine setting valve.

2.1.10.3 ORIFICE WEIRS TO MEASURE DISCHARGE

The orifice weir is commonly used to measure the discharge from a turbine or a centrifugal pump. It does not work when a piston pump is used because the flow from such a pump pulsates too much.

Orifice weirs must be installed in a horizontal position at the end of the discharge pipe. The orifice plate opening must be sharp, clean, beveled to 45 degrees and have a diameter of less than 80 percent of the diameter of the approach tube to which it is fixed. The orifice plate must be vertical and centered on the end of the approach tube. There must be no leakage around the perimeter of the orifice plate mounting. The piezometer tube must not contain entrained air bubbles at the time of pressure head measurement. The latter measurement must be at least three times the diameter of the orifice.

2.1.11 WATER SAMPLING EQUIPMENT

Water samples should be taken during the pumping test. The sample should be taken at the end of the pumping test, 15 minutes before the test is stopped. It does not matter what type of pumping test it is.

According to Hobbs and Marais (1997) the person that takes the water sample should wash his or her hands before taking the sample. A 240 ml sample bottle should be used and this container should be rinsed at least three times with the water that is going to be sampled, i.e. that being pumped from the borehole. Fill the bottle so that a space of five to ten millimeters is left at the top. If the sample is to be sampled for macro-elements, the prescribed preservative should be added.

2.1.12 FLOOD LIGHTS

Long pumping tests always carry on during the night and it is always difficult to take water level readings or to determine the delivery from the pump in the dark. It is therefor important to make sure that a strong and reliable flashlight or a floodlight forms part of the equipment on a pumping test outing. When electricity is available, electric floodlights can be placed at strategic places on the test terrain and by the flick of a switch, the necessary light is supplied to take readings easily.

2.1.13 OTHER EQUIPMENT

Normally the pumping test site is in a remote area and then accommodation can become a problem. Because the pump-testing contractor must be present at the pumping test site for the duration of the pumping test, it is very important that he should make arrangements to camp or stay at the site. A list of equipment needed is included in ***Appendix B***.

CHAPTER 3

PERFORMING A PUMPING TEST

3.1 PRE ARRIVAL ON SITE ACTIONS

The pump test contractor must be appointed and he should be in possession of a letter of appointment before any actions to perform the pumping test are taken. A letter must confirm a telephonic appointment before any action is taken.

A date to perform the pumping test must be mutually agreed upon by the pumping test contractor and the person or authority that requires the pumping tests. If a representative is acting on behalf of the person or authority that requires the pumping test, all negotiations should be done with him.

The owner of the property should also be informed that a pumping test is going to be performed on his property and that there will be some activity on the property. This will even continue through the night with the aid of floodlights.

The removal of existing pumping equipment from the boreholes to be tested must be sorted out before the commencement of the pumping test. If it is the responsibility of the pump test contractor he should inform the owner of the pump prior to the pumping test that the pump is going to be removed from the borehole for a period of time. If the pump is used to fill up a reservoir the owner can do so before the equipment is removed.

All pumping activities from the pumping borehole as well as the aquifer should be stopped at least 72 hours prior to the start of the pumping test. During the pumping test no pumping from boreholes in the vicinity of the pumping test borehole should take place. This can have a negative effect on the results of the pumping test. The responsibility to negotiate the seizure of all pumping activities in the vicinity of the borehole where the pumping test is to be done should be cleared before the start of the test. If it is the responsibility of the pump test contractor all the affected parties should be contacted long before the start of the test.

The pump test contractor should plan the trip to go and do the pumping test properly. The equipment specified on the checklist ***(Appendix B)*** must be acquired and assembled. All the equipment must be tested at the office to ensure that it works properly before leaving for the pumping test. Camping equipment must also be packed and permission to stay on the property must also be obtained from the owner prior to the pumping test.

Information on trig beacons in the area where the pumping test is going to be performed should also be obtained. This information will be used to survey the pumping as well as the observation boreholes. This includes the elevation (z coordinates) as well as the positions (x and y coordinates).

3.2 ARRIVAL ON SITE ACTIONS

Everything had been organized and now the contractor goes out to the site to do the pumping test. The events that take place after the arrival on site normally takes place in the same sequence every time and normally the one action must be finished before going on to the next task or action.

The different actions that take place during a pumping test will be discussed below. Detail on some of the topics was taken from the Minimum Standards and Guidelines for groundwater resources development for the community supply and sanitation program drawn up by PJ Hobbs and assisted by SJ Marais (1997). This was done because this thesis was written for South African conditions and aquifers.

3.2.1 LOCATE CORRECT BOREHOLES (PUMPING AND OBSERVATION)

From the maps supplied with the tender documents by the representative of the person or authority that requires the pumping test the contractor must now locate the borehole to be tested as well as all the observation boreholes. It will be best if the representative can be present on site on the first day of the pumping test so that all the boreholes involved in the pumping test can be located together. By doing this there can be no uncertainties.

The contractor can also verify the positions of the boreholes if the representative supplied their coordinates. This can be done with the aid of a Global Positioning System (GPS). After all the relevant boreholes had been identified they should be clearly marked and numbered.

The possibility of additional observation boreholes should also be investigated. The owner of the property or the person staying on the property can supply information about possible additional observation boreholes. This person should therefor be requested to supply information in this regard.

From the information on the observation boreholes it must be decided which boreholes would be used for observation boreholes. The distances that these observation boreholes are away from the pumping borehole as well as their location in relation to the pumping borehole will help in making a decision in this regard.

3.2.2 REMOVAL OF EXISTING EQUIPMENT AT BOREHOLE

Before the pump testing equipment can be installed into the borehole to be tested the existing equipment must be removed. This can either be the responsibility of the pump test contractor or that of the person or authority who wants the test done.

Great care should be taken when removing the existing equipment from the pumping as well as the observation boreholes. Normally the equipment had been in the boreholes for a long time and connections are rusted and very difficult to disconnect and to remove.

A tripod type of frame fitted with a block and tackle or a winch can be used to remove the equipment. The equipment should be neatly placed and stored away from the borehole to be tested so that it does not interfere with the pumping test. As much as possible information on the equipment should be recorded (Hobbs and Marais, 1997). This includes:

- ☐ the manufacturers name
- ☐ type of pump
- ☐ type of motor fitted to the pump
- ☐ the depth to which the pump was installed
- ☐ the power rating of the motor
- ☐ the diameter, length and quantity of pump column sections.

All deficiencies and breaks on the equipment should be carefully written down and it should be reported to the representative as well as the owner of the equipment. The depth of the pump before removal as well as specifications on the equipment should be written down.

If the contractor is responsible for the removal of the equipment, he should also reinstall the equipment to the same condition that it was found in. If equipment in the identified observation boreholes might interfere with the pumping test it should also be removed. The same procedure as described above should be followed when removing this equipment.

3.2.3 DETERMINING THE DEPTH AND DIAMETER OF THE BOREHOLE

The depth of the borehole should be determined in order to determine at what depth the pump to be used during the pumping test must be installed. To determine the depth of the borehole a bailer attached to a cable or a rope is used. The bailer is lowered into the borehole and when it reaches the bottom of the borehole the rope or cable is marked so that the length can be determined with the aid of a tape measure. The collar of the borehole is normally used as the reference point to where the measurements are taken. The depth of the borehole should be written down on the data sheet with the other information.

The bailer that is lowered into the borehole also serves another purpose. When the bailer is lowered into the borehole it can be determined whether or not the borehole had been closed up. Sometimes the sides fall in or tree roots block the borehole and it will be impossible to put the pump testing equipment into the borehole. The depth determined with the bailer can be compared to the depth supplied by the owner or representative.

The bailer should also be used to remove any loose debris lying at the bottom of the borehole. The silt inside the borehole may interfere with the pumping test and therefor it will be better to remove it before the pumping test commences.

The depth of the observation boreholes should also be determined. This can be done by using a weighted line and plumb bob.

The diameter of the borehole must be measured with a tape measure. This information should also be written down on the data sheet. Normally the boreholes used in this country have got diameters of 160 - 165 millimeter, but it must definitely be measured.

3.2.4 DETERMINING POTENTIAL YIELD (SLUG TEST) AND DETERMINING POSSIBLE PUMPING RATE

Before the slug test is done, the diameter of the borehole should be measured. Because the slug test was developed for 165 millimeter diameter boreholes, the test can only be performed on boreholes with the same diameter (165 millimeter). Before the slug test is done, the rest or static water level of the pumping borehole must be determined. This means that the distance from the collar of the borehole to the water level must be measured.

A rope must be attached to the slug with the prescribed volume and the distance from the collar of the borehole to the water level should be marked on the rope. This is done to ensure that the whole slug is submerged during the slug test. Insert a dipmeter into the borehole and get a stopwatch ready so that the water levels can be measured at certain time intervals after the slug had been lowered into or taken out of the water. The contractor can now start with the slug test (Vivier et al., 1995).

The slug is now quickly lowered into or taken out of the water and the increased or lowered water level is measured while the stopwatch is started. The time taken for the water level to stabilize to at least 90 % of its original value is recorded. From the recession time versus yield chart ***(Fig. 2.4)*** the maximum yield of the borehole in l/h can be determined. This will give the contractor an idea of whether additional pumping tests will be warranted. If the possible yield of the borehole is found to be less than 0.3 l/s, then the consultant should be informed and a decision to continue or discontinue the testing should be taken. If the yield is more than 0.3 l/s the testing can continue.

3.2.5 INSTALLING PUMPING EQUIPMENT

If the slug test indicates that the possible yield from the borehole will be sufficient, other pumping tests can commence. The contractor must now install the pump testing equipment in the borehole that will be pump tested. There are mainly two types of pumps that are used for pump testing purposes. A positive displacement pump or a mono pump is used and in some instances a negative displacement pump or submersible pump is used. The type of pump that is going to be used will determine the method of installation into the borehole.

If a mono pump is to be used for the pumping tests, this is the way that the contractor will go about installing the pump into the borehole. A tripod frame and winch can be used to perform this task. The section housing the rotor-stator is attached to the cable of the winch and is lowered into the borehole. The shaft is connected to the rotor and the first rising mains column is attached to the housing. This is done by pushing it over the shaft. The section is lowered further into the borehole and when it has been lowered far enough the next shaft and column is attached. This procedure continues until the intake of the pump is at the desired depth. Then the frame or stand housing the discharge head is placed over the borehole and fixed to the shafts and columns going down the borehole. From the discharge head the horizontal delivery piping is attached. The power supply to the pump is now placed into position and it is connected to the pump by making use of vee-belts. The power supply can be a diesel or petrol engine with a gearbox or a variable speed throttle.

If a submersible pump is to be used for the pumping test the pump can be installed into the borehole by using the same tripod frame and winch. The power supply is attached to the pump and it is properly sealed to prevent any water from getting into connections and causing the power to fail. The winch cable is securely attached to the pump in order to lower it down the borehole. In some cases an additional safety rope is also attached to the pump to ensure that the pump can be removed from the borehole if the winch cable snaps. The delivery pipe is also fixed to the pump and care should be taken that all connections are watertight. In some cases shorter lengths of delivery pipes are used and then care should be taken that all connections are watertight. The non-return valve fitted at the bottom of the pump column should be checked to ensure that after the pump is stopped, no return flows takes place via the delivery piping and pump. If this happens it will have a negative effect on the accuracy of the recovery test.

In some cases the rising mains of a mono pump can have a large diameter (140-millimeter) and this can cause problems if the borehole diameter is not large enough. It can result in difficulty to install and remove the pump and it might also prevent the contractor from installing other equipment such as pressure probes or dipmeters in the borehole. The limited diameter of the borehole and the large diameter of the rising mains of the pump may prevent the contractor from installing a large enough pump in order to obtain good results during a pumping test. The contractor should know the diameters of the different pumps to his disposal and he should try and obtain the diameter of the pumping borehole before the pumping test.

3.2.6 PLACEMENT OF PUMP (DEPTH)

In many instances the depth at which the pump is to be placed will be specified in the contract, but if this is not the case then the contractor must take that decision. The pump should be installed as low as possible in the borehole to ensure that the maximum available drawdown of the water in the aquifer is possible. This is very important, especially during longer pumping tests or in tests where the aquifer is strained. The behavior of the water levels during shorter pumping tests differs significantly from long duration tests. After longer pumping times and higher abstraction rates the true behavior of the aquifer starts showing, especially when the main fractures are dewatered and water starts flowing from the matrix. This can cause the yield and therefor the water levels inside the borehole to drop significantly. This can even result in the water level reaching the intake level of the pump if it is not installed deep enough.

The pump should however not be installed too low in the borehole because debris and silt at the bottom of the borehole can be sucked into the pump. This will have a negative influence on the delivery of the pump and it might even result in the breakdown of the pump. According to the South African Bureau of Standards code of practice on the Development, Maintenance and Management of Groundwater Resources (SABS 0299-4:1998 Part 4: Test-pumping of water boreholes) if no information about the main water strike is known, the inlet of the pump should be placed between 3 and 5 meters from the bottom of the borehole.

Depending on depth of borehole, the table below ***(Table 3.1)*** (Hobbs and Marais, 1997) gives an indication of the distance at which the pump must be installed above the bottom of the borehole.

DEPTH OF WATER IN BOREHOLE	TEST PUMP INSTALLATION DEPTH
Less than 5 meters	Do not install pump
Between 5 and 30 meters	Between 1.5 and 2.5 meters above bottom
Between 30 and 60 meters	Between 2.5 and 3.5 meters above bottom
Between 60 and 90 meters	Between 3.5 and 4.5 meters above bottom
More than 90 meters	Between 4.5 and 5.5 meters above bottom

Table 3.1: Guidelines for test pump installation depth

If the available drawdown (water column) in the borehole is less than 5 meters then a pumping test should not be performed. The initial drawdown during a pumping test can be ascribed to the storage effect in the borehole (well bore storage) and it lasts for only a few minutes, depending on the abstraction rate. In most instances this initial drawdown is more than 5 meters which makes a pumping test in a borehole with only 5 meters of available drawdown a futile exercise.

3.2.7 INSTALLING DISCHARGE PIPING

The rising main had been connected to the pump and now the contractor must divert the water away from the pumping borehole. The water must be diverted in such a way that it does not affect the results of the pumping test in any way. The water should therefor not be able to flow back into the borehole and more importantly, it should also not be able to circulate back into the aquifer.

To ensure no influence from the pumped water it should be discharged away from the borehole. Horizontal delivery pipes are used to channel the water from the borehole to the point of discharge. According to Hobbs and Marais (1997) this point should be at least 50 meters away from the pumping borehole and in some instances it should even be up to 300 meters away. When the contractor has to decide where the water that is pumped from the borehole is to be discharged, he should first determine the slope of the ground or the general gradient at the pumping borehole. The delivery pipes should be placed in such a way that the water will naturally drain away from the borehole and aquifer. During a pumping test a lot of activity is taking place at the pumping borehole and the immediate vicinity. Water draining back to this area will make it impossible to move around on the site.

If a negative displacement pump or submersible pump is used for the pumping test, the volume of water pumped from the borehole during the pumping test is sometimes regulated with the aid of a valve. This valve is installed in the horizontal section of the delivery pipe and with this valve the delivery of the pump can either be increased or decreased. The discharge from a positive displacement pump is regulated with increasing or decreasing the revolutions from the motor driving the pump.

The discharge from the borehole during the pumping test is also measured on the delivery side of the pump. In some cases a volumetric flowmeter is installed in the delivery piping.

3.2.8 MEASURING DISCHARGE WATER OR PUMP DELIVERY

The rate at which water is pumped from the borehole during a pumping test must be measured and recorded at regular intervals. This information is very important because it is one of the parameters used in determining the possible yield of the borehole. There are various methods of determining the discharge rate during a pumping test, some expensive and some not that expensive. In some cases the contract will specify the type of discharge measurement that should be used during the pumping test.

If no method is specified, the volumetric method will most probably be used. This is a cheap and easy method to use and the equipment does not take up a lot of space during travelling to the site. In this method a container with predetermined volume is filled and the time taken to fill this container is logged. To ensure that a correct answer is obtained the measurement must be repeated at least three times and the average of the three times should be recorded. The container must be placed level on the ground next to the end of the delivery pipe and the stopwatch should be capable of measuring in at least one-tenth of a second. The size of the container used in this method depends on the pumping rate during the test. There are certain guidelines (Hobbs and Marais, 1997) for the container sizes and they are described in Chapter 2 ***(Table 2.1).*** Care should be taken that the end of the delivery pipe from the pump is not disturbed too much because this can affect the delivery from of the pump.

If discharge measurement is required with the aid of a flow meter such a meter should be installed on the horizontal section of the delivery pipe of the pump. The delivery pipe should be straight and of uniform diameter for a distance of at least four times the diameter of the pipe before the meter. A properly calibrated flow meter with a similar diameter to that of the discharge pipe should be used. There must be no turbulent flow or entrained air in the discharge pipe before the meter. The flow meter must be such that the operator should be able to adjust the flow with a course as well as a fine setting.

Another method of measuring the discharge from the pump is to install an orifice weir at the end of the discharge pipe. The orifice plate opening must be sharp, clean, beveled to 45 degrees and have a diameter less than 80 percent of the diameter the approach tube to which it is fixed. The piezometer tube must not contain entrained air bubbles at the time of pressure head measurement.

The discharge rate from the pump should be checked at the prescribed intervals and it should be recorded on the data sheet. The intervals are described in detail when the different pumping tests are discussed later in the thesis. The revolutions of the pump motor or the valves at the flowmeter should be adjusted to keep flow constant. The connections between the discharge piping and the discharge measuring equipment should be watertight.

3.2.9 INSTALLING WATER LEVEL MEASURING EQUIPMENT

Water level measurement inside the pumping borehole as well as the identified observation boreholes can be done with the aid of pressure probes and data loggers. This must be decided before the start of the pumping tests and the specifications of the equipment should be described in the contract. The contractor will be responsible to supply the equipment.

The pressure probes with an acceptable accuracy and sufficient cable length is lowered into the pumping as well as observation boreholes. The position of the pressure probe in the pumping borehole must be such that the pumping activity does not interfere with the accuracy of measurement. Turbulence caused by the pumping activity should not affect the readings produced by the pressure probe. To ensure that this does not happen the pressure probe should be installed at least two meters above the pump. The pressure probe must also be installed deep enough so that the water level during pumping does not reach it. This also applies for the pressure probes in the observation boreholes.

The range of a pressure probe determines the accuracy of the probe. The higher the range the less the accuracy. A probe with a ten-meter range has got an accuracy of 1 centimeter over the full range, an acceptable accuracy in the industry (Hobbs and Marais, 1997). But sometimes the drawdown during pumping is more than ten meters. This means that the pressure probe will not be able to measure the total drawdown. However there is a way around this limitation. The probe can be set up so that it will be able to measure the first ten meters of drawdown. During the pumping test the probe can be lowered another ten meters to measure the rest of the drawdown. If necessary the probe can be lowered even more, provided that a sufficient length of cable is available. By doing this the probe can be utilized to measure the total drawdown to an acceptable accuracy. This technique also applies for the pressure probes in the observation boreholes, although the drawdown in the observation boreholes is normally not that dramatic. With a simple adjustment to the data it will represent the actual drawdown picture.

The drawdown measured with the pressure probe during a pumping test is stored on a data logger. The contractor must now attach the pressure probe to a data logger. The data logger converts the electronic signal from the pressure probe to a height of pressure above the pressure probe. Normally a multi channel data logger is used and therefor several pressure probes can be attached to one data logger. The data logger should be placed centrally on the test site so that all the pressure probes can be connected to it. The data logger can be set up so that the water levels are stored at specified intervals. These intervals should be negotiated with the consultant before the commencement of the pumping test. A laptop computer or data reader can be used to extract the data from the data logger.

These data logging systems normally work on a 12 volt power supply. The power can either be supplied from a 220 volt system brought down with a transformer or a solar panel and regulator and in some cases a 12 volt battery is sufficient. The battery must be capable of keeping the system going for the duration of the test. The contractor is responsible to supply the power for the water measuring equipment. Now the system is operational and it should be set up properly.

3.2.10 DETERMINING REST OR STATIC WATER LEVEL

Before the contractor can set up the data logging equipment or start with the pumping test, rest or static water level measurements must be taken inside the pumping and observation boreholes. Installing the pump and the pressure probe in the pumping borehole has the same effect as a slug during a slug test. The static water level inside the borehole will rise, causing a pressure gradient. The water level will return to its original level with time, but it is good practice to check it against the original static water level taken for the slug test. A dipmeter is used to measure the distance from the collar of the borehole to the water level. This is known as the static or rest water level. The water levels in all the boreholes are measured and recorded on the data sheets. With this information each channel on the data logger can be set up properly.

3.2.11 SETTING UP THE DATA LOGGING EQUIPMENT

The data logger should be powered and the reading on the display should be taken. If the range of the pressure probe is ten meters the probe should be lowered into the water so that a reading of close to ten meters is obtained. The pressure probe should now be fixed to the collar of the borehole in such a way that it remain stationary at the same level for the duration of the test, except if the contractor lowers it to measure more drawdown. The pressure probe can be checked by powering the data logger and by pulling it up out of the water. The reading on the data logger should change when this happens. This procedure must be followed for every pressure probe that is installed. The borehole numbers must be entered into the correct channel of the data logger. For example if the number allocated to the pumping borehole is UO5 and the pressure probe from this borehole is connected to the first channel on the data logger, then the number UO5 should be entered for channel one. In order to prevent confusion the logging channel for every borehole should be noted on the data sheets. A data reset should be done on the data logger to get rid of all previously recorded data. The data logger should be allowed to register for a few minutes before the commencement of the pumping test. This will establish a definite reference line on the data logger. Now the data logging equipment is set up properly and the contractor can start with the actual testing.

3.2.12 CALIBRATION TEST

The contractor can now continue with the actual pumping test, but the pumping rate at which the test must be conducted is still unknown. In some instances the abstraction rate for the pumping test can be prescribed as part of the contract and then this pumping rate will be used. But sometimes this is not the case. The contractor must try to determine the optimum rate at which the pumping test should be done so that the yield potential of the borehole can be determined and the productivity of the aquifer can be evaluated. The abstraction rate should allow the contractor to gather the maximum amount of information about the borehole as well as the aquifer supplying the water to the borehole. During a pumping test the maximum amount of drawdown in the borehole should be achieved so that the parameters and characteristics of the borehole over the whole depth of the borehole can be determined.

If too low a pumping rate is used no strain will be placed on the aquifer and shortcomings or constraints might not be picked up. If the pumping rate is too high the water level inside the borehole will drop rapidly and it will reach the pump intake before the true characteristics of the borehole as well as the aquifer can be assessed.

To determine the optimum pumping rate the contractor will do a calibration test on the borehole. Water is pumped from the borehole at three or more different pumping rates over short sequential periods of time (Hobbs and Marais, 1997). Normally the pumping period for the calibration test is 15 minutes. The response of the water level to each known pumping rate is measured and recorded as per prescribed time schedule ***(Table 3.2)***. A complete calibration test data sheet will be provided in ***Appendix C***. The calibration test provides a means of assessing the yield potential of the borehole according to the magnitude of the water level decline associated with each pumping rate. From this information the correct pumping rates for a stepped drawdown test as well as a constant rate pumping test can be decided.

Time (minutes)	Drawdown (meters)
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	

Table 3.2: Time schedule for calibration test

To perform the actual calibration test the pump test contractor must do the folowing:

- ☐ Insert the dipmeter into the borehole or the plastic tube inside the borehole and determine the static water level. Record the information on the data sheets.
- ☐ If no plastic tube is installed, insert the dipmeter into the borehole and determine the static water level.
- ☐ Make sure that the stopwatch is zeroed and working properly.
- ☐ Make sure that the data logger had been reset and that it is working properly.
- ☐ See to it that the equipment to measure the discharge from the pump is in place and that it is ready.

- ☐ Make sure that the capacity of the pump is known. Strain the pump so that about one third of the capacity will be discharged during the first run of the test.

- ☐ Start the pump.

- ☐ Measure the drawdown in the pumping borehole with the dipmeter as per the above prescribed time intervals.

- ☐ Measure the discharge from the pump at the beginning as well as at the end of the first run of the test.

- ☐ Stop the pump after the prescribed time has passed.

- ☐ Measure the recovery in the borehole as per the prescribed time intervals.

- ☐ Allow the water level to recover to more than ninety percent of the original static water level.

- ☐ Repeat the test for two-thirds as well as full capacity of the pump.

- ☐ Using this information the contractor must decide which pumping rates to use for the stepped drawdown as well as the constant rate tests.

The chart below ***(Fig. 3.1)*** is an example of a calibration test done prior to a pumping test. From this figure it is clear that the drawdown of about 10 meters obtained in 15 minutes with the full pumping rate was much to high and this would have caused the water level to drop below the pump intake within a few hours. The second and third pumping rates produced drawdowns of between three and five meters and because of this a pumping rate of 3600 l/h was chosen for this particular pumping test.

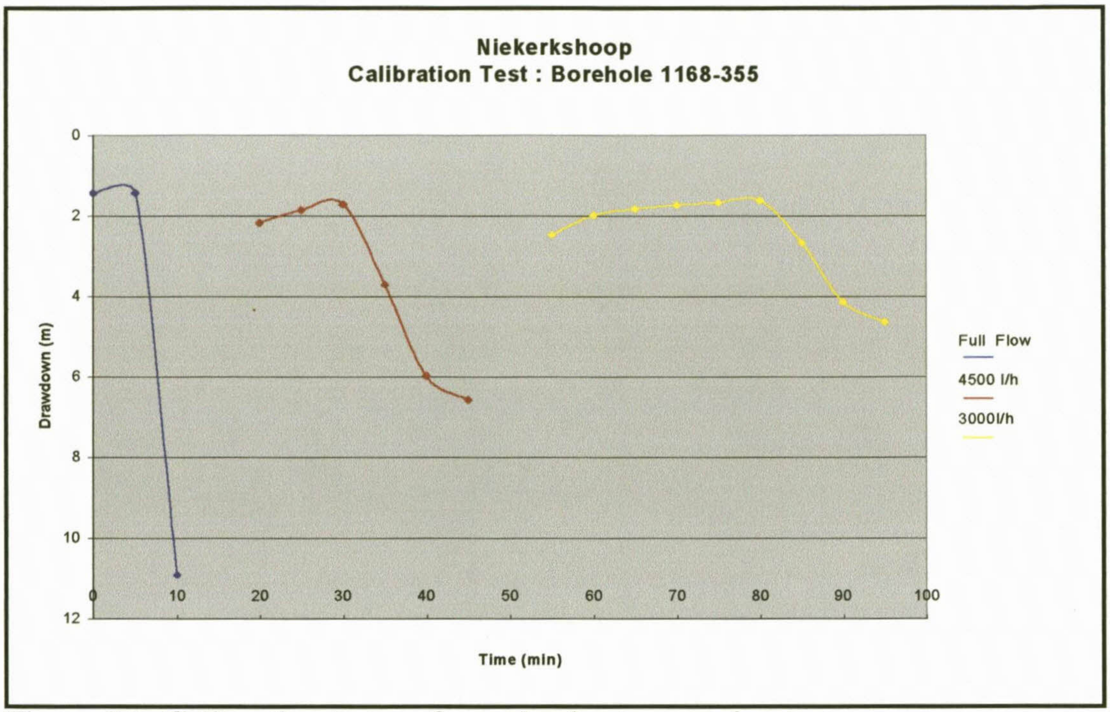


Figure 3.1: Calibration test performed prior to pumping test

3.2.13 STEPPED DISCHARGE OR STEPPED DRAWDOWN TEST

The stepped drawdown test is a single-well test and it is performed to evaluate the productivity of a borehole. It also gives an indication of the optimum yield at which the borehole can be subjected to constant discharge testing if required. The results of a stepped drawdown test will indicate whether further pump testing in the form of a constant discharge test is warranted or whether the borehole is judged to be sufficiently weak (potential yield less than 0.5 l/s) to make a utilization recommendation without further testing. If the result of the stepped discharge test is positive, then a constant rate pumping test must be performed.

In performing a stepped discharge test the borehole is subjected to three or more sequentially higher pumping rates, which is maintained for an equal length of time (Kruseman and De Ridder, 1990; Hobbs and Marais, 1997). The test is done by pumping the borehole at a low constant discharge rate until the drawdown stabilizes. The constant discharge rate is then increased and the borehole is pumped until the drawdown stabilizes again. The pumping rate is then increased again and the process is repeated. The time per pumping rate should be between 60 and 120 minutes. A step length of 100 minutes is recommended for the test. The drawdown in the borehole in response to each of the pumping rates must be measured and recorded in accordance with a prescribed time schedule.

The time schedule for a drawdown as well as a recovery step is given in the table ***(Table 3.3)*** below. A complete stepped drawdown data sheet will be supplied in ***Appendix C.*** The actual pumping rate maintained during each step of the test should also be measured and recorded. At the end of the pumping steps the recovery inside the borehole should also be measured for the same period (if pumping lasted for 300 minutes, then recovery should be measured for 300 minutes).

Time	**Drawdown**	**Time**	**Recovery**
(minutes)	**(meters)**	**(minutes)**	**(meters)**
1		1	
2		2	
3		3	
4		4	
5		5	
6		6	
7		7	
8		8	
9		9	
10		10	
11		11	
12		12	
13		13	
14		14	
15		15	
16		16	
17		17	
18		18	
19		19	

20		20	
30		30	
40		40	
50		50	
60		60	
70		70	
80		80	
90		90	
100		100	
110		110	
120		120	
		150	

Table 3.3: Time schedule for each step of stepped drawdown test

To perform the actual stepped drawdown test the pump test contractor must do the following:

- Insert the dipmeter into the plastic tube inside the pumping borehole and determine the static water level. Record the information on the data sheets.

- If no plastic tube is installed, insert the dipmeter into the borehole and determine the static water level.

- Make sure that the stopwatch is zeroed and working properly.

- Make sure that the data logger had been reset and that it is working properly.

- In order to determine parameters such as effective radius of the borehole and storativity of the aquifer the contractor must take water level readings in the observation boreholes. Therefor make sure that measurements are taken in the observation boreholes at the prescribed times.

- See to it that the equipment to measure the discharge from the pump is in place and that it is ready.

- By using information from the slug as well as the calibration tests, work out what the different steps (abstraction rates) for the stepped drawdown test must be. Set the pumping rate on the pump so that a low first constant discharge rate increment will be delivered.

- Start the pump.

- Measure the drawdown in the pumping borehole with the dipmeter as per the prescribed time intervals. Record this information on the data sheets.

- Measure the discharge from the pump at the beginning of the discharge increment. After that check the discharge after 7, 15 and 60 minutes. Then take a final reading just before the end of the step.

- After about 10 minutes into the test take a water sample. The borehole number, date and time must be indicated on the bottle. Take another sample just before pumping is stopped.

- By now the drawdown will have stabilized and the chosen time interval (say 100 minutes) will have passed.

- After the prescribed time increase the delivery of the pump to the second constant discharge rate increment.

- Measure the second constant discharge rate increment from the pump. Check the discharge at the same intervals as prescribed above.

- Measure the drawdown at the prescribed time intervals. The drawdown will eventually stabilize.

- Increase the discharge rate to the third constant rate increment after the prescribed time. Follow the same procedure as described above.
- Just before the pump is stopped, take another water sample.
- After the prescribed time stop the pump and start the recovery. Measure and record the recovery.
- Allow the water level to recover for the same period of time as the length of pumping.

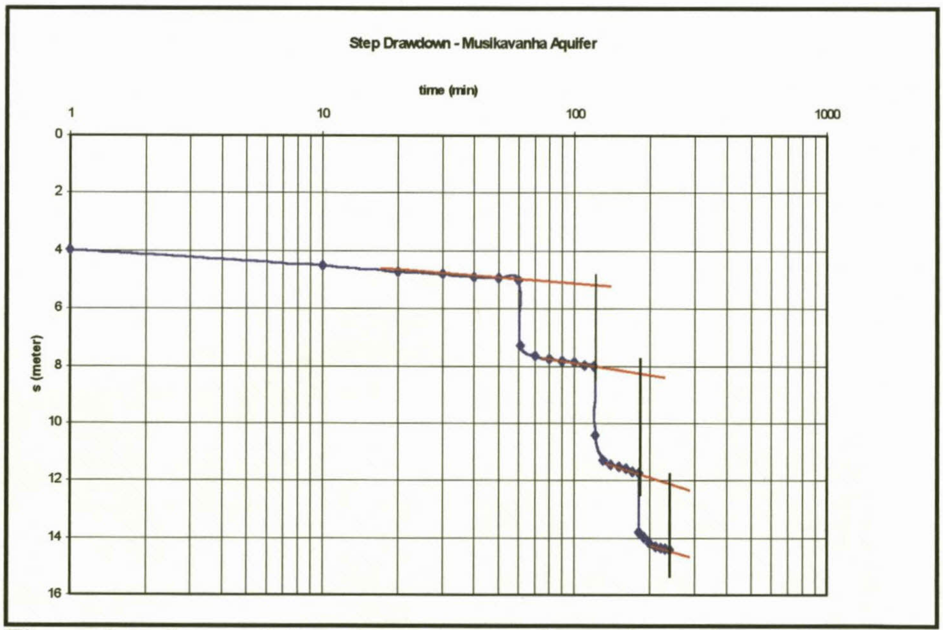


Figure 3.2: Stepped drawdown test performed on a borehole

The chart above ***(Fig. 3.2)*** is an example of a stepped drawdown test performed on a borehole. The effect on the water level with the increased pumping rate can clearly be seen.

It should be noted that later on in this thesis ***(Chapter 7)*** a revised step drawdown test with random time intervals per pumping rate would be proposed. Usually equal time increments are selected for a stepped drawdown test, but in the proposed test, equal time increments are not important. Start with a very low pumping rate and increase the abstraction rate after any time (e.g. 5 minutes, 15 minutes, 40 minutes or 50 minutes).

3.2.14 MULTI RATE TEST

This test is very similar to the stepped drawdown test, but there are some differences in the method of performing the test. This test will indicate whether further pumping tests is warranted or whether the borehole is judged to be sufficiently weak to make utilization recommendations without further testing. This test will give an indication of whether the borehole is well developed or not. With this method the borehole efficiencies for the different abstraction rates can be determined. The main difference between this test and the stepped discharge test is that in determining the drawdown values (s), no extrapolation is necessary, this means that no guesswork takes place. The pumping rates may also be increased as well as decreased during the test, something not possible during the stepped discharge test. Additional transmissivity and storativity values can also be obtained while doing this test, also not possible with the stepped discharge test.

In performing a multi rate test the borehole is subjected to three or more sequentially higher pumping rates, which is maintained for an equal length of time (Hobbs and Marais, 1997). A complete multi rate pumping test data sheet will be supplied in ***Appendix C***. The test is done by pumping the borehole at about one third of the expected operational yield of the borehole. After a certain time pumping is stopped and recovery takes place. After recovery increase the pumping rate to approximately two thirds of the expected operational yield and pump the borehole for the same time interval as in the first case. Recover again after pumping. Repeat the procedure for a pumping rate equal to that of the expected operational yield of the borehole. Increase the pumping rate to approximately 1.25 or 1.5 the expected operational yield of the borehole and repeat the procedure. A step length of 60 minutes is recommended for the length of the pumping times. The drawdown in the borehole in response to each of the pumping rates must be measured and recorded in accordance with a prescribed time schedule.

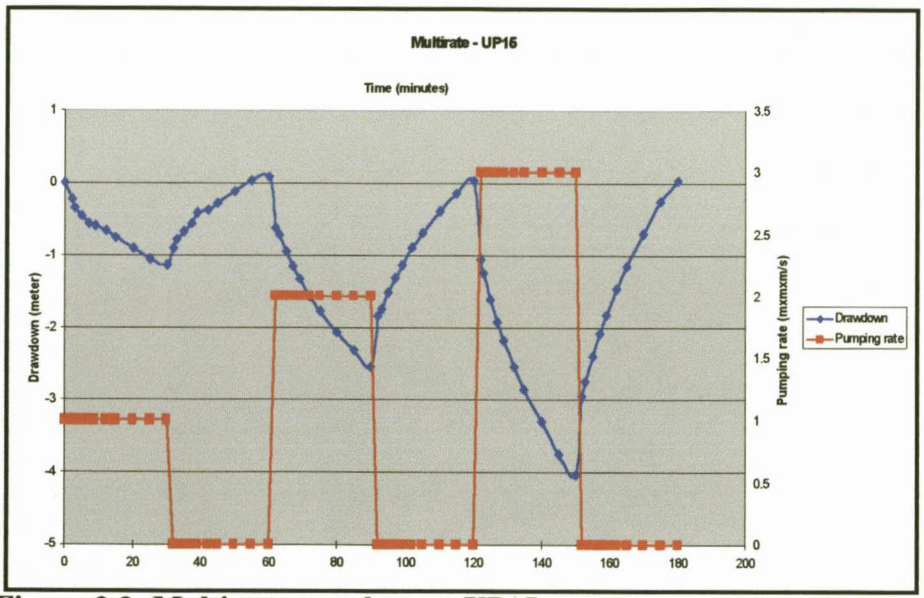


Figure 3.3: Multi rate test done at UP15

The chart above *(Fig. 3.3)* is an example of a multi rate test done on the campus test pumping terrain at the university. The blue line represents the drawdown in the borehole while the red line indicates the pumping rates.

To perform the actual multi rate test the contractor must do the following:

- ☐ Insert the dipmeter into the plastic tube inside the pumping borehole and determine the static water level. Record the information on the data sheets.
- ☐ If no plastic tube is installed, insert the dipmeter into the borehole and determine the static water level.
- ☐ Make sure that the stopwatch is zeroed and working properly.
- ☐ Make sure that the data logger had been reset and that it is working properly.
- ☐ In order to determine parameters such as the transmissivity and storativity of the aquifer the contractor must take water level readings in the observation boreholes. Therefor make sure that measurements are taken in the observation boreholes at the prescribed times.

- See to it that the equipment to measure the discharge from the pump is in place and that it is ready.

- By using information from the slug as well as the calibration tests work out what the expected operational yield of the borehole will be. For the first step in the multi rate test the pumping rate should be approximately one third of the expected operational yield. Set the pump so that this discharge rate increment will be delivered.

- Start the pump.

- Measure the drawdown in the pumping as well as the observation boreholes with the dipmeter as per the prescribed time intervals. Record this information on the data sheets.

- Measure the discharge from the pump at the beginning of the discharge increment. After that check the discharge after 7, 15 and 60 minutes.

- After about 10 minutes take a water sample. The borehole number, date and time should be indicated on the bottle.

- After the prescribed time stop the pump and measure the recovery. Recovery must be measured for the same time interval as used for pumping.

- Increase the pumping rate to approximately two thirds of the expected operational yield of the borehole and proceed with the pumping for the same time interval as in the first instance. Check the discharge at the same intervals as prescribed above.

- Measure the drawdown at the prescribed time intervals. Remember to measure the drawdown in the observation boreholes as well.

- For the third interval increase the discharge rate to approximately the expected operational yield of the borehole. Repeat the procedure and after the prescribed time stop the pump. Measure the recovery again.

- Take another water sample.

- For the next interval increase the discharge rate to approximately 1.25 or 1.5 the expected operational yield of the borehole. Repeat the procedure and after the prescribed time stop the pump. Measure the recovery again. During this increment care should be taken that the water level does not reach the intake of the pump.

3.2.15 CONSTANT RATE TEST

This test is performed to assess the productivity of the aquifer according to its response to the abstraction of water. This response can be analyzed to provide information with regard to the hydraulic properties of the groundwater system. With this information the optimum yield for the long and medium term utilization of the borehole can be determined.

A constant rate pumping test is performed by pumping water from a borehole at a single pumping rate which is kept constant for an extended period of time (Kruseman and De Ridder, 1990; Hobbs and Marais, 1997). It is critical that the pumping rate during the entire duration of the test be kept as constant as possible. The pumping rate should be set at a yield, which can be maintained for the duration of the pumping test, and in the process utilize more than 70 percent of the available drawdown. The available drawdown however should not be exhausted. The drawdown in water level in the borehole as well as the observation boreholes is measured according to the prescribed time schedule. Before starting with the constant rate pumping test the borehole should be allowed to recover completely from the stepped discharge or multi rate tests. If the borehole is recovered over night, the water level will return to within a few centimeters of the original water level.

The actual pumping rate maintained during the test should be measured and recorded regularly. The pumping rate must be checked and adjusted if necessary after 7, 15, 60, 120 and 180 minutes. From then on the pumping rate should be checked whenever the water level measurements are taken. At the end of the constant rate test the recovery inside the borehole should be measured.

The time schedule for a constant rate test is given in the table ***(Table 3.4)*** below. A complete constant rate data sheet will be supplied in ***Appendix C***.

Time (minutes)	Time (minutes)	Time (minutes)	Time (minutes)	Time (minutes)
1	11	25	240 (4h)	1800 (30h)
2	12	30	300 (5h)	2160 (36h)
3	13	40	360 (6h)	2520 (42h)
4	14	50	420 (7h)	2880 (48h)
5	15	60	480 (8h)	3600 (60h)
6	16	75	600 (10h)	4320 (72h)
7	17	90	720 (12h)	
8	18	120	900 (15h)	
9	19	150	1080 (18h)	
10	20	180 (3h)	1440 (24h)	

Table 3.4: Constant rate test prescribed time schedule

To perform the actual constant rate pumping test the contractor must do the following:

- Insert the dipmeter into the plastic tube inside the pumping borehole and determine the static water level. Record the information on the data sheets.

- If no plastic tube is installed, insert the dipmeter into the borehole and determine the static water level.

- Make sure that the stopwatch is zeroed and working properly.

- Make sure that the data logger had been reset and that it is working properly.

- In order to determine parameters such as the transmissivity and storativity of the aquifer the contractor must take water level readings in the observation boreholes. Therefor make sure that measurements are taken in the observation boreholes at the prescribed times.

- See to it that the equipment to measure the discharge from the pump is in place and that it is ready.

- By using information from the slug, calibration, stepped discharge and multi rate tests work out what the pumping rate for the constant rate pumping test should be. The pumping rate should be such that the water level inside the borehole does not drop to below the intake of the pump at any time during the pumping test. Strain the pump so that this desired discharge would be delivered by the pump.

- Start the pump.

- Measure the drawdown in the pumping as well as the observation boreholes with the dipmeter as per the prescribed time intervals. Record this information on the data sheets.

- Measure the discharge rate from the pump at the beginning of the test. After that check the discharge after 7, 15, 60, 120 and 180 minutes. From then on the pumping rate should be checked whenever the water level measurements are taken.

- A water sample must be taken after about 10 minutes of pumping and another one just before the end of the test. The borehole number, date and time must be indicated on the sample bottle.

- After the prescribed time, stop the pump and measure the recovery. Recovery must be measured for the same time interval as used for pumping.

The chart below ***(Fig. 3.4)*** is an example of a constant rate test that was done on borehole UO5 on the campus test site. It can clearly be seen that there was a rapid drawdown at the beginning of the test and that it decreased towards the end of the test.

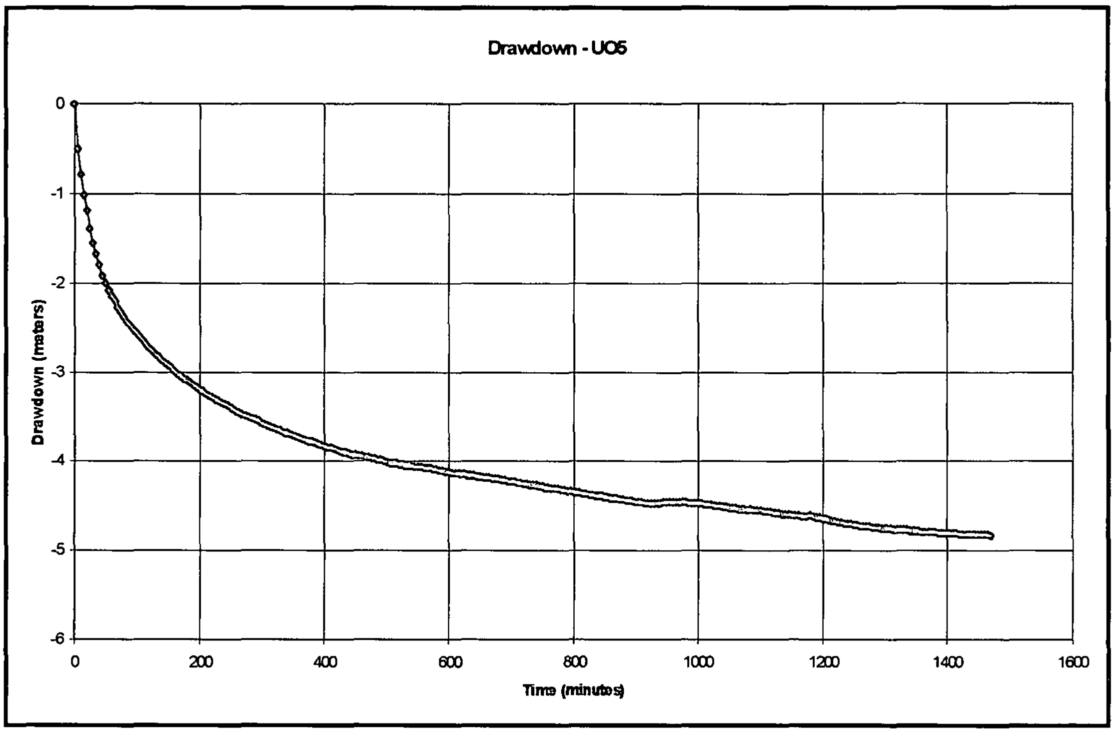


Figure 3.4: Constant rate pumping test done on UO5

3.2.16 RECOVERY TEST

When the pump is shut down the water levels in the pumping borehole as well as the observation boreholes will start to rise. It is very important to measure the recovery because parameters such as the transmissivity of the aquifer can be determined by using the recovery data (Kruseman and De Ridder, 1990; Hobbs and Marais, 1997). This will act as an independent check on the results obtained with the pumping test and at a fraction of the cost of the pumping test.

In some instances recovery data is more reliable than pumping test data because the recovery takes place at a constant rate whereas constant discharge during pumping is sometimes very difficult to obtain in the field. By making use of the information gathered with a recovery test the number of hours that a borehole should be pumped at a tested rate, can be determined.

The recovery of the water level should be measured for a period equal to the duration of the constant rate pumping test or until the water level has recovered fully, whichever occurs first. Water level measurements should be taken at the same intervals as during the constant rate pumping test.

The chart below ***(Fig. 3.5)*** is an example of a recovery test that was performed on borehole UO5 on the campus test site. The last section of the chart represents the recovery test.

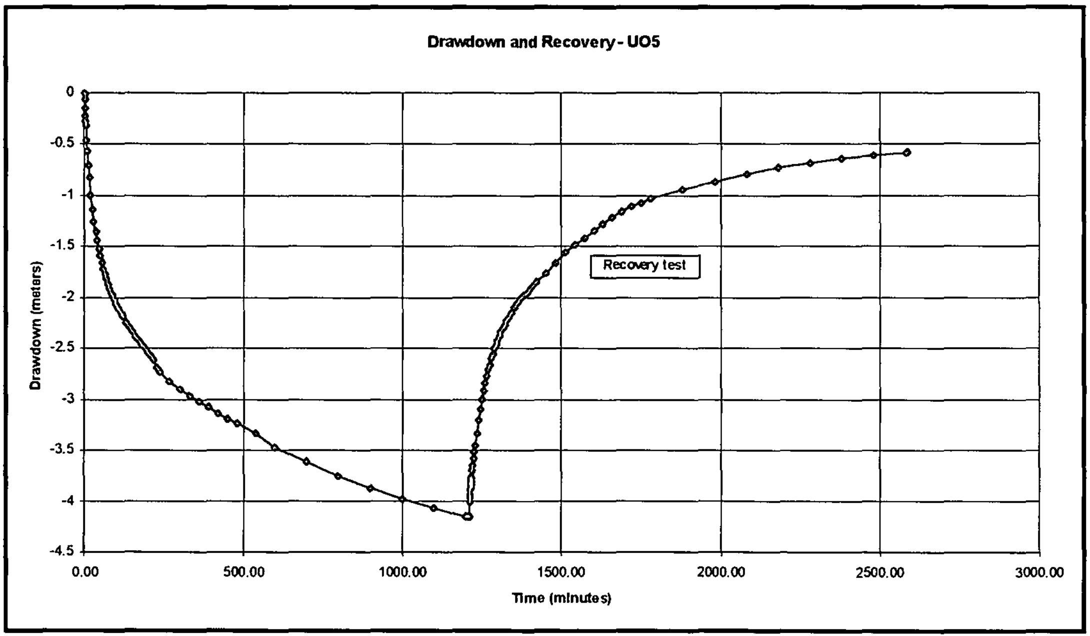


Figure 3.5: Recovery test on UO5

3.2.17 DURATION OF THE CONSTANT RATE PUMPING TEST

The duration of a pumping test is determined by the importance attached to the borehole that is being tested. The period of pump testing also depends on the type of aquifer that is being tested as well as the degree of accuracy desired in establishing the hydraulic characteristics of the borehole and aquifer. According to Kruseman and De Ridder, (1990), shortening the length of the pumping test to save money is not recommended because the cost of running a pumping test a few hours longer is low compared with the total cost of the pumping test.

Better and more reliable data are obtained if pumping continues until steady or pseudo-steady flow has been attained. At the beginning of the pumping test the cone of depression develops rapidly because the pumped water is initially abstracted from the aquifer storage immediately around the borehole. But as pumping continues the cone of depression expands and the gradient becomes less. More water becomes available from the aquifer as the cone of depression expands from the borehole. In some boreholes a steady state or equilibrium occurs within a few hours, while in others pumping must continue for days before a steady state is achieved. In some cases a steady state is never achieved, even if pumping continues for years. If a steady state has been achieved, simple equations can be used to analyze the data and reliable results regarding the aquifer can be obtained.

The duration of the constant rate pumping test shall not be less than 12 hours and in some instances it might even last for 72 hours or more (Hobbs and Marais, 1997). This criterion is set according to the Reconstruction and Development Program rules of South Africa. According to the South African Bureau of Standards code of practice on the Development, Maintenance and Management of Groundwater Resources (SABS 0299-4:1998 Part 4: Test-pumping of water boreholes) the duration of a constant rate pumping test must be:

- 48 hours for a low yielding borehole if water is to be supplied to a town or village
- 72 hours for a high yielding or main borehole if water is to be supplied to a town or village
- 48 hours if the borehole is to be fitted with an engine driven pump to supply water to a rural village
- 48 hours or more if the water is to be used for irrigation with a high cost consequence if failure occurs.

Another rule of thumb is to run a constant rate pumping test for a minimum length of eight hours when the borehole is to be fitted with a hand, solar or wind driven pump.

The test should last for at least forty-eight hours when the borehole is to be equipped with an electrical or diesel driven pump, which is to be operated on a daily basis.

A good practice is to, while the pumping test is in progress, plot the water levels obtained during a constant rate pumping test on semi-log paper (the time is plotted on the logarithmic scale). If considerable changes in the gradient of the curve are noticed, it may be considered to extend the duration of the test. From this additional information the new gradient can be established, from which new parameters can be determined. In many circles the duration of constant rate pumping tests remains a controversial issue. Different opinions exist about this issue and it will be investigated and discussed in more detail later in this thesis. Continued pumping without achieving significant drawdown does not make any sense. In order to be cost effective, the pump test contractor should not just continue with a constant rate pumping test for several hours without obtaining information that makes sense. To specify the duration of a constant rate pumping test beforehand therefor is not acceptable.

3.3 ABORTING TESTING

It is inevitable that in some instances pumping tests will be interrupted. These interruptions might be planned or in some cases it might be due to breakdowns or other problems.

If the data collected during a pumping test is evaluated during the test and it is found that sufficient information had been collected for an adequate scientific evaluation thereof, the consultant can order the pumping test contractor to stop with the test.

If the pumping test is not performed according to the prescribed criteria as set out before in the contract, the consultant can order the pumping test contractor to stop the test and to do the test over. In this case the pumping test contractor should allow the water level in the borehole to recover to the original rest water level or to within five percent thereof. Then the next attempt to do the pumping test can start.

During a pumping test pumping can be interrupted due to mechanical failure or breakdowns. If something like this takes place there are certain steps that needs to be taken to correct the situation. For each of the different pumping tests there is a different procedure that needs to be followed (Hobbs and Marais, 1997).

3.3.1 ABORTING CALIBRATION TEST

After the stoppage or breakdown in the test start to record the recovery of the water level as per the prescribed time intervals. The water level must be recovered to the initial or rest water level or to a level within five percent of the initial water level. Fix the breakdown and then start the calibration test over again. Do not take the information gathered prior to the breakdown into account, but start the test as if it is the first attempt.

3.3.2 ABORTING STEPPED DISCHARGE TEST

After the stoppage or breakdown record the time and start to measure the recovery at the prescribed time intervals. If the breakdown occurred during the first or second step of the stepped discharge test, recover the borehole to the initial water level or to within five percent thereof. After the recovery restart the stepped discharge test as if is the first attempt at the test. If the breakdown occurs during the third step of the stepped discharge test, and the stoppage can be fixed within five minutes, continue at the same pumping rate prior to the breakdown and finish the test. Only one breakdown like this is allowed.

If a second breakdown occurs during the test, proceed as described for the first step breakdown, recover and restart the test from the beginning after the recovery. If the breakdown occurs during the fourth step of the test, proceed in the same manner as a breakdown in the third step. If the breakdown at this stage can not be fixed within five minutes, continue and measure the recovery as per the prescribed time intervals as if the test had been fully completed.

3.3.3 ABORTING MULTI RATE TEST

If the breakdown occurs during the first step of the multi rate test, recover as prescribed and restart the test as if it is the first time. If the breakdown occurs during the next steps of the test, recover to the initial water level and do the step over as if has not been performed before.

3.3.4 ABORTING CONSTANT RATE PUMPING TEST

Note the time at which the breakdown occurred and start the recovery of the water level as per the prescribed time. If the breakdown occurred within two hours after the test was started, fully recover or recover to within five percent of the initial water level and restart the test over again.

If the breakdown occurs later than two hours into the test and the breakdown can be fixed within the time spans given in the table below ***(Table 3.5)***, continue with the test at the same pumping rate as before the breakdown.

TIME BREAKDOWN OCCURRED	PERIOD ALLOWED FOR REPAIR
2 – 4 hours	6 minutes
4 – 6 hours	12 minutes
6 – 8 hours	18 minutes
8 – 10 hours	24 minutes
10 – 12 hours	30 minutes
12 – 14 hours	36 minutes
14 – 16 hours	42 minutes
16 – 18 hours	48 minutes
18 – 20 hours	54 minutes
Longer than 20 hours	60 minutes

Table 3.5: Period allowed for breakdown and continuation of testing

If the breakdown can not be fixed and if the pump cannot be started within one hour of the breakdown occurring, recover the water level to the initial water level or within five percent thereof. Then restart the pumping test as if it is the first attempt. If the breakdown occurs after approximately 80 percent of the planned duration of the constant rate test, continue with the recovery as per prescribed time intervals. The elapsed time allowed with regard to selected constant rate test durations in order for this specification to be acceptable is given in the table below ***(Table 3.6).***

CONSTANT RATE TEST DURATION	ALLOWABLE TIME ELAPSED
24 hours	20 hours (80 % of total time)
36 hours	30 hours (83 % of total time)
48 hours	38 hours (79 % of total time)
72 hours	60 hours (77 % of total time)

Table 3.6: Period after which constant rate test can be considered completed

3.4 OTHER IMPORTANT MEASUREMENTS TO BE TAKEN

As much as possible information should be gathered during the pumping test because anything of importance left out during the pumping test might result in the test being a failure. At the time it might not seem important to include the information in the data sheet, but at a later stage it will be impossible to obtain that specific piece of information. A golden rule is never to guess at any information that has not been measured. The integrity of the pump test contractor might be on the line. So when in doubt, measure.

The diameters of all the boreholes, including the observation boreholes must be measured. The diameter of the pumping borehole is important when doing a slug test. The theory for slug tests was developed with information from 165-millimeter boreholes. The theory for slug tests can therefor not be used on other diameter boreholes. The diameters of boreholes are required in most of the software packages.

The distances to observation boreholes from the pumping borehole must be measured. Parameters such as storativity is distance dependent, so this information can be evaluated against the distances that observation boreholes are away from the pumping borehole. The straight-line distance should be recorded and it is recommended that the distances between the observation boreholes be measured as well.

For all the boreholes used in the pumping test the collar heights must be measured. This is the height from the ground to the top of the concrete column housing the casing of the borehole. This measurement is important because all water level measurements are taken with the concrete column as reference. This measurement allows the user to relate the information inside the borehole to ground level.

3.5 ADDITIONAL INFORMATION OF AREA

As much as possible information, how irrelevant it might seem at the time, should be collected during the pumping test. This information might come in handy at a later stage and it might even clear up uncertainties that may come out during the pumping tests. The pumping test contractor must therefor try to obtain information on the following.

3.5.1 BOUNDARIES

In practice no aquifer extends infinitely and they are bounded laterally in one way or another. At some point a boundary will start to interfere with the abstraction of water from that aquifer. A boundary may consist of a geological barrier that delineates the lateral extent of the aquifer or it may consist of a geological formation with lower permeability, or even zones within a formation of lower permeability. In some cases these boundaries may even show in the geology, protruding from the ground. The pump test contractor must keep his eyes open for these formations and he must make notes of all possible boundaries, including their distances away from the pumping borehole.

Groundwater will normally follow the natural gradient of the topography of the surface of an area. The pump test contractor should take note of the general topography of the area surrounding the borehole being pump tested. A borehole situated next to a mountain range may be influenced by that mountain range. The mountain range may act as a boundary on the aquifer. Therefor it is important that the pump test contractor make notes or even a schetch of the area showing all mountains, koppies and hills. Distances from the borehole to these protrusions should also be noted.

3.5.2 WATER ABSTRACTION

Before the pumping test is performed, all pumping activities should be stopped in the immediate area of the borehole to be tested. This should be arranged beforehand and pumping should be stopped at least 72 hours before the pumping test starts. The groundwater level should have enough time to recover to its natural static or rest water level position. The pump test contractor must make enquiry's into whether pumping activities was stopped in time for the aquifer to recover. If somebody kept on abstracting water from the aquifer within this recovery period prior to the pumping test it must be noted. The abstraction rates as well as the length of time that water was abstracted must be written down.

The pumping test contractor should also keep an eye open to see whether any pumping activity takes place during the pumping test. The pumping activities must be monitored and pumping rates as well as pumping times must be written down. This information can be used to interpret uncertainties in the drawdown curves of the pumping test.

3.5.3 RECHARGE

Although recharge due to rainfall normally has a delayed effect, all rainfall figures during the pumping test period should be written down. Normally rainfall figures are available (farmers, the public and weather bureau) and the pumping test contractor should include these figures in his report. Rainfall figures prior to the pumping test should also be acquired and it should also be included in the report.

Dams and rivers situated close to the pump testing site can cause recharge to the aquifer and it is good practice to mention this in the report that will be drawn up after the pumping test is completed.

3.5.4 IRRIGATION

All irrigation activities prior as well as during the pumping test should be written down by the pump test contractor and it should be included in the report on the pumping test. Sometimes water from an external source such as a river, dam or canal far away from the pump testing site is used for irrigation and this water can act as a recharge to the aquifer. The pumping test contractor should keep an eye open for this and it should be mentioned in his report. This external influence could have a negative effect on the results of the pumping test.

3.5.5 WATER LEVEL RESPONSE TO SEASONS

It is general knowledge that the water levels in aquifers fluctuate during the different seasons. This is caused by the time of year that recharge normally takes place as well as the amount of abstraction that takes place at different times of the year. Some farmers that make use of groundwater extensively keep record of the groundwater levels in their area. In some areas, like in the Molopo district the government monitors groundwater levels and the pump test contractor should make inquiries to obtain information in this regard. This information should be supplied in his report. This can help in determining the availability of water in the aquifer at different times of the year and this can influence the determination of the possible yield of a borehole.

3.6 PHOTOGRAPHS

A good set of photographs can yield valuable information. The results of the pumping tests performed by the contractor will in many cases be interpreted and evaluated by independent people without any knowledge of the area where the pumping test was performed. Photographs will provide these people with an idea of how the terrain and the surroundings look. Possible boundaries can also be described in a panoramic photograph image of the area.

3.7 PLOTTING POSITIONS OF BOREHOLES ON MAPS AND LOOKING AT AERIAL PHOTOGRAPHS

The pump test contractor should try to obtain a 1 : 50 000 map of the area where the pumping test is taking place. The positions of the pumping as well as the observation boreholes should be plotted on these maps. A map must be included in the report on the pumping test because a map can supply a lot of information about the area surrounding the test area. Detail on a map can include surface contours, hills, mountain ranges, access roads, rivers and boreholes.

Aerial photographs can also supply information that can help to understand the area surrounding the borehole better. A good copy of an aerial photograph with the positions of the different boreholes plotted on it should also be attached to the report of the pump test contractor.

3.8 CHECKING COORDINATES WITH GPS

A Global Positioning System should be used by the pump test contractor to determine the latitude and longitude (x and y coordinates) of all the boreholes involved in the pump testing. Although the accuracy is not similar to that of a survey, the method of determining the position is sufficient to plot the positions on the 1 : 50 000 map. Normally the height measurement (z coordinate) of a GPS is not very accurate and it should not be used in any calculations.

3.9 SURVEYS

If it is specified in the contract the contractor should make use of a land surveyor to determine the accurate latitude, longitude as well as the height of the boreholes involved in the pumping test. Sophisticated survey equipment is used to tie the boreholes in with the trig beacons with latitude, longitude and height situated in the area. The collar height of each borehole is determined and is used in calculations.

3.10 CHANGE IN WATER COLOR AND TEMPERATURE

During the pumping test the contractor should regularly look at the color of the water and any change in the watercolor should be noted (Hobbs and Marais, 1997). The time at which the change in color took place must also be written down and the contractor must describe the color that the water changed to.

Regular temperature readings should also be taken at the discharge point from the pump. The temperature readings should be logged against time and any change in temperature should be mentioned.

3.11 REMOVAL OF THE EQUIPMENT

After all the pumping tests had been conducted and satisfactory results were obtained the pumping test contractor can now start to remove his equipment from the boreholes. First the data logging equipment can be removed and after that the pumping equipment.

3.12 REINSTALLATION OF EXISTING EQUIPMENT

After the equipment of the pumping test contractor had been removed from the borehole the equipment that was removed to perform the tests can be reinstalled. All the equipment should be installed to the same condition that is was found in and the contractor should ensure that everything is in working order. The reinstallation of the equipment should be done to the satisfaction of the owner.

3.13 CLEANING UP OF THE TERRAIN

Before the pumping test contractor leaves the terrain he should make sure that the site is properly cleaned. All papers and loose material should be picked up and it should be removed. The condition of the terrain should meet the approval of the owner of the property.

3.14 EVALUATION OF THE FIELD DATA AND OTHER INFORMATION

The data that was gathered during the pumping test must now be prepared and evaluated to determine the different parameters and characteristics of the borehole and aquifer. This is normally done at the pumping test contractor's office and it is presented in the form of a report to the consultant or the owner. The evaluation of the field data from a pumping test will be discussed in detail later on in this thesis.

CHAPTER 4

DEFINITIONS AND FLOW DIAGNOSTIC INTERPRETATION

4.1 GENERAL INFORMATION

Before pump test data can be analysed, a better understanding of basic concepts, definitions and characteristics connected to specific flow regimes, will make the successful interpretation of such pumping test data a much easier task.

In this chapter the basic concepts, definitions and characteristics involved in groundwater hydraulics will also be discussed. In determining the characteristics of a specific borehole, the charts or plots of the drawdown data of the pump tests performed at the borehole can be analysed. The plots or charts include:

- ☐ First and second derivative plots of the drawdown data.
- ☐ Straight-line analysis in log-log plots.
- ☐ Straight-line analysis in semi-log plots.
- ☐ Special plots such as drawdown versus square root of time, drawdown versus fourth root of time and drawdown versus inverse square root of time.

4.2 AQUIFER TYPES

An aquifer can be defined as a saturated permeable geological unit that is permeable enough to yield economic quantities of water to boreholes. The most common aquifers in South Africa are fractured rock aquifers. They make up about ninety percent of all the aquifers in the country (Kirchner and Van Tonder, 1995).

There are mainly three types of aquifers from which water is abstracted by means of boreholes.

4.2.1 CONFINED AQUIFER

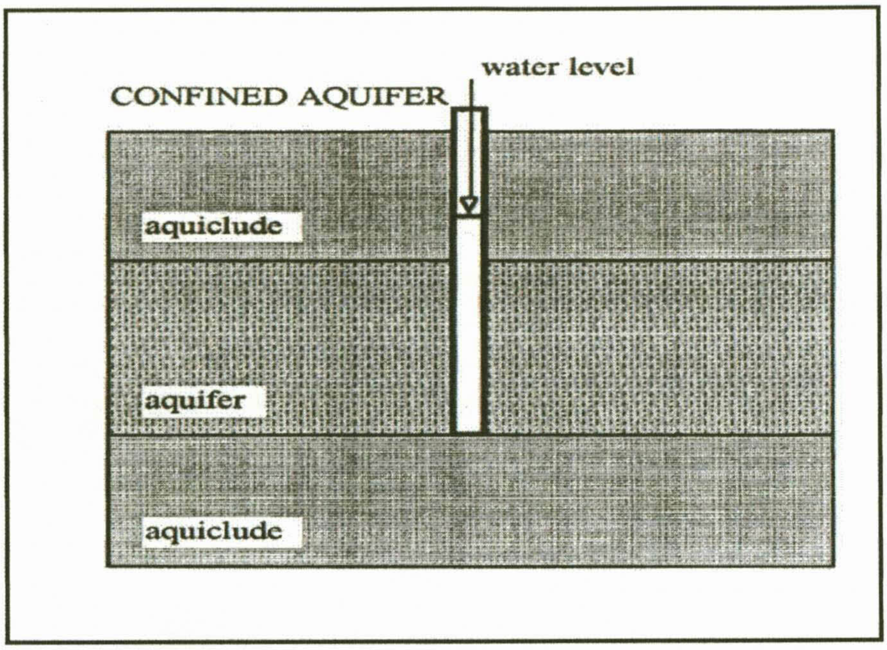


Figure 4.1: Confined aquifer

According to Kruseman and De Ridder (1990) a confined aquifer ***(Fig. 4.1)*** is bounded above and below by an aquiclude (an impermeable geological layer or unit that in theory does not transmit water at all). Dense unfractured igneous or metamorphic rocks are typical aquicludes. In practice there will be some sort of water movement, although very little. Due to the over and underlying layers in a confined aquifer the pressure of the water in the water bearing layer is usually higher than that of the atmosphere, so puncturing this layer will result in the water level rising above the aquifer.

4.2.2 UNCONFINED AQUIFER

This type of aquifer is also known as a water table aquifer ***(Fig. 4.2)*** and it is bounded by an aquiclude (an impermeable geological layer or unit that in theory does not transmit water at all) at the bottom, but it is not restricted by any confining layer at the top. The water table or static water level forms the top of the aquifer. Water inside a borehole drilled into an unconfined aquifer is at atmospheric pressure and it does not rise above the water table.

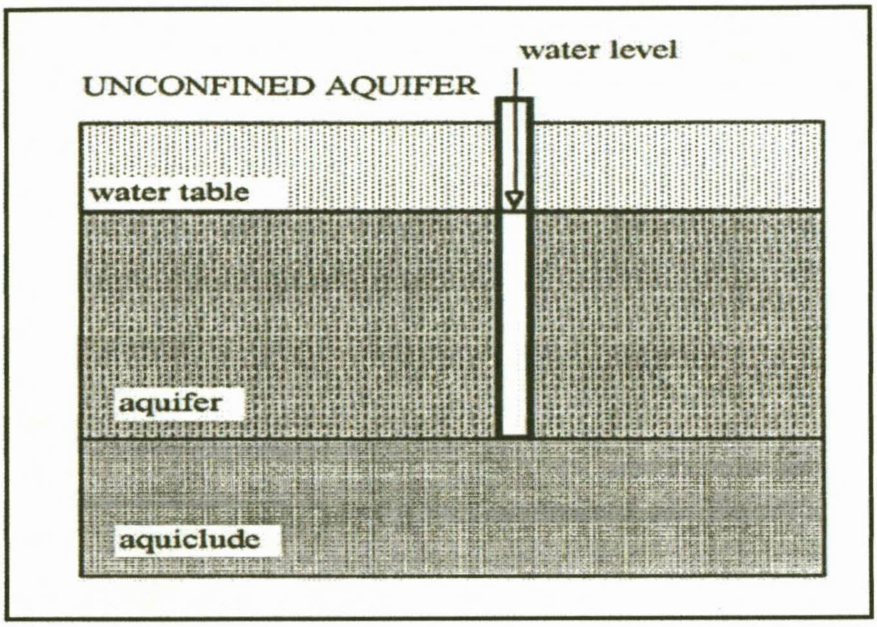


Figure 4.2: Unconfined or water table aquifer

4.2.3 SEMI-CONFINED AQUIFER

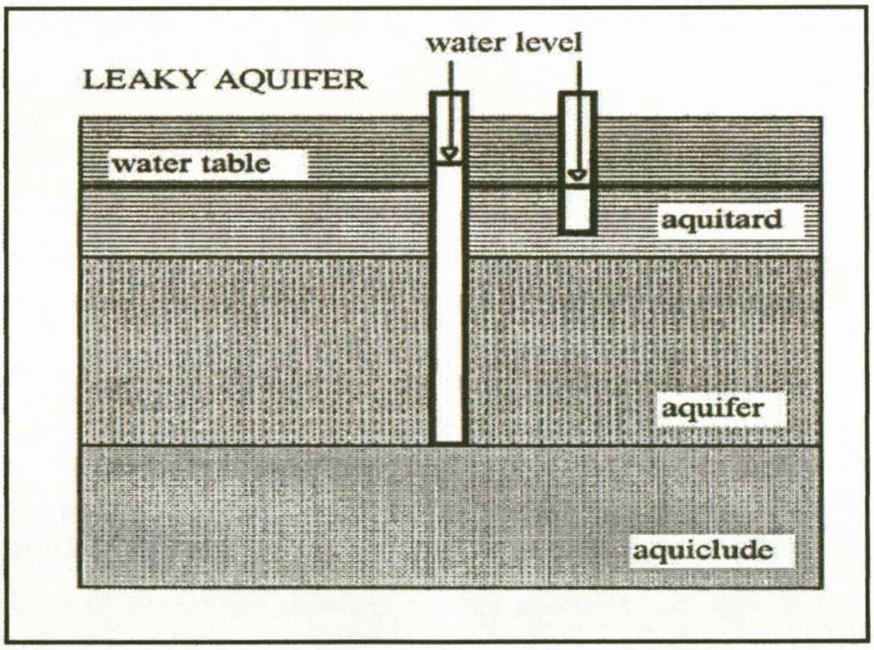


Figure 4.3: Semi-confined or leaky aquifer

A semi-confined or leaky aquifer ***(Fig. 4.3)*** is an aquifer of which the upper and lower boundaries are aquitards (a geological unit that is permeable enough to transmit water in significant quantities when viewed over large areas and long periods) or one boundary is an aquitard and one boundary is an aquiclude. Clays, loams and shales are typical aquitards. Water is free to move through the aquitards, either upward or downward. If a semi-confined aquifer is in hydrological equilibrium, water inside a borehole drilled into the aquifer may coincide with the water table. The water level may also be above or below the water table, depending on the recharge or discharge conditions (Kruseman and De Ridder, 1990).

An example of semi-confined or leaky aquifers is the Karoo aquifer, typical of South Africa. These aquifers consist of sandstone, shale and mudstone with dolorite intrusions and can be viewed as multi-layered aquifers. The top layer usually displays water table conditions while the other layers are confined or semi-confined.

4.3 BOUNDED AQUIFERS

In deriving the theoretical equations for borehole hydraulics the following assumptions were made:

- the pumped aquifer is horizontal and of uniform thickness
- the pumped aquifer is of infinite extent.

However, if an aquifer in the field is considered, it is obvious that due to the geological composition of a specific area, few aquifers are horizontal and normally they slope in one direction or another.

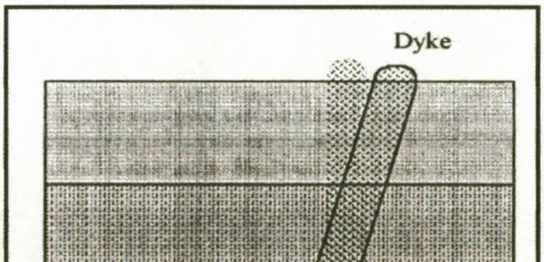


Figure 4.4: Barrier boundary

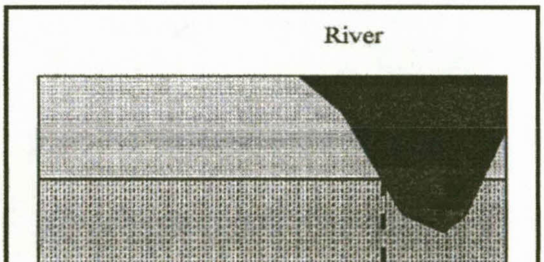


Figure 4.5: Recharge boundary

No aquifer extends to infinity because complex geological processes caused interfingering of layers and pinchouts of both aquifers and aquitards that interfere with the aquifer directly ***(Fig. 4.4)***, causing boundaries.

These boundaries can be a single impermeable layer a distance away from the borehole that can interfere with the movement of groundwater in the aquifer. In this case the effect is normally not as severe as in the case of a double or parallel boundary that has got a larger effect on the aquifer and abstraction from a borehole. In some instances an aquifer can even be surrounded by an impermeable formation and this is called a closed no flow boundary. This type of boundary has got a severe impact on the delivery from an aquifer. Later on in this chapter, when dealing with drawdown and derivative plots, the effects of the abovementioned boundaries on the aquifer and the availability of water from the aquifer will be discussed (Kruseman and De Ridder, 1990).

In some cases aquifers and aquitards are intersected by water bearing structures such as rivers, channels, estuaries or even the ocean ***(Fig. 4.5)***. In this case the structure also acts as boundaries, called recharge boundaries and in most cases this will have a positive effect on the aquifer.

All aquifers and aquitards are laterally bounded in one way or another. These boundaries affect the amount of water that is available in such an aquifer and it also influences the pattern of release of water from that aquifer.

4.4 FRACTURE SYSTEMS

With consolidated and hard rock, a distinction is usually made between primary porosity, which is present when the rock is formed, and secondary porosity which develops later as a result of solution or fracturing. The primary porosity of a dense solid rock in theory may be zero and therefor the rock matrix will be impermeable. In this case the rock may be regarded as a single-porosity system ***(Fig. 4.6 A)***.

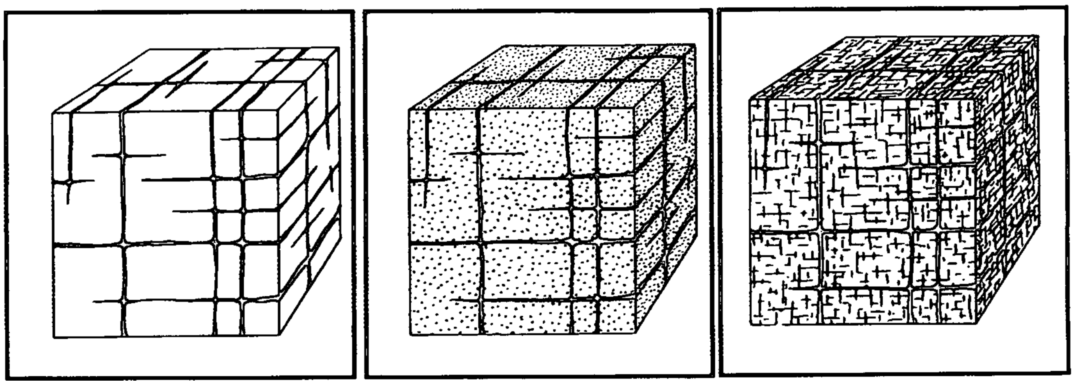


Figure 4.6 A: Single porosity B: Double porosity C: Microfissures

The primary porosity of a granular geological formation such as sandstone can be quite significant. When such a formation is fractured, it can be regarded as a double porosity system ***(Fig. 4.6 B)*** because two types of porosities exist. The primary or matrix porosity and the secondary or fracture porosity (Kruseman and De Ridder, 1990).

According to Kirchner and Van Tonder (1995), a fractured rock mass can be considered a multi-porous medium, conceptually consisting of two major components namely matrix blocks and fractures. Fractures serve as higher conductivity conduits for flow if the apertures are large enough, whereas the matrix blocks may be permeable or impermeable, with most of the storage usually contained within the matrix. In South Africa more than ninety percent of the aquifers are fractured rock aquifers. They are made up of fractures as well as matrix blocks. The figure below ***(Fig. 4.7)*** is an example of a typical fractured rock aquifer and double porosity system. The horizontal as well as vertical fractures can clearly be seen in the picture in the figure below.

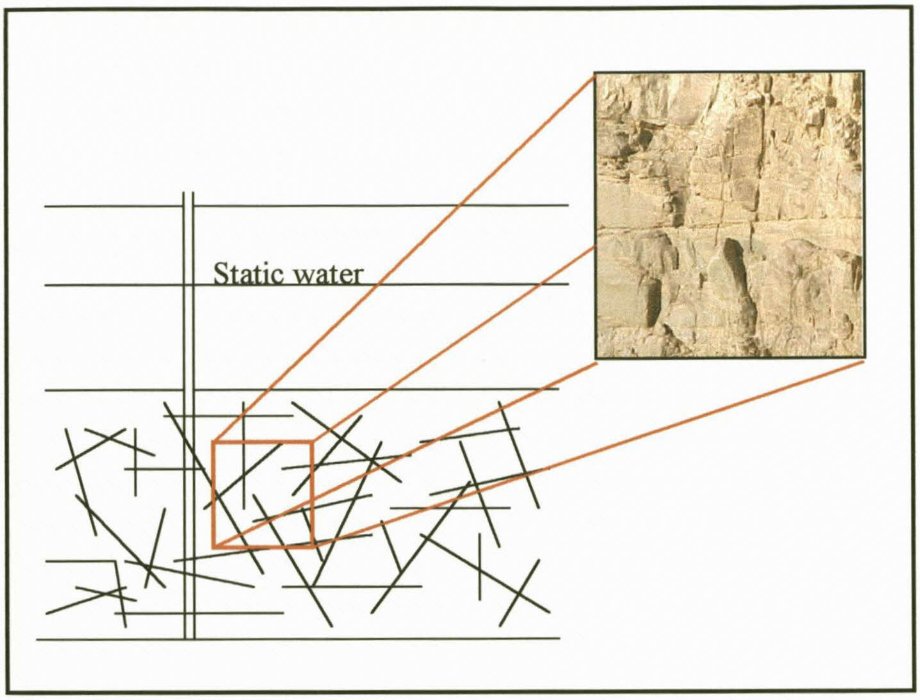


Figure 4.7: Double porosity system

In some crystalline rocks the main fractures are accompanied by a dense system of microfissures which increases the porosity of the rock matrix ***(Fig. 4.6 C)***.

4.5 ANISOTROPY AND HETEROGENEITY

According to Kruseman and De Ridder (1990) in deriving most of the borehole hydraulic equations the assumption was made that aquifers and aquitards are homogeneous and isotropic. This means that the hydraulic conductivity (K) is the same throughout the geological formation and that it is the same in all directions. The individual particles in geological formations are seldom spherical or round and when they are deposited under water they tend to settle on their flat sides. This results in the horizontal hydraulic conductivity being more than the vertical hydraulic conductivity. This phenomenon is called anisotropy ***(Fig. 4.8)***.

The composition of geological formations tends to vary significantly in the horizontal as well as the vertical direction. As a result of this these formations are very seldom homogeneous.

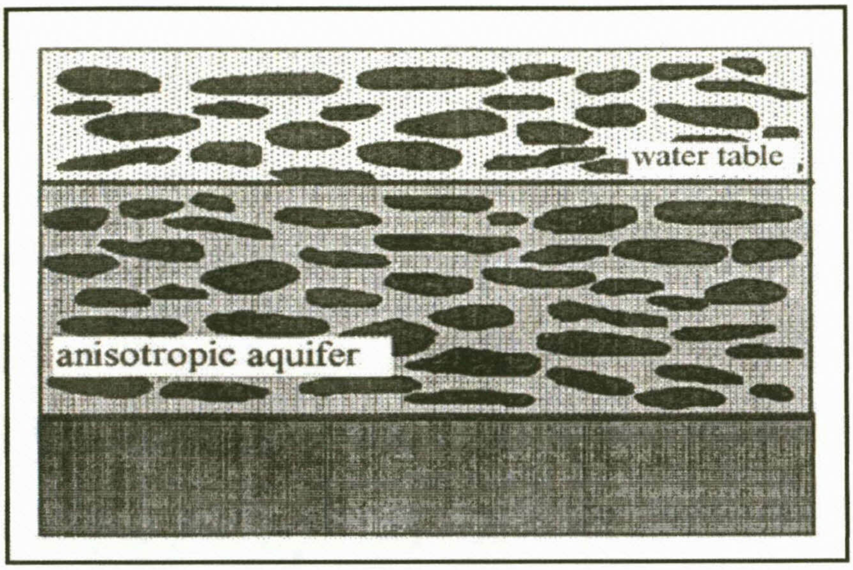


Figure 4.8: Anisotropic aquifer

4.6 STEADY AND UNSTEADY FLOW

If the water level in the pumping borehole and the surrounding piezometers does not change with time it means that steady state flow had been achieved. This flow is independent of time and it occurs when the pumped aquifer is recharged from an outside source such as a river or a reservoir. Rainfall as well as leakage from other over- or underlying aquifers can also result in steady state flow being achieved in an aquifer. Steady state flow is achieved when the change in water level becomes so small inside a borehole that it can be neglected.

As pumping from a borehole continues the water level may eventually drop, but the hydraulic gradient induced by the pumping will not change. This means that the flow towards the borehole has attained a pseudo-steady-state. This term is used for the interporosity flow from the matrix blocks to the fractures. This flow is the result of the difference between the average hydraulic head of the matrix and that of the fracture.

Unsteady state flow takes place from the moment the pump is started until steady state flow is obtained. In practice the flow inside an aquifer is unsteady as long as the changes in water level in the borehole and piezometers are measurable.

4.7 POROSITY

According to Kruseman and De Ridder (1990) the porosity (n) of a rock is its property of containing pores or voids and it can be defined as the ratio of volume of voids to the total volume. The porosity is normally expressed as a decimal fraction or as a percentage. The porosity of sandstone is between 5 and 30 percent and that of fractured crystalline rock is between 0 and 10 percent. The porosity of a fractured system is a feature that is very difficult to calculate correctly with great certainty. Porosity can be subdivided in fracture versus matrix porosity, but this is too simplistic even for double-porosity systems.

For water to move through pores they have to be interconnected. Hard rocks such as secondary dolomites may contain numerous unconnected pores in which the water is stagnant. Water in dead-end pores is also almost stagnant, so these pores are also excluded as far as porosity is concerned. Small interstices cause water to be retained in them because these retention forces are greater than the weight of the water in them. The result of the above is that not all water in a rock mass can be released and this leads to a reduction in the porosity, which is called the effective porosity. A fractured granite, for example, has a matrix porosity of 1 to 2 %, but its effective porosity is less than 1 % because the matrix itself has a very low permeability (De Marsily, 1986).

The effective porosity (kinematic porosity) has to be estimated in order to make meaningful estimates of solute travel times. Methods of the estimation of fracture porosity in the field (currently limited to pumping and tracer tests) are not yet adequate for the task of characterisation.

4.8 HYDRAULIC CONDUCTIVITY

Kruseman and De Ridder (1990) defined the hydraulic conductivity (K) as the volume of water that will move through a porous medium per unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow (m/d).

The hydraulic conductivities of a fractured systems vary considerably and are dependant on:

- density (frequency) and spacing
- aperture (distance between fracture walls)
- length of the fracture
- orientation (random or preferred)
- wall roughness (asperities, including skin factor)
- presence of filling material
- fracture connectivity
- channelling (preferred paths)
- porosity and permeability of the rock matrix.

The hydraulic conductivity and discharge of a fracture with smooth parallel walls are respectively proportional to the square and cube of the aperture, as demonstrated by the following equations:

$$K_f = \frac{\rho g b^2}{\mu\, 12} \tag{4.1}$$

and

$$Q = K_f b\, I \tag{4.2}$$

where K_f = hydraulic conductivity of fracture
Q = discharge of fracture
b = aperture
μ = dynamic viscosity
ρ = fluid density
g = gravitational acceleration
I = hydraulic gradient

Maini and Hocking (1977) give the equivalence between the hydraulic conductivity in a fractured medium and that in a porous medium. For example, the flow through a 100 meter thick cross-section of porous medium with a hydraulic conductivity of 0.0086 m/d could also come from a fracture opening not wider than 0.2 millimetre in a fractured medium with an impervious rock matrix. A porous medium with a K value of 8.6 m/d and a thickness of 10 meters is equivalent to a fracture aperture of 1 millimetre. This shows the immense importance of the flow from one single fracture (in a rock mass) that is not even wide, for example a borehole which intersects one fracture of about 0.6 millimetre aperture could yield approximately 1 l/s. According to a list compiled by Bouwer (1978) the order of magnitude of hydraulic conductivity of sandstone is between 0.001 and 1 m/d and that of fractured or weathered rock (core samples) is between 0 and 300 m/d.

The main factor which controls the K-value of an aquifer is actual size and number of the apertures, although the more fractures of a given aperture present, the greater the permeability of the aquifer (Sharp, 1993). A very striking hydrogeologic feature of a fractured crystalline rock is the variability of the properties. A parameter such as the hydraulic conductivity determined by classical field methods normally varies by several orders of magnitude within the same rock unit and often within short distances.

Within one fracture the hydraulic conductivity can also vary considerably. In situ effective stresses can cause the fracture to be compressed in some areas and this will cause the fracture permeability to decrease with increased depth. Weathering of fractures near the surface may on the other hand cause an increase in the apertures and this will result in an increase in the permeability. In hard crystalline rocks, valleys typically occur in areas of more intensive fracturing and streams and rivers may also tend to follow the directions of the main set of fractures. Anisotropy will be reduced by more sets of fractures, better interconnection between fractures and by smaller fracture spacing. Theoretical studies by Long *et al.* (1985) suggest complex permeability ellipses. Longer fractures, greater fracture density and greater apertures increase hydraulic conductivity. Fracture system characteristics vary spatially and temporally because of geological constraints.

4.9 TRANSMISSIVITY

In calculations of aquifer parameters the transmissivity is usually calculated and the hydraulic conductivity is not used frequently. Transmissivity is the product of the average hydraulic conductivity (K) and the saturated thickness of the aquifer (D). Transmissivity is therefor the rate of flow under a unit hydraulic gradient through a cross-section of unit width over the whole saturated thickness of the aquifer.

From the above we can relate the hydraulic conductivity equation (equation (4.1)) to transmissivity, T, to yield the following equations that can be related to porous media:

$$T = KD \qquad (4.3)$$

and

$$T = \frac{\rho g b^3}{\mu 12} \qquad (4.4)$$

where T = transmissivity

D = saturated aquifer thickness

b = aperture

μ = dynamic viscosity

ρ = fluid density

g = gravitational acceleration

4.10 SPECIFIC STORAGE, STORATIVITY AND SPECIFIC YIELD

The specific storage (S_s) of a saturated confined aquifer is the volume of water that a unit volume of aquifer releases under a unit decline in hydraulic head. The release of water from storage under conditions of decreasing head takes place because of the compaction of the aquifer due to increasing effective stress and the expansion of the water due to decreasing pressure.

The storativity (S) of a saturated confined aquifer with thickness D is the volume of water released from storage per unit surface area of the aquifer per unit decline in the component of hydraulic head normal to the surface. In a vertical column of unit area extending through the confined aquifer, the storativity equals the volume of water released from the aquifer when the piezometric surface drops over a unit distance.

The specific yield is the volume of water that an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline in water table. The values of the specific yield range from 0.01 to 0.30 and are much higher than the storativities of confined aquifers. In unconfined aquifers the effect of elasticity of the aquifer matrix and that of the water are generally negligible. Specific yield is sometimes called the effective porosity.

4.11 WELL BORE SKIN

According to Ingo Bardenhagen (Ph.D thesis, 2000) well bore skin is a thin layer with a very small storage capacity located between the borehole wall and the aquifer that restricts the inflow of water to a pumped borehole. It averages the effects of various sources as clogged screens, gravel pack, too small open area of the screens and mineral precipitation between the borehole wall and the formation. In the presence of well bore skin an additional drawdown is observed within the borehole. This effect is also known as well losses or skin effect. Mathematically these losses are described by a linear and a non-linear term (Jacob, 1947). Both terms are respectively constant as long as the discharge rate is constant (Kawecki, 1995). The sum of both well loss components can be represented by a constant total well skin factor ξ, which is simply added to a given well function F (Van Everdingen, 1952) to calculate the total drawdown within the pumped well:

$$F(u,\xi) = F(u) + \xi \tag{4.5}$$

where u is the argument that describes the relation between the aquifer parameters T and S as well as the geometry of the abstraction source over the extraction period. The drawdown affected by a skin is a curve parallel to that without skin effects, whereas no effects appear during the recovery phase, except during the well bore storage period.

4.12 WELLBORE STORAGE

Inside a borehole there exist certain amounts of water that will be removed instantly as the pump is switched on during a pumping test. This water will be pumped out within the first few minutes of the pumping test, depending on the pumping rate. The volume of water released from storage around the borehole due to pumping from the borehole is much smaller than the volume of water that is stored inside the borehole. This will result in the water level inside the borehole dropping rapidly in the beginning of the pumping test. This effect is called well bore storage and it is very common during most pumping tests. It affects early time data, but it can persist for longer periods of time. Well bore storage occurs as a result of a small storativity value. For open boreholes the well bore storage coefficient can be defined as:

$$C_D = 1 / 2S \tag{4.6}$$

where S = storativity

Well bore storage is a nuisance in pumping test analysis because it disguises the aquifer response for many minutes. After the storage effect is over there is a period during which the response undergoes a transition between well bore storage and aquifer response. After a certain period of time a large enough pressure gradient will be created and water will start flowing from the area surrounding the borehole.

There is often a zone surrounding the borehole which is invaded by mud (clogging) during the drilling process and this zone may have a lower permeability than the aquifer and therefor act as a skin around the borehole, causing a higher pressure drop. As a result of this the borehole appears to have a smaller effective radius (called positive skin). In the case where the K-value surrounding the borehole is higher than the K-value of the aquifer, the effective radius is larger than the radius of the borehole (negative skin). Well bore storage effects will be more dominant in the case of positive skin around the borehole.

If the diameter of a borehole is 165 millimetres, then it will store 21.38 litres of water for every meter of drop in drawdown. If water is pumped from the borehole at a pumping rate of 5 litres per second it will take 4.276 seconds to abstract the one meter of water in the borehole. Normally water will not be flowing into the borehole at such a rate in the beginning of the pumping test, resulting in the well bore storage effect taking place.

4.13 TYPES OF FLOW INSIDE AN AQUIFER DURING A PUMPING TEST

As mentioned above, the first type of flow which takes place when the pump is started during a pumping test is the flow from the borehole itself. This is called well bore storage and it lasts for a few minutes at most, depending on the abstraction rate from the borehole.

After this stage water will start to flow from the aquifer into the borehole. The flow from the aquifer can be divided into three different types.

4.13.1 LINEAR FLOW

In a double porosity system, typical to this country, water will be abstracted from the fractures as well as the matrix in the aquifer. The fracture displays semi-confined properties with its own piezometric level and the matrix has got another piezometric level or just water level if it is situated above the fracture. Under natural conditions the two levels have got the same height or usually the piezometric level is a bit lower than the water level of the matrix due to small amounts of water flowing from the matrix to the fracture.

For the correct assessment of the hydraulic parameters of a fractured hard rock aquifer using pumping test data, it is necessary to know how much flow relates to a certain drawdown response of the aquifer. It is therefor important to know the flow geometry, or flow dimension. The area available to flow in an aquifer is a function of the distance to the pumped borehole and can be given by (Black, 1994):

$$A = A_0 r^{(n-1)} \qquad (4.7)$$

Where A = through-flow area

A_0 = through-flow area at the pumped borehole

r = distance to pumping borehole

n = flow dimension

The flow dimension may range from 1 to 3 (Barker, 1988; Black, 1994).

The fracture has got a high permeability, high internal porosity as well as transmissivity, but the volume of water stored in a fracture is negligible, compared to the volume of water contained in the matrix. The higher permeability fractures serve as conduits for flow and the matrix blocks of higher storativity and lower permeability will supply the bulk of the water. When water is pumped from a borehole in a double porosity system, the dominant flow would be from the fracture to the borehole at early times, with some leakage from the matrix. In this case a one-dimensional flow geometry exists and this case results in $n = 1$ (equation (4.7)). The area through which flow occurs will remain constant, regardless of the distance from the pumping borehole. Water flowing inside the fractures will show linear flow behaviour ***(Fig. 4.9 and Fig. 4.10)*** and this will result in a drop in the piezometric head, resulting in more water flowing from the matrix into the fracture. Linear flow can also be described as parallel flow (Kruseman and De Ridder, 1990) due to the parallelism between the streamlines.

4.13.2 BI-LINEAR FLOW

At intermediate time the water level inside the borehole will display a bi-linear flow period ***(Fig. 4.9)*** where water is derived both from the fractures and the matrix. This flow period corresponds to the non-integer flow dimension of $n = 1.5$ (equation (4.7)). Because of the drawdown inside the borehole a cone of depression will start forming around the borehole and this will result in water flowing from the matrix into the fractures and along the fractures into the borehole. Under pumping conditions a noticeable pressure difference exists between the two piezometric levels. Close to the borehole a large pressure gradient exist between the fracture and the matrix, resulting in a large flow from the matrix to the fracture. Further away the pressure gradient becomes smaller and smaller and this will result in less flow to the fracture. Depending on the pumping rate, the leakage from the matrix may be sufficient, leading to a temporary stabilising of the drawdown inside the borehole.

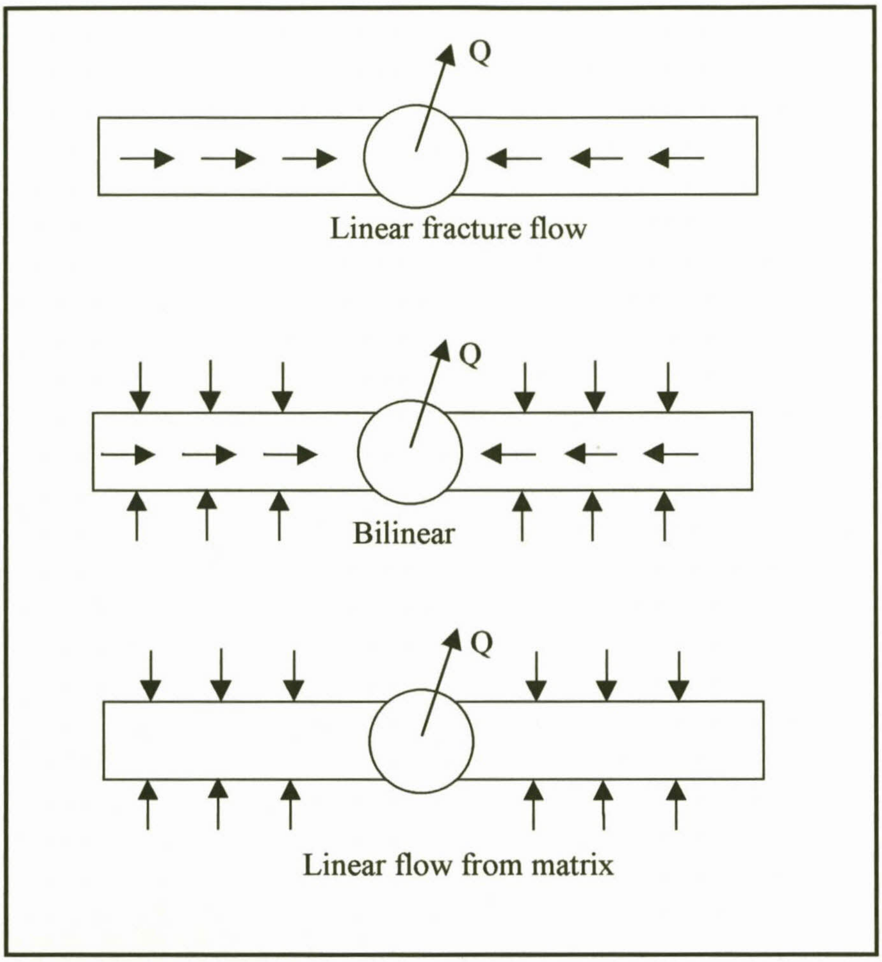


Figure 4.9: Linear and Bilinear flow conditions

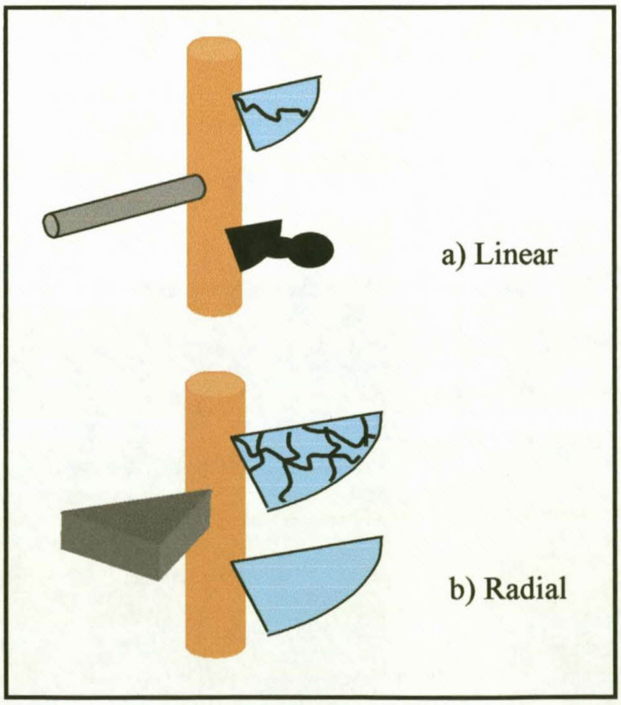


Figure 4.10: Linear and radial flow regimes

4.13.3 RADIAL FLOW

Depending on the pumping rate from the borehole, a few things can happen at later time. If the water level has not dropped below the position of the first horizontal fracture, radial flow ***(Fig. 4.10 and Fig. 4.11)*** behaviour will exist. In this case the cone of depression will be approximately circular. The start of radial flow indicates the time at which the fractured reservoir behaves as homogeneous. During this flow period the flow dimension of n = 2 (equation (4.7)) exists.

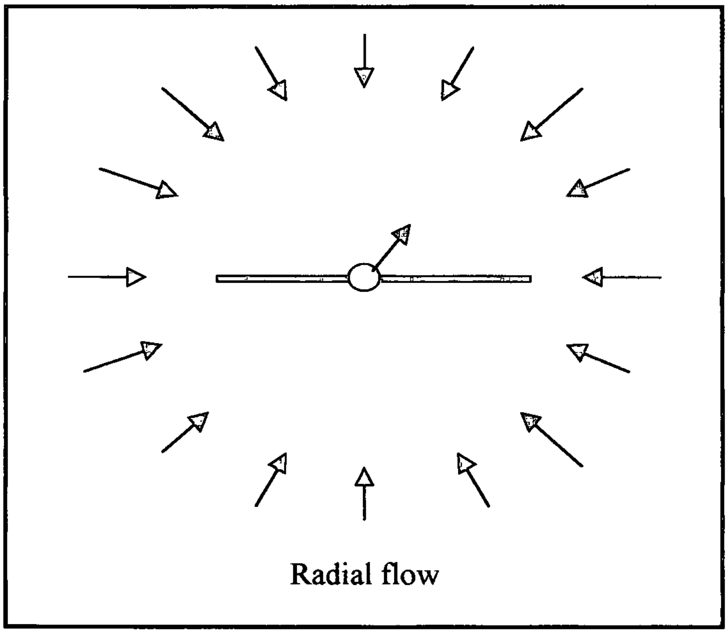


Figure 4.11: Radial-acting flow pattern

The distance from the pumped borehole at which the radial flow starts, determines the dimension of the representative elementary volume (REV), as demonstrated in the figure below ***(Fig. 4.12)***. The REV is the characteristic volume of fractured rock that can be represented by a homogeneous anisotropic medium whose hydraulic properties do not change significantly if an additional volume of rock is added (Long *et al.*, 1982). In some instances a fractured rock can have various REV depending on the scale of the investigation and in some instances it is not possible to define a REV at all (Long & Witherspoon, 1985).

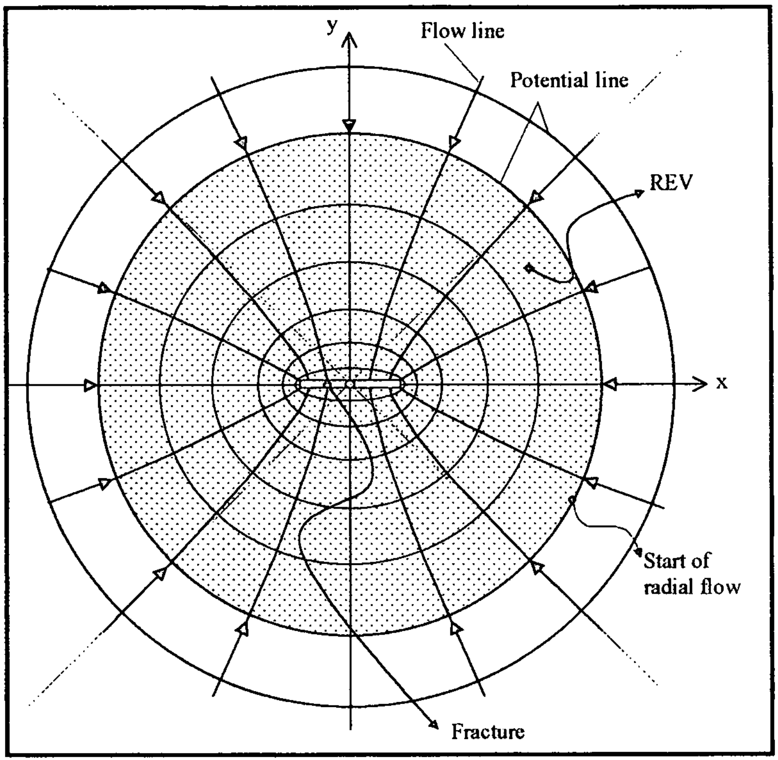


Figure 4.12. REV for a single vertical fracture with infinite conductivity. An observation point beyond the grey area would show only radial-acting flow behavior

Radial flow during a pumping test can only be observed on the derivative plot of head derivative versus time. It appears as a flat line at about 1.5 log cycles after well bore storage and it corresponds to a flat region on the log-log plot.

4.14 DIAGNOSTIC TOOLS TO DETERMINE AND ENHANCE BOREHOLE CHARACTERISTICS

Each and every borehole that is drilled and pump tested will show unique characteristics. The pumping test data obtained at a borehole during a pumping test can be interpreted on different plots or charts to yield the unique characteristics of that particular borehole. The plots that can be interpreted include:

4.14.1 STRAIGHT-LINE ANALYSIS

The flow phases that appear during a pumping test in a typical fractured rock aquifer show characteristic straight-lines either on a semi-log or log-log plot.

4.14.2 SEMI-LOG PLOTS (TYPICAL COOPER-JACOB PLOT)

With this plot the drawdown is plotted on linear scale and the time on logarithmic scale. With this plot certain boundary types can be identified and radial flow can be picked up. The table below ***(Table 4.1)*** gives an indication of the characteristics associated with the different features of the drawdown versus time data obtained during a pumping test.

Feature	Characteristic
Straight line segment (A in Fig. 4.13 below)	Radial acting flow
Flat line (B in Fig. 4.13 below)	Water level has reached fracture
Two parallel lines	Double porosity
Flat line (B in Fig. 4.13 below)	Recharge boundary – leakage from matrix
Steepening of slope at late time (C in Fig. 4.13 below)	Flow from matrix into fracture
Steepening of slope at late time (C in Fig. 4.13 below)	Boundary reached
Doubling of slope of radial acting flow segment	One closed boundary reached
Quadrupling of slope of radial acting flow segment	Two perpendicular closed boundaries reached
Slope = 1 at late time (C in Fig. 4.13 below)	Closed no flow boundary reached

Table 4.1: Semi-log plots – features indicating different characteristics

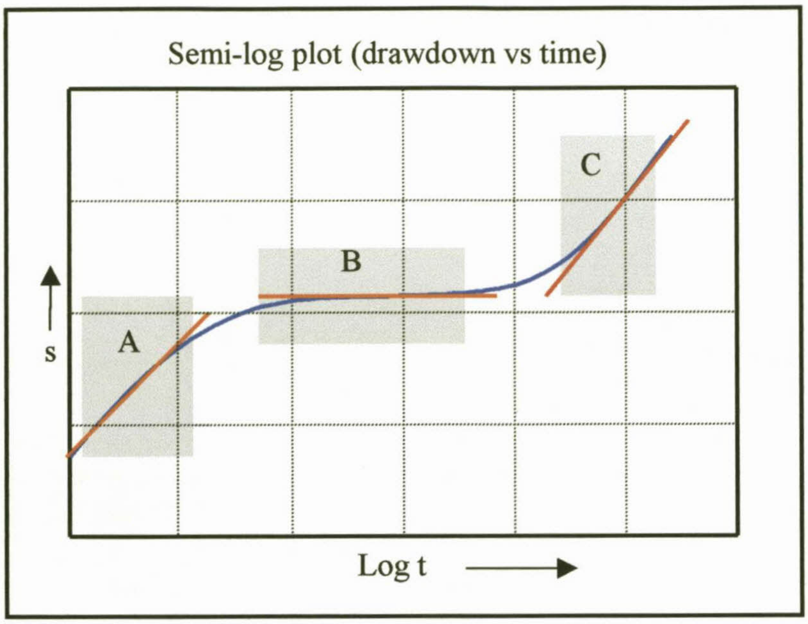


Figure 4.13: Semi-log plot of drawdown versus time

4.14.3 LOG-LOG PLOTS (TYPICAL THEIS PLOT)

This is a very useful plot, in that most of the aquifer responses are easily identified as long as the derivative plot is also interpreted. In this plot the drawdown as well as time are plotted on log scale. The table below ***(Table 4.2)*** indicates the characteristics of an aquifer associated with the different features on the log-log plot of the drawdown versus time chart.

Feature	Characteristic
Slope of 1 at early time (A in Fig. 4.14 below)	Well bore storage
Slope = 0.5 at early time (B in Fig. 4.14 below)	Linear flow from matrix to fracture. If difference between drawdown and derivative = factor 2, the fracture has a large areal extent
Slope = 0.25 at early time (B in Fig. 4.14 below)	Horizontal fracture reached. If the difference between drawdown and derivative =

	factor 4, the fracture has a limited areal extent
Flat line (C in Fig. 4.14 below)	Recharge boundary
Flat line (C in Fig. 4.14 below)	Leakage from matrix = abstraction rate
Flat line (C in Fig. 4.14 below)	Position of fracture reached
Flat line after about 1.5 log cycles after well bore storage (C in Fig. 4.14 below)	Radial flow, must correspond to flat region on derivative plot
Increase of slope at late time (D in Fig. 4.14 below)	Possible boundary reached, must be confirmed with slope = 1 on derivative plot

Table 4.2: Log-log plots – features indicating different characteristics

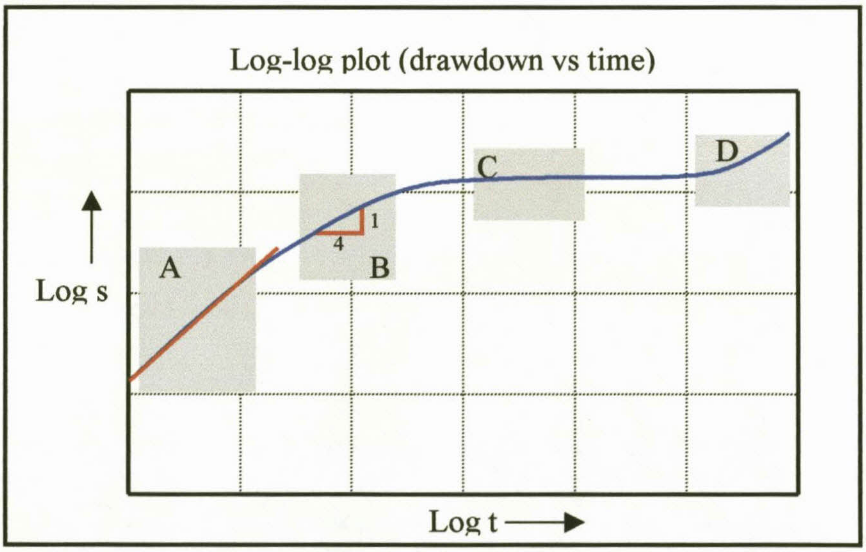


Figure 4.14: Log-log plot of drawdown versus time

4.14.4 DERIVATIVE PLOTS OF DRAWDOWN

Many responses, which can not be seen on the semi-log and log-log plots of drawdown, can be seen on the derivative plot. Derivative plots of pressure head have been in use in the oil fields for many years to evaluate flow regime characteristics (Bourdet *et al.*, 1984; Horne, 1997). The use of derivative plots is of great advantage because they are sensitive to small changes in the drawdown curve and they are independent of factors such as skin effect. The derivative plots provide the following advantages:

- all characteristic straight-line slopes remain the same
- radial-acting flow phases are plotted as a horizontal line, which makes it easy to identify.

Taking the head derivative is a very good method to identify the flow regime in an aquifer, which is estimated from:

$$d(H)/d(\ln t) = (n\Sigma x_i y_i - \Sigma x_i \Sigma y_i) \,/\, (n\Sigma x_i^2 - (\Sigma x_i)^2) \qquad (4.8)$$

where: the summation is from 1 to n and

n = number of points to be averaged, usually n = 5 or n = 7 is the best

$x_i = \ln(t_i)$ at point i , (t = time)

$y_i = h_i$, i.e. head H or (drawdown) at t_i

The user of a derivative plot must however be careful because derivatives applied to real data often show too much noise. Smoothing of the drawdown derivative would overcome the problem, but this can in turn produce misleading artefacts. This problem can be overcome by using recovery data which are usually less noisy as they are not influenced by variations in the discharge rate from the pump. The table below ***(Table 4.3)*** indicates the characteristics of an aquifer associated with the different features on the derivative plot.

Feature	Characteristic
Slope = 1 at early time (A in Fig. 4.15 below)	Well bore storage
Downward trend after well bore storage (B in Fig. 4.15 below)	Fracture flow
Slope = 0.5 at early time	Long fracture (usually factor 2

	difference between drawdown and derivative
Slope = 0.25 at early time	Finite fracture (usually horizontal) with factor 4 difference between drawdown and derivative
Upwards slope = 1 at late time (E in Fig. 4.15 below)	Closed boundary reached
Downward slope = 1 at late time (E in Fig. 4.15 below)	Pseudo steady state flow reached
Strong downward trend	Position of fracture reached
Strong downward trend	Recharge boundary reached
Strong downward trend	Constant head boundary reached
Dip in the derivative plot (B and D in Fig. 4.15 below)	Double porosity aquifer
Heaps at late time	Each heap represents another fracture
Flat line about 1.5 log cycles after well bore storage (C in Fig. 4.15 below)	Radial flow, must correspond to flat region on Log-log plot

Table 4.3: Derivative plots – features indicating different characteristics

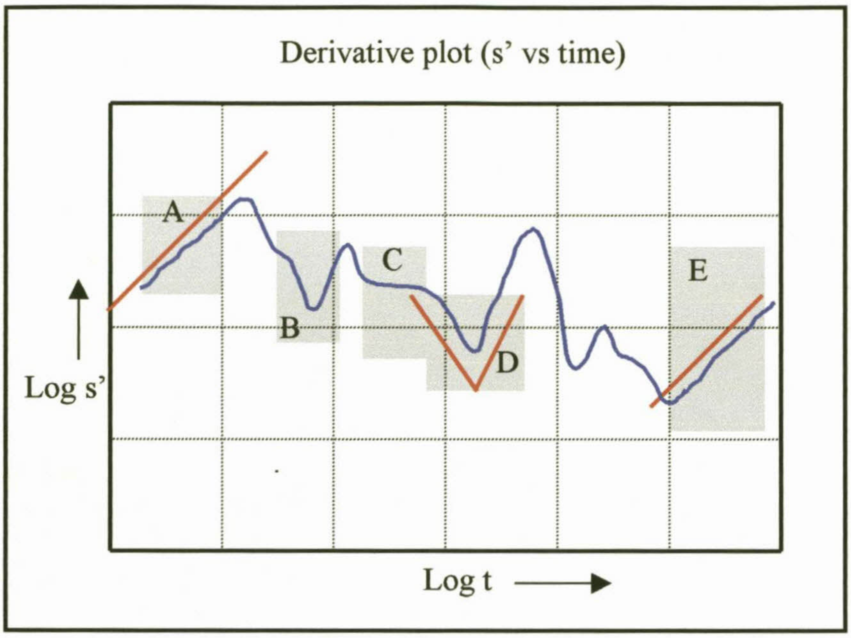


Figure 4.15: Derivative plot of head derivative (s') versus time

It is important to note that it is almost always possible to draw a straight line through a small portion of the data, but meaningful deductions can only be made if the portion of data is large enough for proper characterisation.

4.14.5 LINEAR PLOTS

In this plot the drawdown as well as time are plotted on a linear scale and this results in the drawdown data being displayed in a certain way. Although the Cartesian or linear plot cannot be used to diagnose pseudo steady state flow, it can be used to estimate the drainage area during pseudo steady state response. The Cartesian plot should be used in conjunction with other plots to determine the characteristics of an aquifer. The table below ***(Table 4.4)*** indicates the characteristics of an aquifer associated with the different features on the linear plot of the drawdown versus time chart.

Feature	Characteristic
Steep straight line at late time – slope usually > 1 (B in Fig. 4.16 below)	Closed boundary reached
Flat line (A in Fig. 4.16 below)	Recharge boundary reached
Flat line (A in Fig. 4.16 below)	Position of fracture reached

Table 4.4: Linear plots – features indicating different characteristics

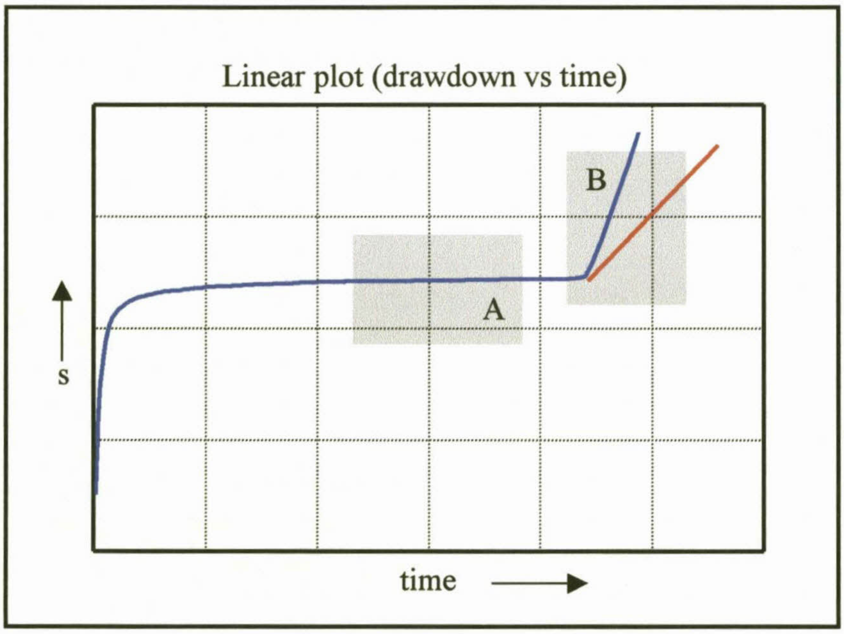


Figure 4.16: Linear plot of drawdown versus time

4.14.6 SQUARE ROOT OF TIME PLOTS (TIME = $t^{0.5}$)

This plot is done by plotting the drawdown on a linear scale in the vertical and by taking the square root of the time and plotting it on the horizontal axis. This plot is only useful for fractured rock aquifers. Special features on this plot help in identifying characteristics such as linear flow, found in some fractured aquifers as well as horizontal fractures (early times). The table below ***(Table 4.5)*** indicates the characteristics of an aquifer associated with the different features on the drawdown versus square root of time plot.

Feature	Characteristics
Straight line (A in Fig. 4.17 below)	Linear flow from the matrix to the fracture at early time
Straight line at early time (A in Fig. 4.17 below)	Infinite fracture (no boundary reached) or uniform flux

Table 4.5: Square root of time plots – features indicating different characteristics

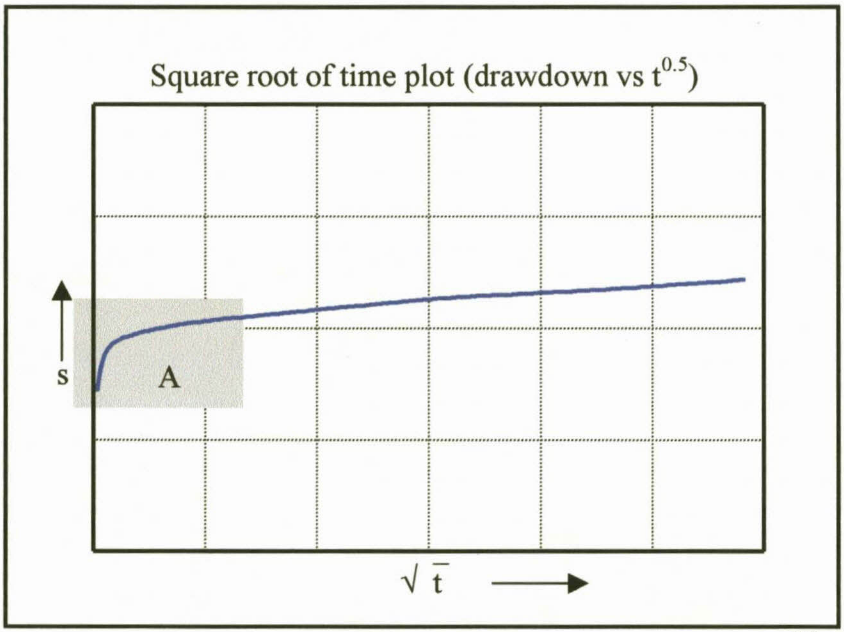


Figure 4.17: Square root of time plot – drawdown versus $t^{0.5}$

4.14.7 FOURTH ROOT OF TIME PLOTS (TIME = $t^{0.25}$)

This plot is done by plotting the drawdown on a linear scale in the vertical and by taking the fourth root of the time and plotting it on the horizontal axis. This plot is only useful for fractured rock aquifers. Special features on this plot help in identifying characteristics such as bi-linear flow, found at early times in finite conductive fractures. The table below ***(Table 4.6)*** indicates the characteristics of an aquifer associated with the different features on the drawdown versus fourth root of time plot.

Feature	Characteristics
Straight line at early time (A in Fig. 4.18 below)	Finite fracture
Straight line at early time (A in Fig. 4.18 below)	Bi-linear flow from matrix

Table 4.6: Fourth root of time plots – features indicating different characteristics

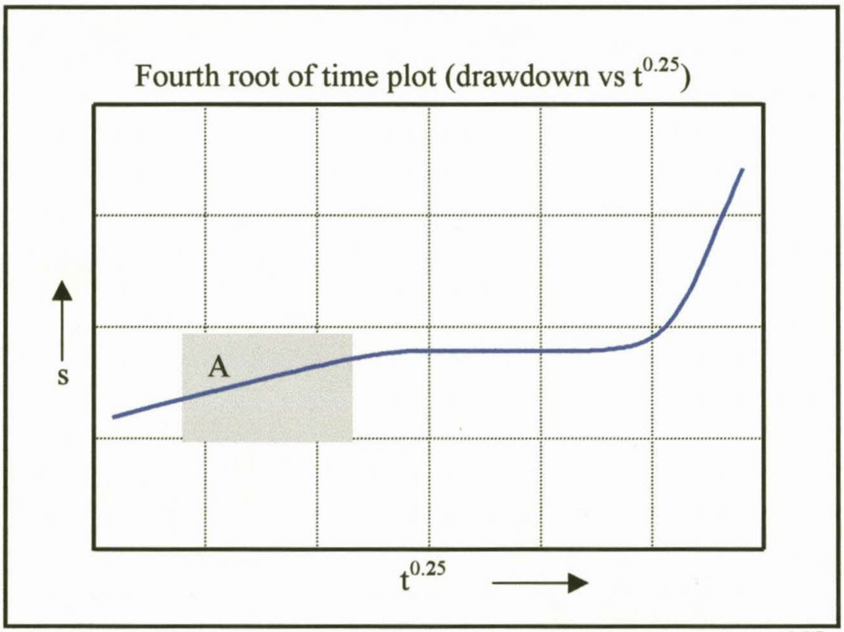


Figure 4.18: Fourth root of time plot – drawdown versus $t^{0.25}$

4.14.8 INVERSE SQUARE ROOT OF TIME PLOTS ($1/t^{0.5}$)

This plot is done by plotting the drawdown on a linear scale in the vertical and by taking the inverse square root of the time and plotting it on the horizontal axis. This plot is only useful for fractured rock aquifers. Special flows such as three-dimensional (spherical) and hemispherical flows can be identified with the aid of this plot. The table below ***(Table 4.7)*** indicates the characteristics of an aquifer associated with the different features on the drawdown versus inverse square root of time plot.

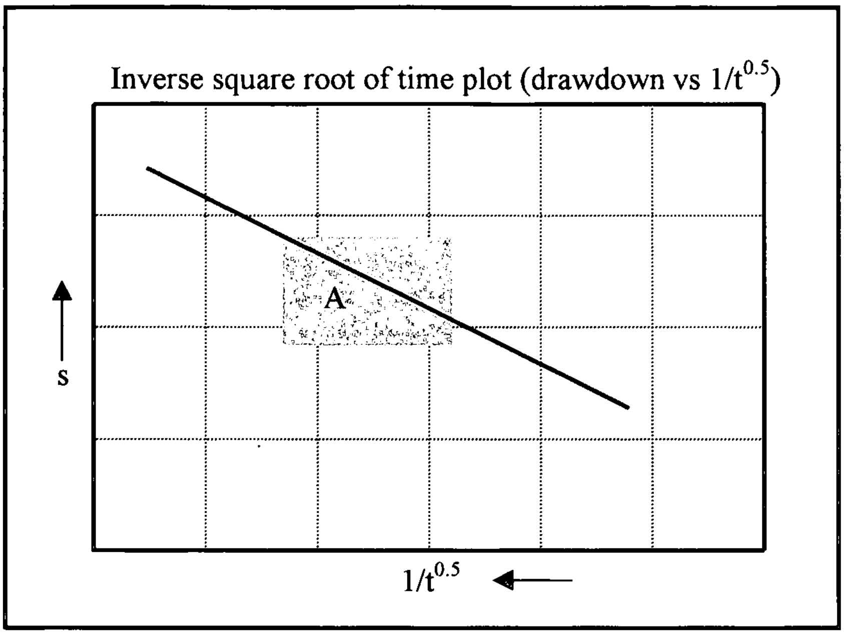


Figure 4.19: Inverse square root of time plot of drawdown versus $1/t^{0.5}$

Feature	Characteristics
Straight line (A in Fig. 4.19 above)	Spherical flow

Table 4.7: Inverse square root plots – features indicating different characteristics

4.14.9 IDENTIFYING DIFFERENT BOUNDARY CONDITIONS

On the different plots principal boundary types can be identified. The table below ***(Table 4.8)*** gives an indication of the boundary type and how it can be recognised on the different plots.

Boundary type	How to recognise them
Infinite boundary	No deviation from radial flow behaviour at late time (straight line on semi-log plot through all points)
Constant head	Flat region in drawdown response at late time,

	downward trend in head derivative
Impermeable no-flow boundary	At most doubling of slope on semi-log plot or doubling of flat region on derivative plot
Two parallel no-flow boundaries	Slope = 0.5 on log-log and derivative plot at late time
U-shaped no-flow boundary	Slope = 0.5 on log-log and derivative plot at late time
Closed no-flow boundary	Straight line with slope = 1 at late time on derivative plot

Table 4.8: Principal boundary types and how to recognise them

4.14.10 HOW TO IDENTIFY THE DIFFERENT CHARACTERISTICS ON THE DIFFERENT PLOTS

For a person not used to interpreting straight line as well as special plots it might be difficult to get to the correct conclusions in the beginning. An important point to make is that the different plots definitely complement each other and certain characteristics can be verified on the different plots. Because of this all the plots should be treated as a unit and they should be interpreted in that way. By practising and repetition the geohydrologist will succeed in interpreting the different plots more accurately, as is the case in everything that we do. The table below ***(Table 4.9)*** will give an indication of which plot will reflect what characteristic for a specific flow regime or response.

Characteristic, flow regime or response	Plot to use	Feature on plot
Well bore storage	Log-log	Slope = 1 at early time
	Derivative	Slope = 1 at

		early time
	Derivative	Hump in head derivative
Radial flow	Semi-log	Straight line segment
	Derivative	Flat line about 1.5 log cycles after well bore storage
Linear flow (limited fracture network)	Log-log	Slope = 0.5 at early time
	Derivative	Slope = 0.5 line fit on derivative. Usually factor 2 difference between drawdown and derivative
	Square root of time	Straight line
Bi-linear flow (good fracture network	Log-log	Slope = 0.25 at early time
	Derivative	Slope = 0.25 line fit on derivative. Usually factor 4 difference between drawdown and derivative
	Fourth root of time	Straight line
Position of	Semi-log	Flattening of

fracture		curve at fracture position
	Log-log	Flattening of curve at fracture position
	Derivative	Hump in derivative
	Linear	Flat line
Double porosity	Derivative	Characteristic dip
Single no-flow boundary	Semi-log	Doubling of slope
	Log-log	Increase of slope at late time, must be confirmed with derivative
	Derivative	Horizontal line with derivative value = 2d0, where d0 = infinite acting flow line
Double no-flow boundary	Semi-log	Tripling of slope at most
	Derivative	Horizontal line with derivative value = 3d0, where d0 = infinite acting flow line
Closed no-flow boundary	Semi-log	More than tripling of slope

	Derivative	Slope = 1 at late time
	Linear	Steep straight line at late time
Two parallel no-flow boundaries	Derivative	Slope = 0.5 at late time
	Log-log	Slope = 0.5 at late time
U-shaped no-flow boundary	Derivative	Slope = 0.5 at late time
	Log-log	Slope = 0.5 at late time
Recharge boundary	Semi-log	Flat line or decrease in slope
	Log-log	Flat line
	Linear	Flat line
	Derivative	Strong downward trend

Table 4.9: Different plots reflecting different characteristics for specific flow regimes

Now that we have got a better understanding of the basic concepts, definitions and characteristics we can proceed to analyse data obtained from a pumping test in the field. The next chapter will assist the reader in the analysis of a pumping test in order to determine specific parameters for a borehole and aquifer.

CHAPTER 5

EVALUATION OF PUMPING TEST DATA

5.1 INTRODUCTION

Before the pump test data can be analyzed the purpose and objectives of a pumping test must be looked at. The general objectives of borehole hydraulic and yield analysis are:

- ☐ a better understanding of the aquifer system
- ☐ the quantification of its hydraulic characteristics (parameters) and
- ☐ the assessment of both the optimum yield and the efficiency of the borehole.

The hydraulic head response to stressing the aquifer system reflects both the aquifer and pumped borehole conditions.

Pumping tests like the constant rate, variable rate, recovery and slug tests are conducted primarily to assess the aquifer conditions while borehole performance tests such as step drawdown and multi rate tests are used to obtain information on the optimum yield and the condition and efficiency of the borehole. The interpretation of pump test data is based on mathematical models that relate the drawdown response to pumping an aquifer to the discharge of the pumped borehole.

The flow from an aquifer to the borehole that is being pumped is a combination of Darcy's equation for groundwater flow with a continuity equation and equations of state for the groundwater and porous medium. Initially the flow in a fractured rock aquifer takes place through the fractures and at a later stage water is taken from the matrix blocks. Important physical parameters of the subsurface that appear in groundwater equations include porosity (n), hydraulic conductivity (K), transmissivity (T) as well as storativity (S). For the correct assessment of the hydraulic parameters of a fractured rock aquifer using pumping test data, it is necessary to know how much flow relates to a certain drawdown response of the aquifer, i.e. it is necessary to know the flow geometry or flow dimension. The values of the hydraulic parameters for hard rock aquifers are scale dependent because of the heterogeneity of the rocks. The closer the piece of hard rock is investigated, the greater the variability in the parameters.

The analysis of pump test data relies on models, with characteristics assumed to be representative of the real aquifer. Such models comprise the type of aquifer (homogeneous or heterogeneous) and initial boundary conditions. Theoretical models allow type-curve matching and straight–line procedures to be used in the analysis of pumping test data. Models like the double porosity model, single fracture model, generalized radial flow model and homogeneous porous model were used to develop suitable analytical methods for pumping tests in fractured hard rock aquifers. Most, if not all, of these models have got inherent problems such as:

- an assumption that the aquifer is confined.
- an assumption of an infinite conductivity in the fracture.

In South Africa the main objective of a pumping test normally is to determine the possible long-term sustainable yield of a specific borehole. In this case the available discharge (Q) is the only important issue. In many rural areas groundwater is the only available water resource and the proper development and management of this scarce commodity is of utmost importance. The recently developed Flow Characteristic or FC method (Van Tonder *et al.*, 1998) should be used to determine the possible long-term sustainable yield. This method was developed for fractured rock aquifers and includes the following features:

- it is applicable for both porous and fractured rock aquifers
- the late T and drawdown to boundary methods are special cases of the FC method
- it does not require the S-value as a priority
- it includes boundary conditions
- a risked-based abstraction rate (Q) could be estimated.

5.2 STEPS IN ANALYZING PUMPING TEST DATA

The most appropriate analytical method should be used to interpret pumping test data. To ensure a careful and proper selection, the interpretation of pumping test data involves a sequence of steps (Lloyd, 1999). The figure below ***(Fig. 5.1)*** shows the different steps that should be used.

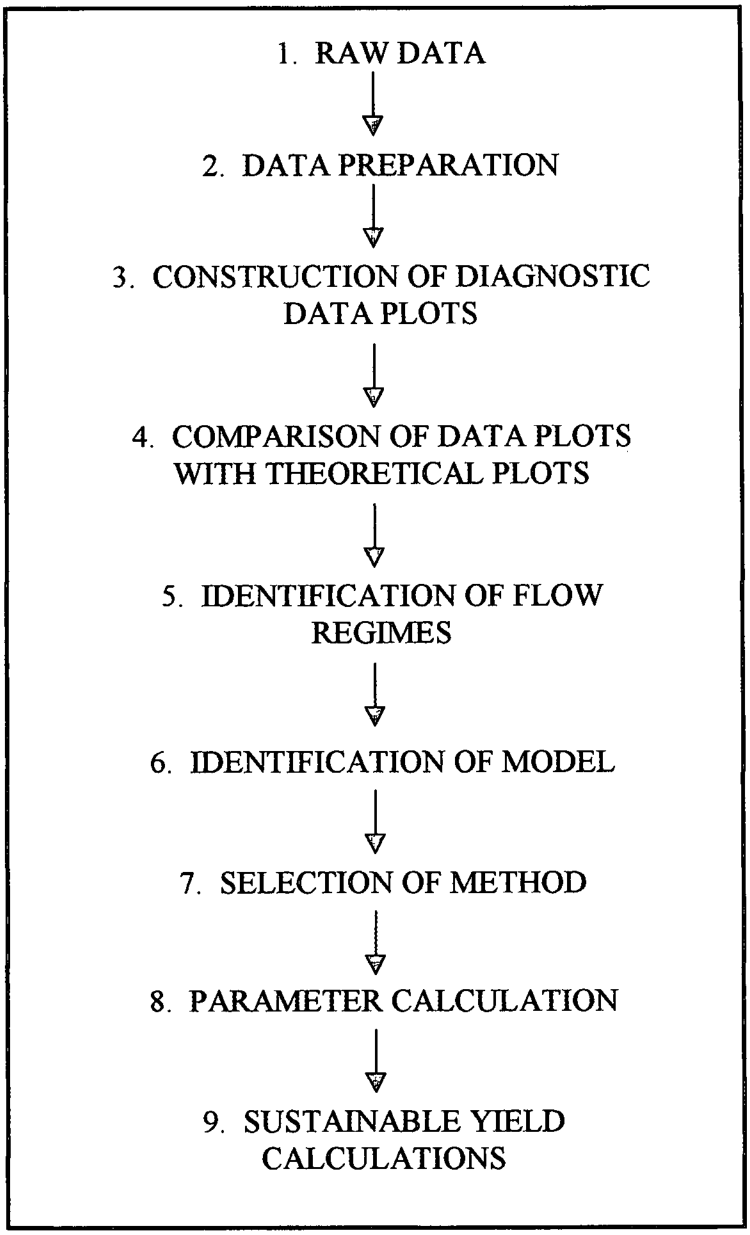


Figure 5.1: Sequence of steps involved in interpretation of single borehole pumping test data

5.2.1 RAW DATA

The first step is to go out and do the pumping test and to obtain the drawdown versus time readings from the pumping as well as observation boreholes. These readings can either be hand readings taken with a diptape or dipmeter and stopwatch or it can be readings obtained with a data logger and pressure probes installed in the boreholes. This data as it is collected in the field is known as raw data and it will be used in the analysis of the borehole and aquifer.

5.2.2 DATA PREPARATION

The raw data needs to be prepared and refined before it can be used in the different software packages. In about all the field data obtained from a pumping test there are certain things that has to be edited or revised so that the data can be entered into software. The drawdown data obtained during a pumping test can, as a first check, be checked against the recovery data obtained after pumping had stopped.

5.2.2.1 EDITING DRAWDOWN AND TIME READINGS

If the hand readings had been taken the data has to be read into a text file in order to read it into the different software packages. An abstract of the raw data taken as hand readings in the field can be seen in the first and second column of the table below ***(Table 5.1)***. The time is written down as the actual time of day and the readings are the actual readings on the diptape or dipmeter.

TIME OF DAY	READING ON DIPMETER	TIME ELAPSED (minutes)	DRAWDOWN (s in meters)
14:21	13.34	19	3.56
14:22	13.46	20	3.68
14:27	13.59	25	3.81
14:32	13.67	30	3.89
14:42	13.78	40	4.00
14:52	13.85	50	4.07

15:02	13.98	60	4.20
15:17	14.07	75	4.29
15:32	14.21	90	4.43
16:52	14.37	120	4.59
17:22	14.48	150	4.70
17:52	14.63	180	4.85

Table 5.1: Raw data from pumping test as well as converted data

The time is converted from actual time of day to the time elapsed from the start of the pumping test. This can be seen in the third column of the table above ***(Table 5.1)***. The reading on the dipmeter is also converted into a drawdown from the initial static water level prior to the start of the pumping test. The converted dipmeter readings or drawdown (s) can be seen in the fourth column in the table above ***(Table 5.1)***.

5.2.2.2 PROBE LOWERED OR RAISED

All pressure probes have got a specific measuring range, which means that the probe will be able to measure only a predetermined head of water. This may range between 2.5 and 40 meters and the probe will be installed at close to this range below the static water level. If the water level inside the pumping borehole is measured with a data logger and pressure probe with a certain range, it might happen that the drawdown in water level inside the borehole is more than the range of the probe. If this happens the water level will drop to below the position of the pressure probe and it will not be able to measure the drawdown. To prevent this from happening the contractor will, just before the water level reaches the probe, lower the probe further down the borehole. By doing this the pressure probe will be able to measure the rest of the drawdown. In some cases it might even be necessary to lower the probe more than once. The red line on the chart below ***(Fig. 5.2)*** is an example of where the pressure probe had to be lowered in order to measure all of the drawdown during the pumping test. The same procedure had to be followed during the recovery stage of the pumping test, where the pressure probe had to be raised in order to enable it to measure all of the recovery inside the borehole. The lowering and raising of the pressure probe does not have a negative effect on the accuracy of the data because the data can easily be edited to give the true reflection of the drawdown inside the borehole. The blue line on the chart below ***(Fig. 5.2)*** represents the drawdown data after the corrections had been made.

It may also happen that, although the pressure probe has got sufficient range, the water level drops to below the probe. In such a case the same procedure as described above will be followed so that the total drawdown in the borehole can be recorded.

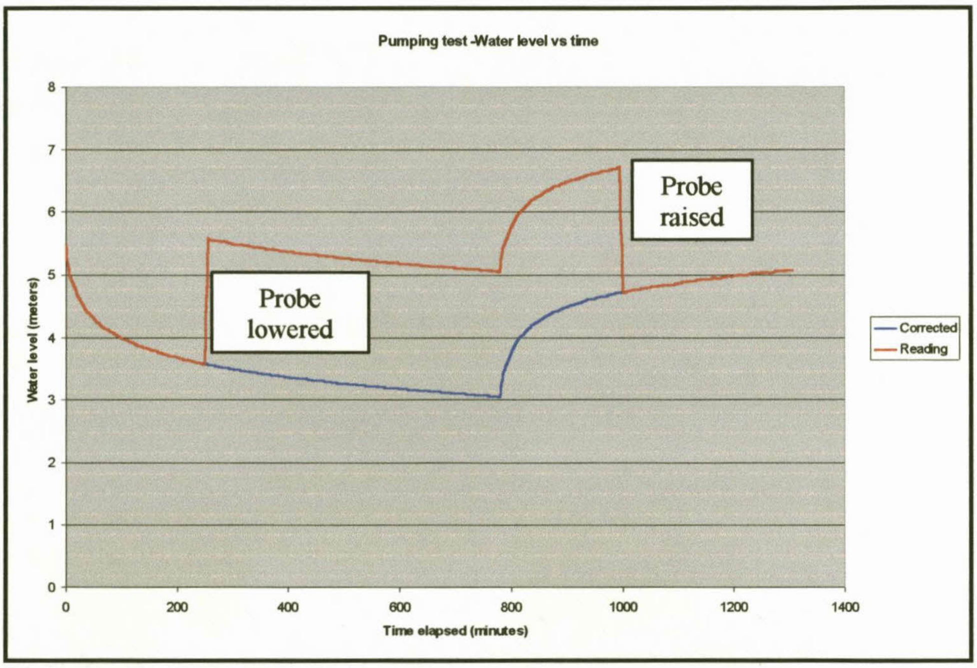


Figure 5.2: Chart of raised and lowered pressure probe

5.2.2.3 INCORRECT READINGS TAKEN

If a 72-hour constant rate pumping test is conducted, it is inevitable that water level readings will have to be taken during the night. Sometimes people are not properly equipped or they are sleepy and tired and this might lead to readings being taken incorrectly. The person preparing pump test data to be used in software should screen the raw data for mistakes like this. In the figure below ***(Fig. 5.3)*** it can clearly be seen that one of the readings was taken incorrectly and that it should be corrected before the data can be used. Normally wrong readings will stand out and it is therefor easy to pick them up, but sometimes these reading are only a few centimeters out and then it is very difficult to pick them up. It may happen that something strange is picked up on one of the special plots (derivative plot) and only then will the person analyzing the data be able to identify the problem on the drawdown or raw data.

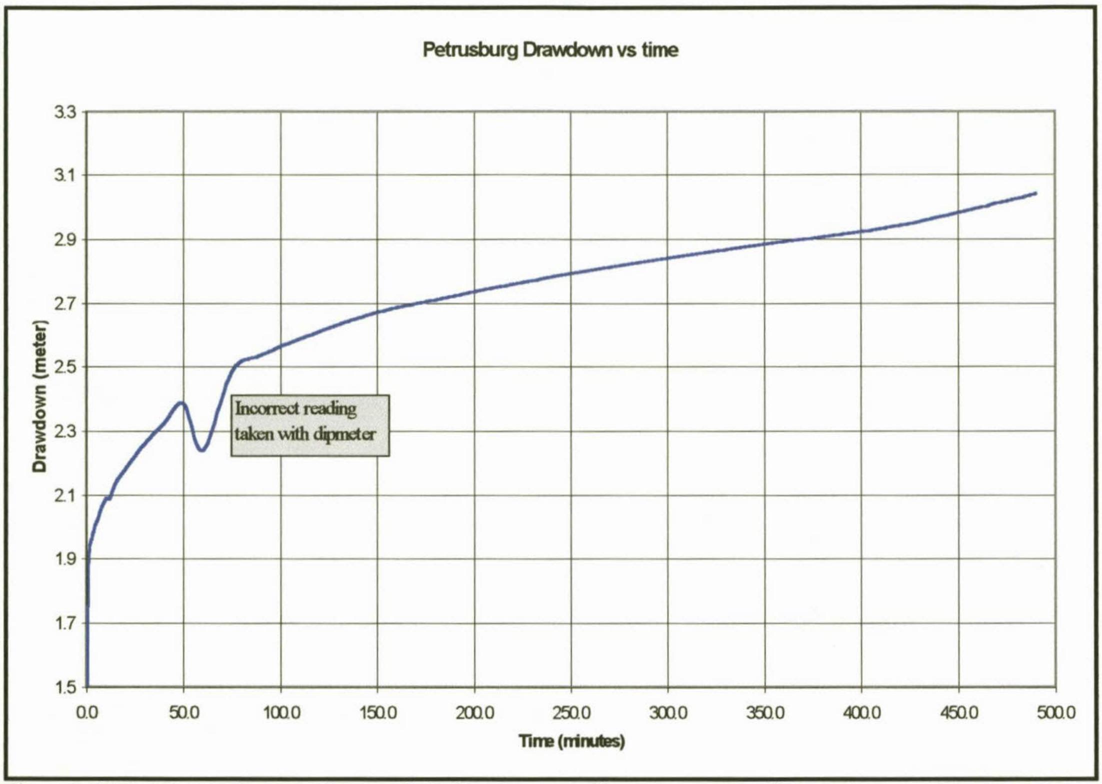


Figure 5.3: Drawdown data with incorrect dipmeter reading

5.2.2.4 DISTORTED HAND READINGS

Drawdown versus time readings should be taken at specified intervals and at later times in the pumping test these readings can be taken further apart. During a 72-hour constant rate pumping test the later readings are taken at half-hour and even at hourly intervals. This may result in data being recorded incorrectly or data not being representative of what is really happening during the pumping test.

An electronic data logger taking readings at small intervals will prevent such errors from creeping in. The data logger readings taken at these small intervals can be used to obtain all the significant or important events occurred during the pumping test. If no such events took place the data can be filtered and used in the software. It is important that all events influencing the drawdown curve should be logged and as can be seen in the figure below ***(Fig. 5.4)*** this is not always the case when only hand readings are taken. The red line represents the hand readings taken during this pumping test while the blue line represents the drawdown readings taken with the aid of an electronic data logger. It can clearly be seen that there are significant events taking place during the pumping test and it is obvious that these events were not picked up that well with the hand readings.

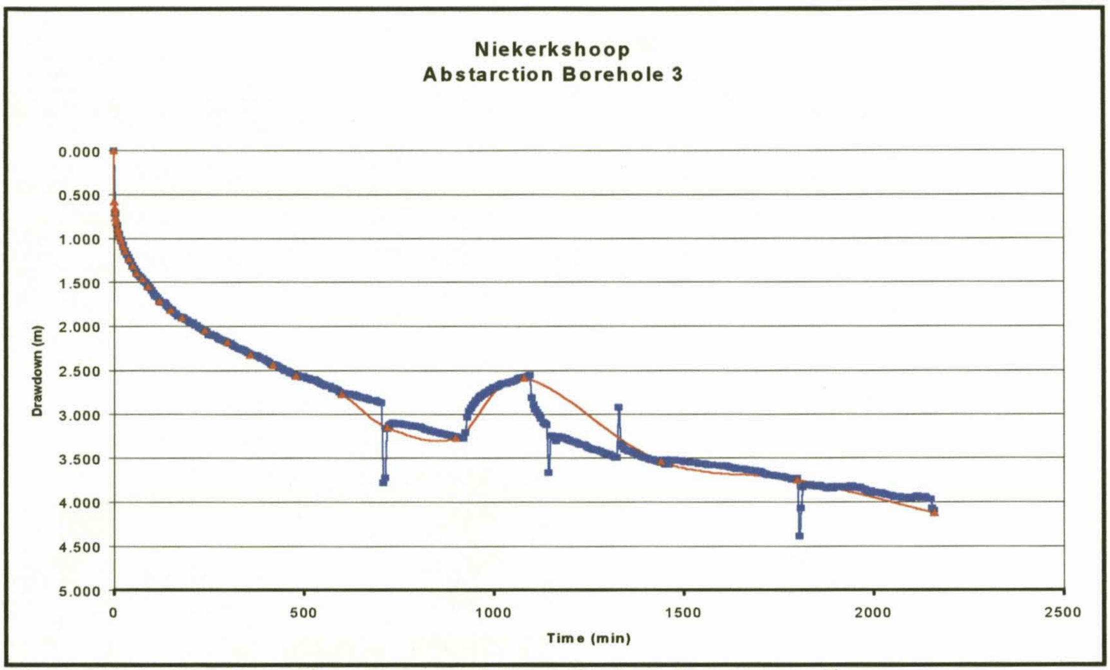


Figure 5.4: Hand readings versus electronic data logger readings

In the example above the hand reading taken at 1080 minutes may even be seen as a reading taken incorrectly, especially if no data logger readings were available to verify that the hand reading was correct. This assumption would have been incorrect and it could have resulted in predicting an incorrect sustainable yield for this particular borehole.

5.2.3 CONSTRUCTION OF DIAGNOSTIC DATA PLOTS

Now that the raw data had been checked and corrected, it can be read into the different software packages so that it can be properly analyzed. Once this has been done a series of diagnostic data plots can be constructed. These plots include:

- First and second derivative plots of the drawdown data.
- Straight-line analysis in log-log plots.
- Straight-line analysis in semi-log plots.

- Special plots such as drawdown versus square root of time, drawdown versus fourth root of time and drawdown versus inverse square root of time.
- Linear plots of drawdown versus time since pumping started.

Constructing these plots form the basis of proper pumping test analysis (Kruseman et al., 1990; Horne, 1990). The drawdown response of an aquifer to pumping depends on the aquifer and borehole conditions, which may dominate at different times. This means that different flow periods may dominate at different times during a pumping test. Different theoretical models describe the specific drawdown responses for the different aquifer and borehole conditions. The figure below ***(Fig. 5.5)*** is an example of diagnostic plots constructed from the drawdown versus time data collected during a pumping test. These charts can be constructed separately or in some cases they are constructed automatically as a unit in some software packages. This is the case with the newly developed Flow Characteristic Method (FC method) where the drawdown versus time data is imported into the software and then all the different plots are presented as a unit. This makes the interpretation of the data that much easier.

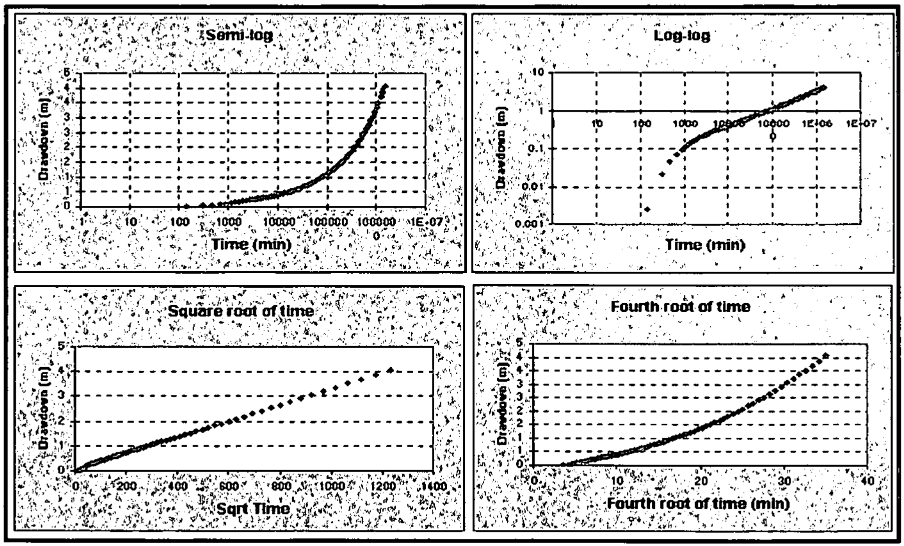


Figure 5.5: Different types of diagnostic plots of drawdown data

An additional powerful diagnostic plot is the derivative plot introduced into the petroleum industry by Bourdet et al. (1983); Bourdet et al. (1989); Horne (1990) and more recently in groundwater studies (McConnell (1993); Spane and Wurstner (1993) amongst others. The derivative plot ***(Fig. 5.6)*** provides a simultaneous presentation of the data on a log-log plot of drawdown versus time and rate of drawdown change versus time.

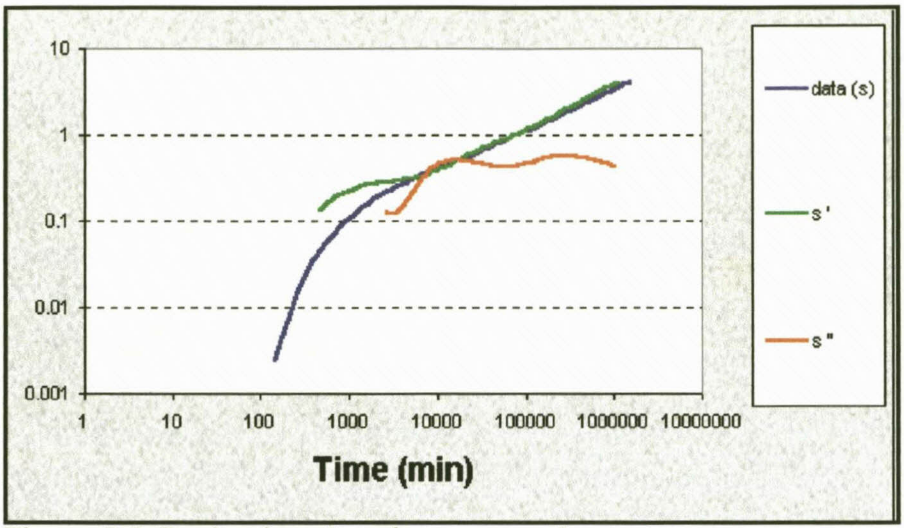


Figure 5.6: Derivative plot of pump test data

It is important to note that the different diagnostic data plots should not be looked at in isolation. The plots should be used as a unit to identify the different characteristics of the pumped borehole as well as the aquifer. After plotting the data on the different diagnostic data plots the data can be analyzed properly and the different conclusions can be made for the first time. All characteristics should be identifiable after this stage.

5.2.4 COMPARISON OF DATA PLOTS WITH THEORETICAL PLOTS

To identify a certain aquifer condition or characteristic the observed drawdown behavior should be compared with the theoretical or known response on the different diagnostic plots. Characteristics such as:

- well bore storage
- linear flow
- bi-linear flow
- radial flow
- fracture positions
- double porosity

- ☐ and boundary conditions

show specific trends or characteristics on the different theoretically determined diagnostic plots and it is these trends that should be compared to the diagnostic plots of the drawdown versus time data.

Care should however be taken when comparing the time-drawdown data observed during a test because it may start and end at any point of a theoretical time-drawdown curve and as a result of this one or more theoretical flow periods may not be reflected in the observed data. For example, an early time linear flow period may be too short to show up in the observed data, or a pumping test may not have been continued long enough to record the effects of aquifer boundary conditions.

In addition, different flow periods may overlap and hide one another. It may be that well bore storage overlap a period of linear flow in fractures and in some cases barrier boundaries may hide the late time radial flow period in a dyke aquifer system. Leakage from the layers on top may hide radial Theis flow. Diagnostic plots allow the dominating flow periods to be identified.

5.2.5 IDENTIFICATION OF FLOW REGIMES

When water is abstracted from a borehole certain types of flow or flow regimes will exist at certain times during the pumping test. These flow regimes will differ from borehole to borehole and it will depend on factors such as abstraction rate and aquifer geometry and geology. The different flow regimes as well as the associated characteristics will be shown on the different diagnostic plots of the drawdown versus time data collected during the pumping test.

To analyze a pumping test correctly the Geohydrologist should be able to identify important characteristics such as:

- ☐ Inner boundary conditions (i.e. well bore storage effects, well bore skin, fracture skin and the lateral extent of the fracture or fracture zone)

- Outer boundary conditions (i.e. especially no-flow boundaries but also fix head boundaries)
- Characteristic flow regimes (the choice of the correct part of the curve to be fitted by looking at the flow dimension that is prevailing during that specific part of the test).

Table 4.9 in Chapter 4 presents an overview of the main flow periods present during a pumping test as well as the characteristics associated with the flow periods. The different features presenting the flow periods on the different plots are also described in the table.

5.2.6 IDENTIFICATION OF MODEL

Based upon the different types of flow periods as well as the associated aquifer and borehole conditions identified when looking at the different diagnostic plots ***(Table 4.9)***, an appropriate aquifer model or models should be selected for interpreting the pumping test data obtained during the pumping test in the field. The choice of model and the associated choice of a suitable part of the time-drawdown data to be used in the analysis are a crucial step in the interpretation procedure. If a wrong model is chosen for a set of time-drawdown data, the hydraulic parameters calculated for the real aquifer will be incorrect or completely wrong.

The interpretation of pumping test data is based on mathematical models that relate the drawdown response to the discharge of the pumped borehole and the results obtained from this short duration test are then used to estimate the borehole performance over a period of many months (even years). The mathematical model could be interpreted by the application of analytical or numerical techniques.

Currently two kinds of models are applied in fractured rock aquifers, namely the single fracture model and the double porosity model. Some of these models have inherent problems, as the following short discussion indicates.

5.2.6.1 SINGLE FRACTURE MODEL

The pumped borehole may intersect a major fracture, fault or dyke. When such a linearity has a much higher hydraulic conductivity in comparison with the remaining part of the hard rock aquifer, it may significantly influence at least part of the time-drawdown behavior of the fractured hard rock aquifer. Single fracture models deal with such a situation. The main types of single fracture models are:

- ☐ infinite conductivity fracture model
- ☐ uniform flux fracture model
- ☐ finite conductivity fracture model and
- ☐ the dyke model.

The first three models have been developed for artificially fractured boreholes in petroleum reservoirs. Only the dyke model has been developed for groundwater purposes. The equivalent system in a single fracture model is a homogeneously confined aquifer of large areal extent, which is dissected from top to bottom by a vertical fracture of relatively short length or by a dyke of infinite length. The pumped borehole fully penetrates the fracture or dyke.

5.2.6.1.1 INFINITE CONDUCTIVITY FRACTURE MODEL

A pumped borehole tapping an assumed plane fracture of infinite conductivity will initially receive water from the aquifer by linear flow towards the fracture (and the borehole) and after continued pumping the water will flow towards the borehole by radial flow (e.g. Gringarten *et al.*, 1974). The assumption of an infinite conductivity in the fracture, however, cannot be considered realistic for highly conductive fractures in hard rock aquifers with low permeable rock matrices (Verweiji and Barker, 1999).

5.2.6.1.2 UNIFORM FLUX FRACTURE MODEL

In this vertical fracture model (Gringarten and Witherspoon, 1972), a uniform flux condition is assumed to exist, i.e. water from the aquifer is assumed to enter the fracture at the same rate per unit area. In reality, the flux distribution along a fracture may approach uniformity only if there is a skin, meaning a low permeability layer between the fracture and the aquifer matrix (Cinco and Samaniego, 1981b).

5.2.6.1.3 FINITE CONDUCTIVITY FRACTURE MODEL

Cinco *et al.* (1978) and Cinco and Samaniego (1981a) described the flow to a borehole for a model with a single vertical fracture of finite conductivity. They recognized three different flow periods. These periods are an initial bilinear flow period reflecting the combined result of linear flow within the fracture and linear aquifer to fracture flow, followed by a rarely observed linear flow period and a final radial flow period.

5.2.6.2 DOUBLE POROSITY MODEL

In a double porosity system the Moench model (1984) is usually applied, but it was found from practical application of the method, that the estimated S-values still show the same distance dependency that is experienced when the Theis method is applied to pumping tests in fractured aquifers (Kirchner and Van Tonder, 1995). Six parameters also have to be fitted which makes the solution non-unique.

One of the main problems with all theoretical models is the underlying assumption contained in it. In most cases a confined situation is assumed and practical experience in South Africa has shown that the shallow fractured rock aquifers are usually semi-confined (the fractures) with a water table aquifer (the matrix) situated on top of it. In many cases during the execution of a pumping test some of the fractures are dewatered, with the result that the conditions changed from semi-confined to unconfined at the fracture position. This means that a flattening of the water level is experienced at the position of a fracture because the specific yield of the fracture is much higher than the confined storage coefficient of the fracture.

Dewatering of some fractures during the pumping test also implies that the effective transmissivity is becoming smaller as time is progressing.

This phenomenon could result in a wrong interpretation of a step drawdown or multirate rate test that implies that the non-linear relationship between drawdown and abstraction rate is due to turbulent flow (non-linear well loss coefficient C) in the borehole. However, it will be shown in this thesis that such a non-linear relationship between drawdown and abstraction rate could also occur during laminar (Darcian) flow in fractured rock aquifers.

5.2.7 SELECTION OF CORRECT INTERPRETATION METHOD

More than ninety percent of the aquifers in South Africa are fractured aquifers that consist of a double porosity system. On the one hand there is the interconnected fractures of high permeability and low storativity and on the other hand there is the matrix blocks with the higher storativity and lower permeability. It is therefor suitable to look at the development of double porosity models and the development of these models over the years. Many theoretical models have been developed to describe aquifer response to constant discharge pumping, all of which assume simplified regular fracture systems, and all of which are complex due to the complex mechanism of fluid flow in fractured rocks. A drawback of many of these methods is that they require laborious curve fitting techniques.

Where a homogeneous porous aquifer model applies to a certain set of time-drawdown data from a pumped hard rock aquifer, this data may be analyzed by using one of the conventional theoretical models (methods). The time-drawdown data representing the flow periods in fractured rock aquifers can only be analyzed by using special methods which is based on drawdown equations that include a greater quantity of unknown parameters in comparison with equations for homogeneous porous conditions. Muskat (1937) was one of the first who analyzed the flow in fractured media. Gringarten (1982) reviewed the extensive literature and found that three main types of approaches to the problem are used. They are:

- The deterministic approach, which is based on an accurate and detailed description of the individual fracture system and is mainly used for small-scale problems in geotechnical engineering.

- ☐ The double porosity medium approach, which assumes a uniform distribution of matrix blocks and fissures throughout the aquifer, including single fracture models and multi-porosity/multi-permeability models.
- ☐ The equivalent homogeneous aquifer approach, which considers only main trends of pressure behavior of the fissured aquifer and tries to relate them to a known model of lower complexity.

5.2.7.1 BARENBLATT'S METHOD

The theoretical models form the basis of the type curve methods derived by various researchers for the analysis of pumping test data in fractured rock aquifers. Most of the methods are based on the double porosity theory developed initially by Barenblatt *et al.* (1960). This concept by Barenblatt was used extensively in the petroleum field and it regards a fractured rock formation as consisting of two media. The formation consists of fractures as well as matrix blocks, both of them having their own characteristic properties. Two coexisting porosities and hydraulic conductivities are thus recognized, on the one hand the primary porosity and low permeability in the matrix and on the other hand those of low storage capacity and high permeability in the fractures. This concept makes it possible to explain the flow mechanism as a re-equalization of the pressure differential in the fractures and blocks by the flow of fluid from the matrix blocks into the fractures. No variation in head within the matrix blocks is assumed.

5.2.7.2 KAZEMI METHOD

Two matrix types are generally discussed, the spherical block matrix (Warren and Root, 1963) used to represent aquifers like quartzite and the layered matrix (Kazemi, 1969) adopted for example for sandstones with bedding planes. Warren and Root (1963) introduced a pseudo-steady state block-to-fracture flow solution, which seems to adequately represent field data. Kazemi (1969) however, using numerical models found that the flow is of transient block-to-fracture nature. Although the pseudo-steady state approach simplifies the mathematical computations, it ignores some of the physics of the problem. This implies that the transient approach is clearly superior from a theoretical standpoint.

Warren and Root (1963) and Kazemi (1969) solved the single borehole pumping problem, considering the storativity effect of the fracture domain, by keeping the same basic assumptions as Barenblatt *et al.* (1960) but, allowing for fracture compressibility. However, they neglected the flow in the block domain. The problem was solved by using an idealized fracture network consisting of three orthogonal, continuos and uniform sets of fractures delimiting a systematic array of identical, rectangular parallelepipeds. Each fracture is assumed to be parallel to one of the principal axis of hydraulic conductivity. Therefor, the aquifer is anisotropic with respect to fracture hydraulic conductivity, flow between fractures and matrix blocks is steady state and flow to the borehole via the fractures is unsteady state. Kazemi (1969) extended the method originally developed by Warren and Root (1963) for a pumping borehole to a method, using drawdown data from observation boreholes. If the data for an observation borehole is available, the Kazemi method can be applied to determine the correct values for the storage coefficient of the fracture system (S_f) and the matrix (S). If observation data is not available, the storage coefficient must be estimated. The coefficient $S_f = 10^{-4}$ for fracture systems is considered adequate as it assumes confined conditions at early time. The value of the matrix storage coefficient is more variable and therefor more difficult to estimate.

The method developed by Kazemi (1969) as well as most of the other methods can be used only if the following assumptions are made:

- the aquifer is confined and of infinite aerial extent
- aquifer thickness is uniform over the area that will be influenced by the test
- the borehole is fully penetrating
- the borehole is pumped at a constant rate
- prior to pumping the piezometric surface is horizontal over the area that will be influenced by the test
- flow to the borehole is in an unsteady state.

5.2.7.3 MOENCH METHOD

Moench (1984) proposed a type curve approach for the analysis of double porosity data, which incorporated well bore storage, borehole skin and fracture skin (a thin skin of low permeability material deposited on the surface of the blocks), that serves to impede and therefor it is a more advanced method than the simple straight-line approach proposed by Warren and Root (1963) and Kazemi (1969). The effect of fracture skin in double porosity systems is to delay flow from the matrix blocks to the fractures and gives rise to pressure responses that are similar to those predicted under conditions of pseudo-steady state flow (Moench, 1984). According to Moench, by reducing gradients of hydraulic head in the compressible matrix blocks, fracture skin provides theoretical justification for the pseudo-steady state flow approximations used in the Warren and Root (1963) model. The following assumptions apply to the use of the Moench approach:

- ☐ the aquifer has infinite areal extent
- ☐ the aquifer has uniform thickness
- ☐ aquifer potentiometric surface is initially horizontal
- ☐ pumping and observation boreholes are fully penetrating
- ☐ fractured aquifer represented by double porosity system consisting of low-permeability, primary porosity blocks and high-permeability, secondary porosity fissures or fractures
- ☐ matrix consists of slab-shaped or spherical blocks
- ☐ flow is unsteady
- ☐ water is released instantaneously from storage with decline of hydraulic head.

5.2.7.4 BOURDET AND GRINGARTEN METHOD

Bourdet and Gringarten (1980) showed that the double porosity behavior of a fractured rock aquifer only occurs in a restricted area around the pumped borehole. Outside that area the drawdown behavior is that of an equivalent porous medium. The Bourdet-Gringarten method is based on matching both the early- and late-time data with the Theis-curve, which yield values of T_f and S_f and T_f and $S_f + S_m$ respectively. In order to obtain accurate results, all the drawdown data must fit the

Theis-curve, not just a segment of the drawdown data. It is recommended that this simplified method be used and it was found that this method yields reliable values of T_f. The estimated S-values as obtained with the simplified method as well as the other methods described above, still show distance dependency as first observed by Bredenkamp (1992) and Bredenkamp *et al.* (1994).

5.2.7.5 BARKER METHOD

Barker (1988) developed an analytical method called the generalized radial flow model that consists of a homogeneous and isotropic fracture system characterized by a hydraulic conductivity (K_f) and specific storage (S_{sf}), in which the flow to the borehole is radial and n-dimensional. With this model, Barker presented a way of generalizing the conventional models used for pumping test analysis for arbitrary flow dimensions. For instance, after generalizing the Theis equation, it will describe the drawdown in an arbitrary fractured confined aquifer. In comparison with the conventional Theis equation, two additional parameters are introduced, the flow dimension (n) and the extent of flow region (b). The parameter b has no simple meaning for non-integer flow dimensions. The flow dimension parameter (n) is referred to as a fractal dimension and when:

- ☐ $n = 1$ it implies linear flow
- ☐ $n = 1.5$ it implies bilinear flow
- ☐ $n = 2$ it implies radial flow.

Interpretation procedures based on the generalized radial flow model yield information on flow dimension (n), $K_f\ b^{3-n}$ and $S_{sf}/4K_f$ (Bangoy *et al.*, 1992, 1994; Black, 1994). The general radial flow model proposed by Barker (1988) is the basis of the method for characterizing an arbitrary fractured aquifer system ($n < 2$). The method requires time drawdown data from the pumped borehole and at least two observation boreholes. Provided the number and distribution of observation boreholes are adequate, the Barker method allows different zones in the fractured aquifer to be identified and the characterization of each zone by its diffusivity (K_f/S_{sf}) and the quantity ($K_f b^{3-n}$).

The Barker method, like most other methods, was also developed using certain assumptions. The general assumptions and conditions are:

- ☐ the aquifer is fractured with flow dimensions < 2
- ☐ the aquifer is confined and of infinite areal extent
- ☐ the borehole fully penetrates the aquifer
- ☐ the borehole is pumped at a constant rate, all water pumped comes from storage in the fracture network
- ☐ well losses and wellbore storage are negligible
- ☐ the flow to the borehole is entirely through the fractures
- ☐ the flow to the borehole is in an unsteady state.

5.2.7.6 CINCO-LEY METHOD

Cinco-Ley *et al.* (1978) introduced a semi-analytical model that describes the drawdown in a single vertical fracture with finite conductivity and length, which is embedded in an infinite, isotropic, homogeneous, horizontal matrix limited by upper and lower impermeable boundaries. It considers bilinear flow in the system and is therefore a generalised solution for this type of aquifer's geometry. The Gringarten *et al.* (1974) infinite flux solution is a special case of this model.

The gradient along the fracture cannot be neglected due to its finite conductivity and the solution requires the knowledge of the flux distribution along the fracture in time. The model developed by Cinco-Ley *et al.* (1978) uses a special form of the finite difference method to obtain this distribution.

Cinco-Ley *et al.* (1978) presented a series of type curves for the pumped borehole for relative conductivity values (Cr) in the range of 0.1 to 100 and dimensionless time t_d between 10^{-3} and 10^{3}. The curve that corresponds to Cr $\geq$ 100 practically coincides with the infinite flux solution from Gringarten *et al.* (1974). Using the Cinco-Ley & Samaniego model (1978) in those cases where bilinear flow and radial-acting flow are present (Cr < 100), the following parameters can be determined:

- ☐ Reservoir transmissivity
- ☐ Reservoir storage coefficient
- ☐ Fracture half-length
- ☐ Fracture transmissivity
- ☐ Fracture storage coefficient.

5.2.7.7 RPTSOLV PROGRAM

Because of assumptions such as homogeneity used in developing the above methods as well as the unique composition and characteristics of South African Karoo aquifers some of these methods sometimes produces unrealistic parameter values when interpreting pumping tests. In a fractured porous medium, especially on the scale of a pumping test it is assumptions such as homogeneity that is violated. The mixture of horizontal movement in the fractures and the vertical leakage in the surrounding matrix cannot be accounted for in the analytical solutions. Therefor incorrect and unrealistic values, for especially the storativity of the aquifer are calculated. The distance dependency of the storativity value is the result of the composition of the aquifer as well as the pressure gradients present in the aquifer during a pumping test.

To address the problem of distance dependency of the storativity and to cater for the double porosity systems in South Africa, the program RPTSOLV was developed by Verwey *et al.*, (1995). RPTSOLV is an automated two-dimensional radial finite element model to determine the parameters of the aquifer from the pumping test data. The solution produced by this program (model) is dependent on a number of inputs or parameters. They are:

- ☐ accurate time-drawdown pumping test data
- ☐ boundary conditions
- ☐ conceptual model
- ☐ realistic initial guess of the parameters.

If the initial guesses of the parameters are not good or realistic it may happen that the model reaches a local minimum and not the global minimum. The solution of any numeric model is not completely correct close to the abstraction borehole, i.e. in a radius less than 1 meter from the borehole. It is thus recommended that when analyzing pumping test results in an abstraction borehole, that an observation distance of between 1 and 5 meters be used in the program.

The RPTSOLV program (model) solves for four unknown parameters. They are:

- ☐ transmissivity of the fracture (T_f)
- ☐ transmissivity of the matrix (T_m)
- ☐ storativity of the fracture (S_f)
- ☐ storativity of the matrix (S_m).

The RPTSOLV program will yield a reasonably reliable sustainable daily abstraction rate. When a no-flow boundary is used some distance away in this model, practice has shown that the method usually underestimates the sustainable abstraction rate. The use or application of this program (model) requires an experienced user and by practicing and repetition the user will become more acquainted with the software and initial choices.

5.2.7.8 TEST PUMPING ANALYSIS PROGRAM (TPA PROGRAM)

The complex situation in fractured aquifers requires a decent understanding of the drawdown behaviour if reliable reservoir information is to be obtained. This can be achieved by a detailed diagnosis of drawdown and recovery data in combination with a conceptual model of the geological arrangement in the aquifer. The computer program TPA (Test Pumping Analysis) was designed by Ingo Bardenhagen (2000) for this purpose. The program provides powerful tools for the detailed diagnostic and analysis of the pumping test data, which includes a simulator that can be used for a forward modelling of test curves. The simulator offers solutions for primary aquifers like:

- ☐ confined aquifers
- ☐ leaky aquifers
- ☐ delayed response aquifers and

- double aquifers.

This includes the influences from reservoir boundaries, well bore storage and partial penetration. In the case of fractured aquifers solutions are provided for:

- double porosity systems
- single vertical fractures with finite and infinite conductivity
- horizontal fracture with finite and infinite conductivity
- generalised radial flow
- the influences of reservoir boundaries
- well bore storage and
- partial penetration.

Moench (1984) proposed a type curve approach for the analysis of double porosity data, which includes well bore storage, well skin, and fracture skin and therefore is more advanced than the simple straight-line approach proposed by Warren & Root (1963) and Kazemi (1969). Because of the tremendous increase of computer calculation power the TPA program makes use of a combined approach of straight-line and forward modelling. The advantage of this method lies in the ability to calculate different drawdown scenarios after model calibration to find the optimal abstraction rate for a particular borehole.

Basically two methods of analysis for the drawdown data are used to determine the formation or matrix transmissivity (T_m). The straight-line method (ln-log plot) and a type curve method (log-log plot) are normally used. If recovery data are available, the recovery method of Theis (1935) or Agarwal (1979) can be used. Alternatively, a forward modelling method, using the TPA program can be applied to determine the aquifer parameters for both the drawdown and recovery phase. Note that the determination of the actual fracture transmissivity (T_f) is not possible because it is a priori considered infinite. The above methods can be applied if the following conditions are true:

- matrix is infinite

- ☐ aquifer (fracture and matrix) is confined
- ☐ Darcian flow prevails in the fracture and the matrix
- ☐ borehole and fracture penetrate the aquifer fully
- ☐ negligible well bore storage and fracture storage
- ☐ negligible well bore skin and fracture skin
- ☐ straight-line method can be applied if dimensionless time (td) > 5. Crosscheck, where the first derivative becomes horizontal.

If the transmissivity value is known either from the straight-line approach or the type curve approach, this value should be used as a known parameter in the forward modeling to shorten the time necessary to fit the unknown parameters. The model implemented in TPA program simplifies the model presented by Cinco-Ley *et al.* (1978) by neglecting the influence of the fracture's storage coefficient. It is considered that for the practical times this parameter does not influence the drawdown behavior. Furthermore at this stage the TPA program is not able to model the drawdown of observation boreholes and therefore the unique evaluation of the unknown parameters is not viable.

5.2.8 PARAMETER CALCULATION

Model that is to be used	Aquifer and borehole conditions	Method that is to be used	Parameters that can be calculated
Generalized radial flow model	○ Arbitrary fracture networks (n<2) ○ Pumping test ○ Late-time data	Bangoy *et al.*, 1992	n; $K_f b^{(3-n)}$; K_f; S_{sf}
Double porosity model	○ Double porosity aquifer	Bourdet-Gringarten curve fitting (1980)	T_f; S_f; l; v; S_m
	○ Pseudo steady state interporosity	Kazemi straight line (1969)	T_f; S_f; l; v; S_m
		TPA method	T_f; S_f; T_m; S_m

	flow	RPTSOLV	T_f; S_f; T_m; S_m
	○ Pumping test ○ Single borehole test	Moench (1984)	K_f; K_m; S_f; S_m (where S denotes specific storage and not storativity)
	○ No borehole losses	Bourdet *et al.* Derivative curve (1980)	T_f; S_f; l; v; S_m
	○ No wellbore storage	Warren-Root straight line (1963)	T_f; S_f; l; v; S_m

Table 5.2: Parameters obtained by applying different models

Once the correct method to interpret the pumping test data had been identified or chosen, the parameters for the aquifer can be determined. The time-drawdown pumping test data is entered into the model and the curve fitting or straight-line method can be applied to the data. This procedure will yield the correct parameters for the specific borehole and aquifer. The table above ***(Table 5.2)*** gives an indication of the different parameters obtained when applying the different methods to the drawdown data.

5.2.9 SUSTAINABLE YIELD CALCULATION

The sustainable yield of a borehole is not obtained from conventional pumping test interpretations. These interpretations are used to establish the hydraulic properties of the aquifer. There exist a number of methods for estimating the sustainable yield of a borehole, some of which require parameter values such as transmissivity (T) and storativity (S), values determined by applying the correct method to the pumping test data.

An increasing number of boreholes in Southern Africa have dried up during the past years, in spite of favorable hydrologic conditions. Overestimation of the borehole yield was due to the application of improper extrapolation of drawdown curves, which ignored barrier boundaries and neglected parameter uncertainties arising from the imperfect knowledge of the effective aquifer properties.

The FC-method will be discussed in more detail later on in this thesis.

5.2.10 PUMPING TEST EXAMPLE

In an effort to explain the theory described in this chapter better, an example will be included. The example was taken from actual pumping test data that was collected in the field. The procedure that will be followed in analyzing the data can be broken down into steps.

5.2.10.1 STEP 1 – OBTAINING RAW DATA

Pumping test data from a municipal production borehole (GR2) in the Graaff-Reinet area was obtained. The Geohydrologist needs to determine the possible long-term sustainable yield of this specific borehole in order to supply the residence of Graaff-Reinet with drinking water. The following information was supplied with the pumping test:

Depth of borehole = 53 meters
Final blow yield = 39 l/s
Pumping rate during test = 28.6 l/s
The borehole is situated in the Beaufort Group, Karoo Sequence

The table below ***(Table 5.3)*** represents the time drawdown data where the time was logged as actual time of day and the drawdown as actual readings on the diptape.

Time	Dipmeter Reading (meter)	Time	Dipmeter Reading (meter)	Time	Dipmeter Reading (meter)	Time	Dipmeter Reading (meter)
12:23:00	7.00	13:03:00	13.62	20:23:00	17.26	2:43:00	20.96
12:23:30	11.09	13:08:00	13.72	21:23:00	17.26	4:23:00	21.16
12:24:00	11.52	13:15:00	13.91	22:23:00	17.36	6:03:00	21.36
12:24:30	11.80	13:18:00	13.94	23:23:00	17.56	7:43:00	21.56
12:25:00	11.89	13:23:00	14.12	0:23:00	17.56	9:23:00	21.56
12:25:30	11.97	13:33:00	14.30	1:23:00	17.66	11:03:00	21.76
12:26:00	12.10	13:43:00	14.46	2:23:00	17.96	12:43:00	21.76
12:27:00	12.19	13:53:00	14.64	3:23:00	18.96	14:23:00	22.06
12:28:00	12.22	14:03:00	14.77	5:03:00	18.26	16:03:00	22.16
12:29:00	12.35	14:13:00	14.93	6:43:00	18.46	17:43:00	22.46
12:30:00	12.39	14:23:00	15.07	8:23:00	18.66	19:23:00	22.56
12:31:00	12.46	14:43:00	15.35	10:03:00	18.86	21:03:00	22.66
12:32:00	12.53	15:03:00	15.57	11:43:00	19.16	22:43:00	22.86
12:33:00	12.57	15:23:00	15.77	13:23:00	19.36	0:23:00	22.96
12:34:00	12.65	15:53:00	16.04	15:03:00	19.66	2:03:00	23.16
12:35:00	12.70	16:23:00	16.04	16:43:00	20.06	3:43:00	23.16
12:38:00	12.84	16:53:00	16.46	18:23:00	20.06	5:23:00	23.26
12:43:00	13.00	17:23:00	16.55	20:03:00	20.16	7:03:00	23.46
12:48:00	13.15	17:53:00	16.67	21:43:00	20.76	8:43:00	23.66
12:53:00	13.30	18:23:00	16.83	23:23:00	20.76	10:23:00	23.76
12:58:00	13.54	19:23:00	16.95	1:03:00	20.86	12:03:00	23.86

Table 5.3: Time-drawdown data for GR2

5.2.10.2 STEP 2 – DATA PREPARATION

Elapsed Time (minutes)	Drawdown (s) (meters)	Elapsed Time (minutes)	Drawdown (s) (meters)	Elapsed Time (minutes)	Drawdown (s) (meters)	Elapsed Time (minutes)	Drawdown (s) (meters)
0	0	40.0	6.62	480.0	10.20	2300.0	13.90
0.5	4.09	45.0	6.72	540.0	10.20	2400.0	14.10
1.0	4.52	52.0	6.91	600.0	10.30	2500.0	14.30
1.5	4.80	55.0	6.88	660.0	10.50	2600.0	14.50
2.0	4.89	60.0	7.06	720.0	10.50	2700.0	14.50
2.5	4.97	70.0	7.24	780.0	10.60	2800.0	14.70
3.0	5.10	80.0	7.40	840.0	10.90	2900.0	14.70
4.0	5.19	90.0	7.58	900.0	11.90	3000.0	15.00
5.0	5.22	100.0	7.71	1000.0	11.20	3100.0	15.10
6.0	5.35	110.0	7.87	1100.0	11.40	3200.0	15.40
7.0	5.39	120.0	8.01	1200.0	11.60	3300.0	15.50
8.0	5.46	140.0	8.29	1300.0	11.80	3400.0	15.60
9.0	5.53	160.0	8.51	1430.0	12.10	3500.0	15.80
10.0	5.57	180.0	8.71	1500.0	12.30	3600.0	15.90
11.0	5.65	210.0	8.98	1600.0	12.60	3700.0	16.10
12.0	5.70	240.0	8.98	1700.0	13.00	3800.0	16.10
15.0	5.84	270.0	9.40	1800.0	13.00	3900.0	16.20
20.0	6.00	300.0	9.49	1900.0	13.10	4000.0	16.40
25.0	6.15	330.0	9.61	2000.0	13.70	4100.0	16.60
30.0	6.30	360.0	9.77	2100.0	13.70	4200.0	16.70
35.0	6.54	420.0	9.89	2200.0	13.80	4300.0	16.80

Table 5.4: Edited Time-drawdown data for GR2

The data obtained during the pumping test have to be edited so that the time can be changed to elapsed time and the dipmeter readings must be changed to drawdown. The table above ***(Table 5.4)*** represents the edited time-drawdown data.

A plot ***(Fig. 5.7)*** of the edited drawdown data was made in EXEL and from this plot it is evident that one of the readings is suspect, it plotted to high in relation to the other points. The reading taken at 900 minutes into the pumping test shows a definite spike in relation to the other data on the chart. The readings around 900 minutes were plotted on a separate chart, displayed on the right in the figure below ***(Fig 5.7)***. The reading of 18.96 meters was taken by the pumping test operator at 03:23 in the morning and it may be that he was still sleepy. It seems as though the observer made a 1-meter reading mistake on the dipmeter, a mistake that commonly occurs.

It is suggested that this reading should be corrected and if any uncertainty exist about correcting the reading it is suggested that the reading should be ignored and removed from the pumping test data. After this check had been completed and the data is acceptable, the data can be used in the different diagnostic plots.

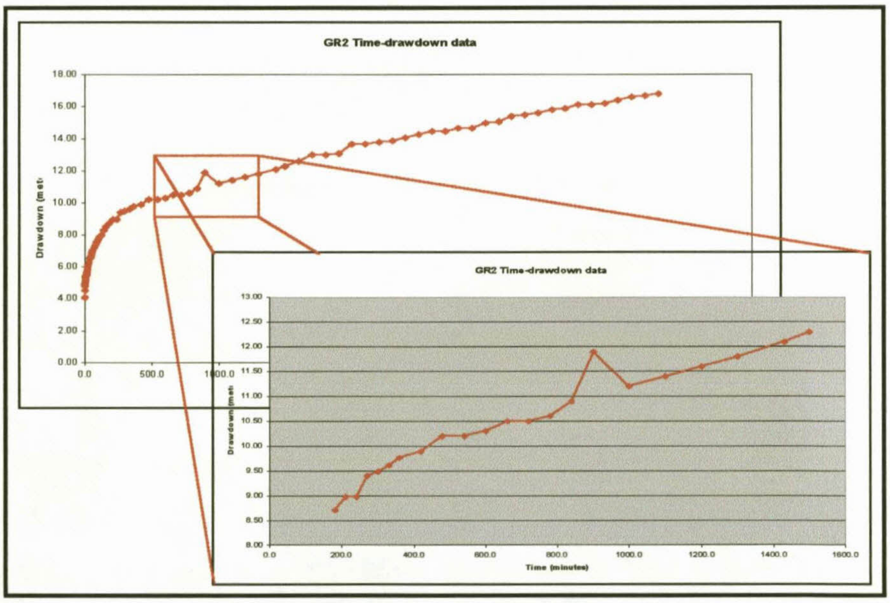


Figure 5.7: Plot of Time-drawdown data of GR2

5.2.10.3 STEP 3 – CONSTRUCTION OF DIAGNOSTIC DATA PLOTS

The different diagnostic plots can be plotted in order to determine the different flow regimes and to determine whether boundaries influenced the abstraction from the aquifer. The figure below ***(Fig. 5.8)*** represents the different diagnostic plots of the drawdown versus time data for GR2.

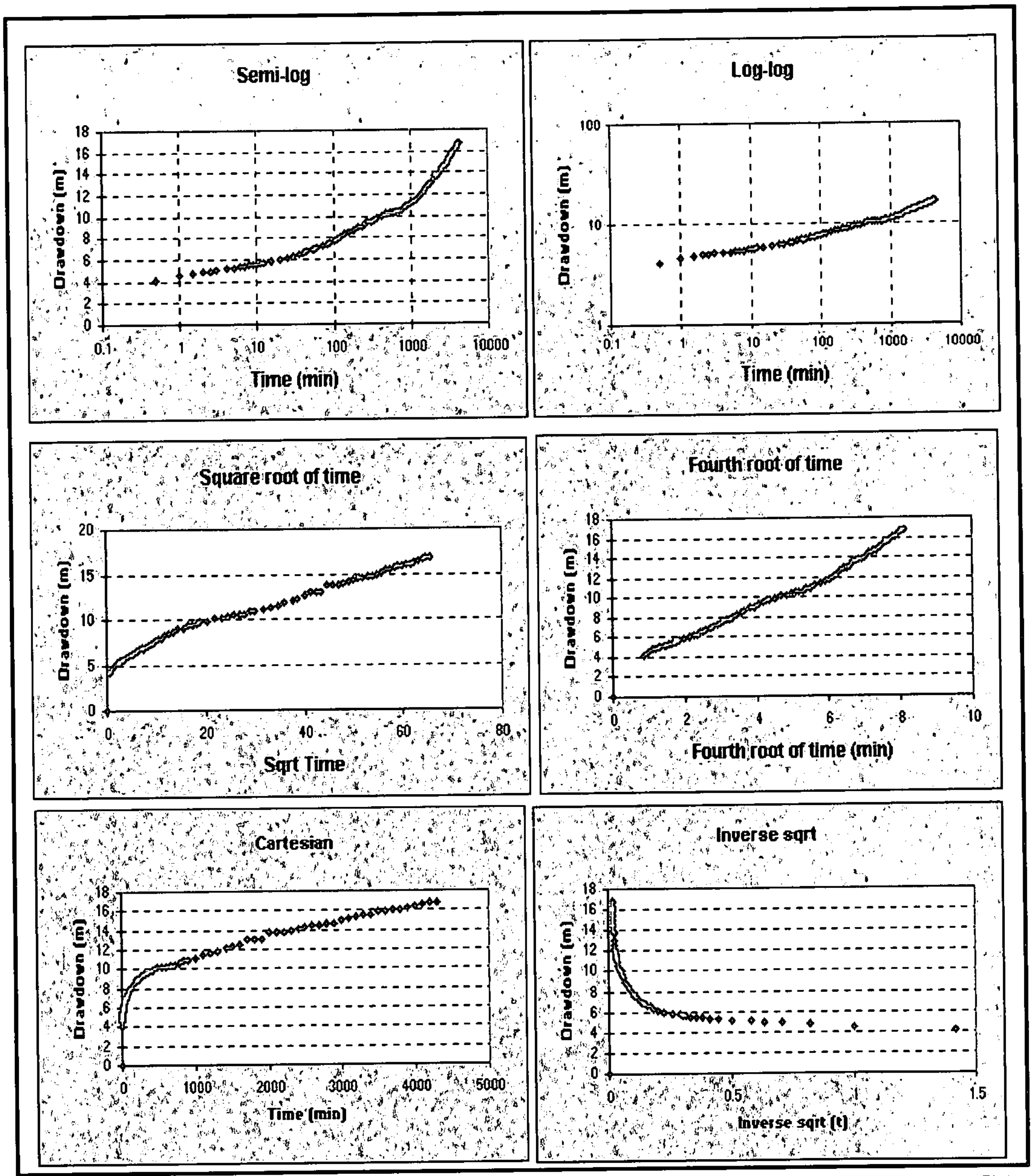


Figure 5.8: Diagnostic plots of drawdown versus time data obtained from GR2

The drawdown versus time data can also be used to construct another diagnostic plot, the derivative plot. This plot will yield a lot of information. The figure below ***(Fig. 5.9)*** is the derivative plot of the drawdown versus time data obtained from GR2. The blue line represents the drawdown versus time data and the green line is the first derivative plot. The red line is the second derivative plot.

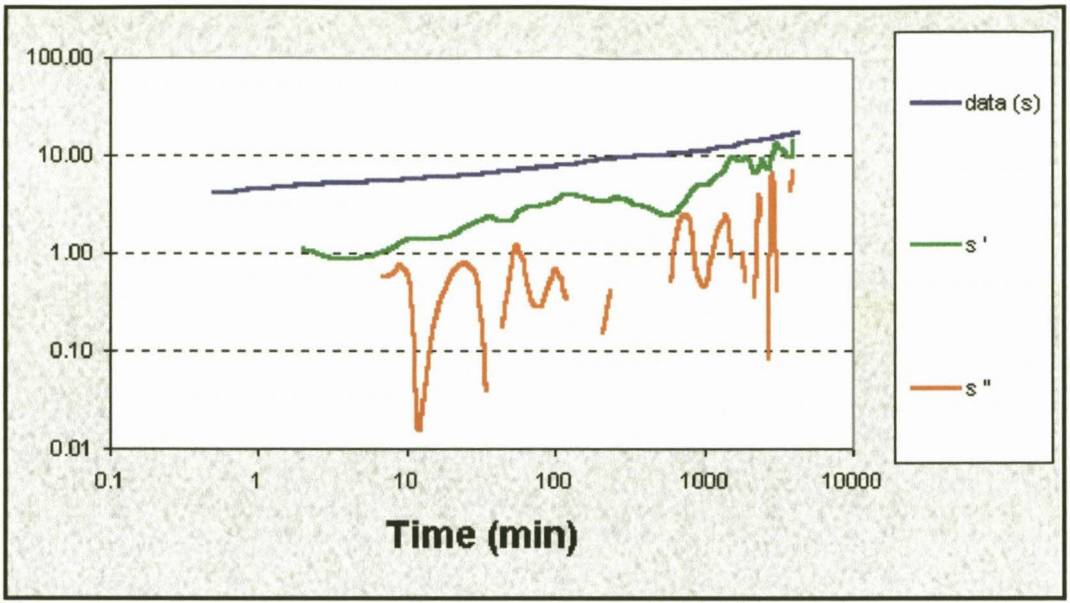


Figure 5.9: Derivative plot of GR2 pumping test data (green and red lines)

5.2.10.4 STEP 4 – COMPARISON OF DATA PLOTS WITH THEORETICAL PLOTS

Now that we have got the correct data and all the different diagnostic data plots certain deductions can be made. The different plots can be compared with theoretical plots to determine characteristics such as well bore storage, fracture positions, porosity systems and boundary conditions.

During pumping there may exist different types of flow regimes at different times. From the diagnostic data plots the different types of flows regimes as well as the associated characteristics can be determined. Based on the different flow types as well as the associated aquifer conditions identified when looking at the diagnostic plots, an appropriate aquifer model or models should be selected to interpret the pumping test data obtained during the pumping test.

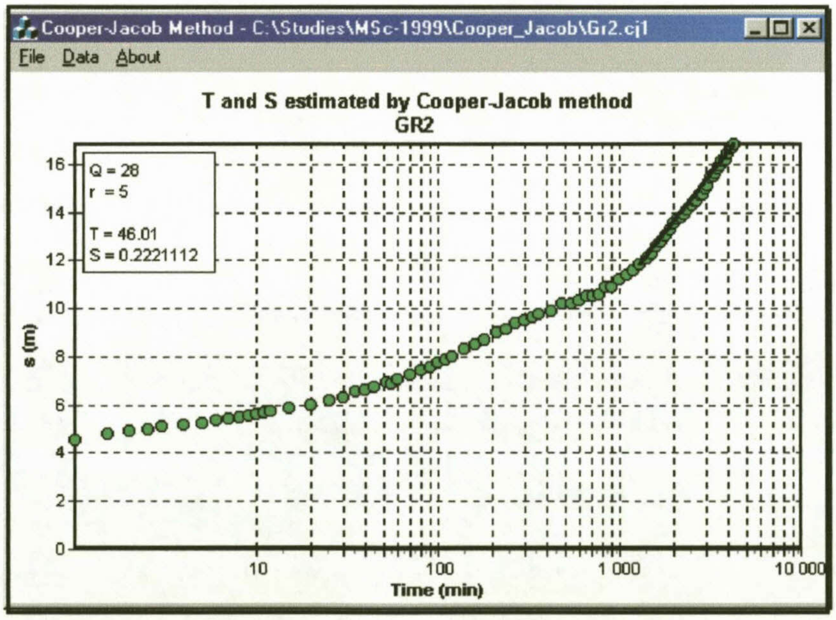
Looking at the different diagnostic data plots the following can be deducted:

- No slope = 1 at early time on the derivative plot, so no indication of well bore storage. Confirmed by early slope less than one on log-log plots.

- Dips on derivative plot indicates a double porosity system (fractures and matrix blocks), so a double porosity model should be used in analyzing the pumping test data.
- Humps on the derivative plot indicate the presence of multiple fractures. A flattening of the line on the log-log and semi-log plots confirms this.
- Slope = 1 at late time on derivative plot indicates that a boundary is reached. This is confirmed by a slope = 1 at late time on the log-log plot.
- Matrix flow becomes dominant at a time of about 19 hours.

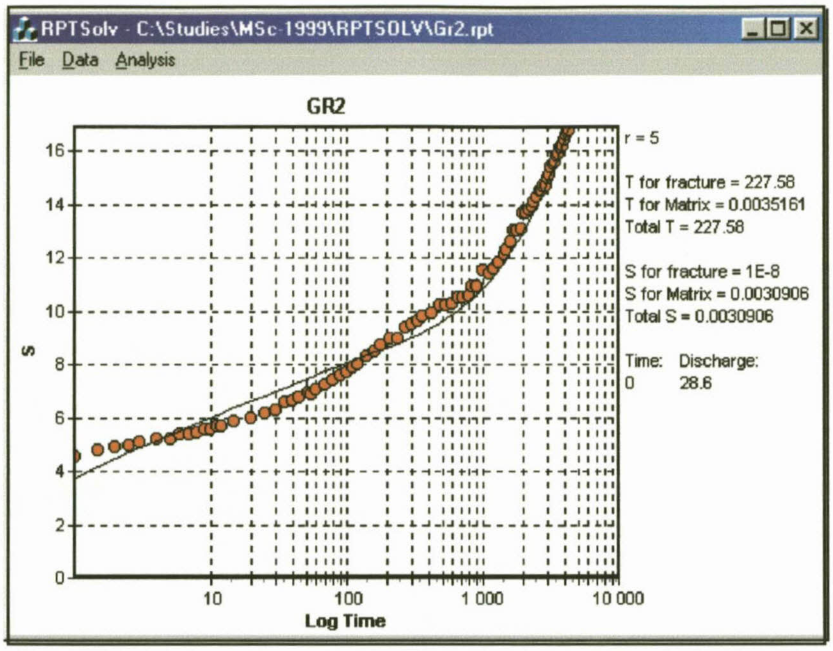
5.2.10.5 STEP 5 – PARAMETER CALCULATION

Once the correct method to interpret the pumping test data had been identified or chosen, the parameters for the aquifer can be determined. The time-drawdown pumping test data is entered into the model and the curve fitting or straight-line method can be applied to the data. This procedure will yield the correct parameters for the specific borehole and aquifer. Three different software packages were used to determine the transmissivity (T) and storativity (S) values. The methods used were Cooper-Jacob method ***(Fig. 5.10)***, RPTSOLV method ***(Fig. 5.11)*** and FC method ***(Fig. 5.12)***.



Q = 28
r = 5
T = 46.01
S = 0.2221112

Figure 5.10: T and S determined with Cooper-Jacob method



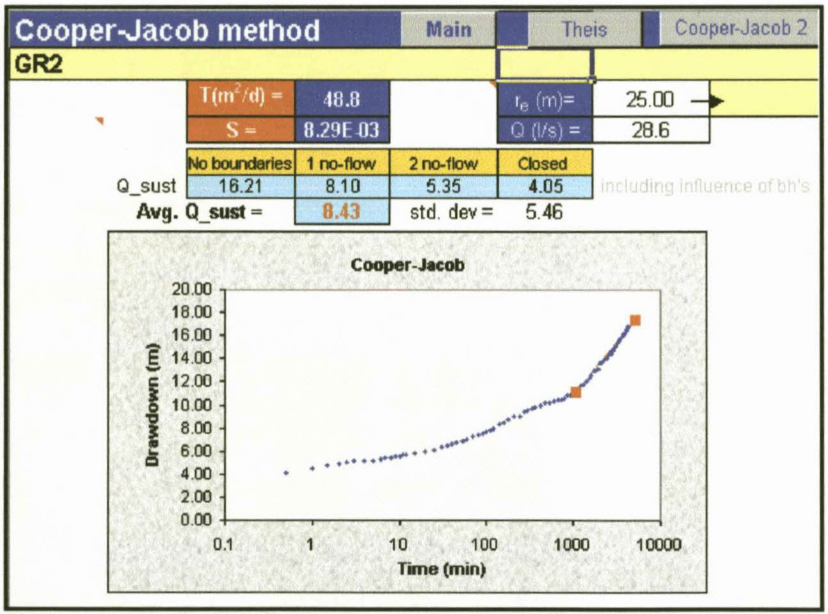
r = 5

T for fracture = 227.58
T for Matrix = 0.0035161
Total T = 227.58

S for fracture = 1E-8
S for Matrix = 0.0030906
Total S = 0.0030906

Time: Discharge:
0 28.6

Figure 5.11: T and S determined with RPTSOLV method



T(m²/d) = 48.8
S = 8.29E-03
r_e (m)= 25.00
Q (l/s) = 28.6

	No boundaries	1 no-flow	2 no-flow	Closed	
Q_sust	16.21	8.10	5.35	4.05	including influence of bh's
Avg. Q_sust =	8.43	std. dev =	5.46		

Figure 5.12: T and S determined with FC method

The last plot is the standard Cooper-Jacob method incorporated in the FC program developed by Van Tonder *et al.* (1998).

The table below ***(Table 5.5)*** gives an indication of the different transmissivity (T) and storativity (S) values obtained with the different methods.

METHOD	TRANSMISSIVITY	STORATIVITY
Cooper-Jacob	46.01	0.222
RPTSOLV	217	0.003
FC method	47.5	0.008

Table 5.5: T and S values for different methods

The transmissivity values obtained from the Cooper-Jacob and FC method are the same because it is the same method. The fit was done to the late data in both these cases. In the case of the RPTSOLV method the fit was done to the early data, hence the much higher transmissivity value. For management purposes the transmissivity value obtained by fitting the line to the late data must be used.

The storativity values vary dramatically in the table above and the reason for this is the distance dependency of the storativity values. Previous tests showed that for the same aquifer system values for S as low as 10^{-6} to as high as 10^{-3} were obtained. Because of the distance dependency of the storativity value determining this value for a pumping borehole gives completely wrong answers, especially if analyzed with a porous flow model or analytical fracture model. To overcome this problem, the numerical two layered radial model (RPTSOLV) was developed. This method yields correct values for S, as can be seen in the table. Typical storativity values for Karoo aquifers are $S_m = 0.001$ (matrix) and $S_f = 0.0001$ (fracture).

5.2.10.6 STEP 6 – SUSTAINABLE YIELD CALCULATION

After the parameters had been determined they can be used along with other information such as the available drawdown and boundary conditions to determine the long term sustainable yield for the borehole. The table below ***(Table 5.6)*** gives an indication of the estimated yield obtained in using the different methods.

METHOD	ESTIMATED YIELD (l/s)
Late T-method	11.68
Drawdown-boundary	8.96
Distance-boundary	5.05
RPTSOLV method	1.96
Square root time method	7.92
FC method	3.50

Table 5.6: Management results with different methods

It should be mentioned that the borehole failed when it was pumped at a rate of 7.70 l/s as a recommended yield. From the table it can be seen that some of the recommended yields are higher and some are lower than 7.70 l/s. The FC method, especially developed for South African aquifer systems gives a yield of 3.50 l/s, which looks very promising. This method will be discussed in detail in the next chapter.

CHAPTER 6

ESTIMATION OF SUSTAINABLE YIELD

6.1 INTRODUCTION

An increasing number of boreholes in Southern Africa have dried up during the past years, in spite of favorable hydrologic conditions. An investigation of reliable estimates for the sustainable yield of the boreholes was therefore required. Overestimation of the borehole yield was due to the application of improper extrapolation of drawdown curves, which ignored barrier boundaries and neglected parameter uncertainties arising from the imperfect knowledge of the effective aquifer properties. Sami and Murray (1998) gave a summary of methods that are commonly used in South Africa to estimate the sustainable yield of a borehole and the methods include:

- the Recovery Method,
- the late T-method,
- the Drawdown-to-boundary Method and
- the Distance-to-boundary Method.

Naafs (1999) compared the methods above using the newly developed Flow Characteristic method (in short FC-method (Van Tonder *et al.*, 1998)) and found that the Recovery method and the late T-method are not to be used because they gave a too high sustainable yield in most of the cases tested. Naafs adapted the late T-method by introducing a variable available drawdown. In the case of this adapted late T-method, it yielded very similar results if compared to the Drawdown-to-boundary and Distance-to-boundary methods. Both the adapted late T-method and the Drawdown to-Boundary methods are special cases of the FC-method.

The following sections show how to estimate the sustainable yield of a borehole by quantifying the effects of no-flow boundaries as well as the uncertainties in the values of transmissivity, storativity and distances to the boundaries.

6.2 ESTIMATION OF THE SUSTAINABLE YIELD OF A BOREHOLE

The ratio of drawdown (s) to pumping rate (Q) is a constant for a borehole or well (if corrected for well losses). This constant only depends on the aquifer properties transmissivity (T) and storativity (S). If t_{long} describes the maximum operation time in which the drawdown (s) shall not exceed a maximum drawdown ($s_{available}$), the extrapolation of the measured pumping test drawdown can be used to determine the sustainable yield ($Q_{sustainable}$):

$$Q_{Sustainable} = Q_{PumpingTest} \frac{s_{Available}(t = t_{long})}{s_{PumpTest}(t = t_{long})} \tag{6.1}$$

where $Q_{Sustainable}$ = Long term sustainable yield

$Q_{PumpingTest}$ = Discharge rate during pumping test

$S_{Available}$ = Available drawdown

$S_{PumpTest}$ = Drawdown obtained during pumping test

t_{Long} = Maximum operation time

The available drawdown is for instance the position of the main water strike in the borehole. If the drawdown exceeds this position, a drastic decrease in the yield of the borehole occurs and it may dry up. Extrapolating the drawdown measured during the pumping test from the time of the end of the pumping test to a time t_{long} of around two to five years, remains a problem. Applying the Theis solution traditionally does this extrapolation. A more sophisticated extrapolation of the pumping test drawdown beyond the time of the end of the measurement is obtained by using a Taylor series expansion based on the extrapolation of the measured drawdown curve including drawdown derivatives, and by accounting for boundaries.

6.2.1 EXTRAPOLATION OF PUMPING TEST DRAWDOWN

The drawdown measured during a pumping test is the sum of the drawdowns due to the production well, s_{Well}, and the boundaries, $s_{Boundary}$:

$$s(t = t_{long}) = s_{Well} + s_{Boundary} \tag{6.2}$$

The drawdown due to the production well (s_{Well}) is extrapolated by a Taylor series expansion around the late measurement points of the drawdown at $t \approx t_{EOP}$ (subscript EOP denotes end of pumping test). The Taylor series expansion is performed with respect to the logarithm of time, $\log_{10}$. A second order approximation is assumed to be sufficient:

$$\begin{aligned} s_{Well}(t = t_{long}) \approx s(t = t_{EOP}) &+ \frac{\partial s}{\partial \log t}\bigg|_{t=t_{EOP}} (\log t_{long} - \log t_{EOP}) \\ &+ \frac{1}{2}\frac{\partial^2 s}{\partial (\log t)^2}\bigg|_{t=t_{EOP}} (\log t_{long} - \log t_{EOP})^2 \end{aligned} \tag{6.3}$$

The time t_{EOP} has to be large enough to ensure that the drawdown has already passed the early time flow behavior caused by well bore storage, fracture flow and double porosity effects. This can clearly be monitored by looking at the derivative plot $\partial s / \partial \log t$ (Van Tonder, 1998) (Bourdet *et al.*, 1984). Usually the effect of the boundaries can only be seen at very late times of the pumping test. The extrapolation of equation (6.3) therefore does not generally include boundary information.

For simple geometries of the boundaries, image well theory is applied to analyze the effects of the boundaries on the drawdown ($s_{Boundary}$).

The analytical expressions and the simplified boundary configurations already yield far better estimates of the sustainable yield than the traditional Theis extrapolation, which assumes an aquifer of infinite extent. The estimate can be improved further by taking into account uncertainties in the required parameters like the late time transmissivity (T), storativity (S), and the distances to the boundaries (a and b).

6.2.2 RISK ANALYSIS BY UNCERTAINTY PROPAGATION

Kunstmann & Kinzelbach (1998) showed computational efficient methods of quantifying uncertainties in groundwater modeling. The Gaussian Error Propagation method can easily and most advantageously be applied to analytical formulas. It is applied to the drawdown equations presented and described below.

The drawdown in the pumping well is a function of the parameters t, Q, T, S, a and b, where a and b are the distances to boundaries. It is assumed that the latter four parameters are not known perfectly, but are within a range around their mean values:

$$T=\hat{T}\pm\sigma_T,\quad S=\hat{S}\pm\sigma_S,\quad a=\hat{a}\pm\sigma_a,\quad b=\hat{b}\pm\sigma_b \qquad (6.4)$$

where T = Transmissivity
S = Storativity
a = distance to boundary
b = distance to boundary
σ = standard deviation

The mean drawdown ($\hat{s}$) can be approximated by evaluating the drawdown equations at the mean values of the input parameters:

$$\hat{s}\approx s(\hat{T},\hat{S},\hat{a},\hat{b}) \qquad (6.5)$$

The standard deviation (describing the uncertainty of the drawdown) can be approximated by the following formula:

$$\sigma_s\approx\sqrt{\left(\frac{\partial s}{\partial T}\bigg|_{T=\hat{T}}\right)^2\sigma_T^{\,2}+\left(\frac{\partial s}{\partial S}\bigg|_{S=\hat{S}}\right)^2\sigma_S^{\,2}+\left(\frac{\partial s}{\partial a}\bigg|_{a=\hat{a}}\right)^2\sigma_a^{\,2}+\left(\frac{\partial s}{\partial b}\bigg|_{b=\hat{b}}\right)^2\sigma_b^{\,2}} \qquad (6.6)$$

σ_s is required at the extrapolation time t_{long}, since the uncertainty of the extrapolated drawdown is of interest. Equation (6.6) shows that the uncertainty σ_s is determined by the input parameter uncertainties $\sigma_T,\sigma_S,\sigma_a,\sigma_b$, and the sensitivities $\partial s/\partial T,\ \partial s/\partial S,\ \partial s/\partial a,\ \partial s/\partial b$.

The sensitivity of the drawdown with respect to the parameters is the sum of the sensitivity of the well drawdown and the sensitivity of the image wells, i.e. the boundary drawdown. In the case of the transmissivity, for instance, it can be written as:

$$\left.\frac{\partial s}{\partial T}\right|_{t=t_{long}} = \left.\frac{\partial s_{Well}}{\partial T}\right|_{t=t_{long}} + \left.\frac{\partial s_{Boundary}}{\partial T}\right|_{t=t_{long}} \qquad (6.7)$$

The well drawdown is extrapolated by a second order Taylor series expansion (Equation (6.3)) from the end of the pumping test to the time t_{long} (that describes the maximum operation period of the borehole in the case of no recharge). Since the extrapolated well drawdown is based on a measured drawdown curve its sensitivity with respect to the parameters cannot be calculated. The sensitivity of s_{Well} is therefore approximated by assuming a Theis sensitivity, e.g.

$$\left.\frac{\partial s_{Well}}{\partial T}\right|_{t_{long}} \approx \left.\frac{\partial s_{Theiss}}{\partial T}\right|_{t_{long}} \qquad (6.8)$$

The analytical expression of the Theis sensitivity can easily be evaluated by a finite difference approximation. The uncertainty of the extrapolated drawdown σ_s can now be included in the estimation of the sustainable yield. The available drawdown has to be corrected by the uncertainty of the drawdown that arises from the imperfect knowledge of the aquifer parameters and the distances to the boundaries:

$$s'_{available} = s_{available} - 2\sigma_s \qquad (6.9)$$

This leads to a risk-oriented estimate of the sustainable yield.

A correction of the available drawdown by two standard deviations yields a probability of 95% for not exceeding the available drawdown (assuming a normal distribution for the uncertain s). A correction by one standard deviation still yields a safety of 68.5%. The owner of the borehole has to decide on the safety requirement (i.e. the probability of failure). In this manner a conservative and therefore sustainable yield should be estimated.

Application of this methodology required the determination of Transmissivity (T) and Storativity (S). These parameters can be estimated by the interpretation of the drawdown curve. Moreover, to get an estimate of the available drawdown and the water strikes (fractures), the flow regime behaviour has to be investigated to identify the main fractures and the water strikes. In the next section a new, heuristic approach for the identification of Transmissivity (T), Storativity (S) and a way to obtain better knowledge on the flow regime, will be presented.

6.3 IDENTIFICATION OF CHARACTERISTIC FLOW REGIMES

6.3.1 USE OF DRAWDOWN DERIVATIVES

A specific flow regime has a characteristic pumping test curve. Derivatives of pressure head have been used for many years in the oil fields to evaluate flow regime characteristics (Bourdet *et al.*, 1984; Horne 1997). Use of the derivative of pressure head versus time is mathematically satisfying because the derivative is directly represented in one of the diffusivity equations, which is the governing equation for all the models of transient pressure behavior currently in use in well test analysis. Consequently, the derivative response is much more sensitive to small phenomena of interest which are all integrated and, hence, diminished, by the pressure head versus time solutions usually present in well test interpretations. Accurate field measurements of drawdown versus time are, however, required.

Analytical equations describing the drawdown in a borehole are of the form:

$$s = 2.3\frac{Q}{4\pi T}\log C \qquad (6.10)$$

where s = drawdown in the borehole

Q = abstraction rate of abstraction borehole

T = transmissivity of the aquifer system

C = a time dependent expression that varies according to aquifer type and contains the ratio T/S where S is the storativity ***(Table 6.1)***.

From Equation (6.10) the derivative of the drawdown with respect to log (t) is found to be:

$$\frac{\partial s}{\partial \log t} = 2.3\frac{Q}{4\pi T} \qquad (6.11)$$

From this equation the T-value can be calculated for each time. The derivative of the logarithmic drawdown with respect to log (t) is given by:

$$\frac{\partial \log s}{\partial \log t} = \frac{1}{\ln C} = \frac{1}{\ln(act_0)} = \frac{1}{b \ln 10} \qquad (6.12)$$

so that the S-value could be estimated from:

$$a = \frac{T}{S} = \frac{10^b}{ct_0} \qquad (6.13)$$

We refer to Equation (6.11) as "derivative", and to Equation (6.12) as "log-derivative". From Equation (6.12) the ratio T/S can be calculated and the combined use of Equations (6.11) and (6.12) therefore gives an S-value for each time. The derivatives are calculated numerically by a linear regression line yielding the slope.

C†)	c	Aquifer
$(2.25Tt_0)/(r^2S)$	$2{,}25/r^2$	Homogeneous porous (Theis-model)
$(2.25T_ft_0)/(r^2S_f)$	$2{,}25/r^2$	Dual porosity (early time)
$(2.25T_ft_0)/[r^2(S_f + bS_m)]$	$2{,}25/r^2$	Dual porosity (late time)
$(16.59Tt_0)/[S(X_f)^2]$	$16{,}59/[(X_f)^2]$	Single vertical fracture
$(40T^3t_0)/[S(W_dT_d)^2]$	$(40T^2)/[(W_dT_d)^2]$	Conductive dyke or fault zone

†)The subscripts f, m and d refer to the fracture, rock matrix and dyke respectively

Table 6.1: Values of the parameter C in Equation (6.10) for a few typical types of aquifers, with X_f the half width of the vertical fracture, W_d the width of the dyke or fault and b a constant= 3 for an orthogonal fracture system and 1 for a linear system (Kruseman and De Ridder, 1990).

The characteristics that can be obtained from the derivative graph are as follows:

- ☐ Well bore storage shows a line with slope = 1 at early time.
- ☐ Infinite radial flow shows a horizontal straight-line 1 to 1.5 log cycles after well bore storage.
- ☐ A double porosity aquifer shows a characteristic dip after well bore storage.
- ☐ A single no-flow boundary shows, at most, a doubling of the derivative and two no-flow boundaries show, at most, a tripling of the derivative.
- ☐ A closed no-flow boundary shows a straight line with slope = 1 at late time.
- ☐ Two parallel and a U-shaped no-flow boundary show a slope = 0.5 on the graph.
- ☐ A recharge boundary (river or dam) shows a drastic decrease in the value of the derivative and positions of fractures are usually seen by a typical sinus wave form (i.e. at the fracture position the derivative decreases and after de-watering of the fracture the derivative increases again).

If the second derivative (say s'') of drawdown is taken, the following important characteristics could be obtained:

- ☐ The value of s'' reaches a value of exactly 1 for a closed no-flow boundary
- ☐ The value of s'' is equal to zero for a homogeneous infinite aquifer (Theis model).

6.3.2 A HEURISTIC APPROACH FOR THE ESTIMATION OF EFFECTIVE T-AND S-VALUES

The effective T-and S-values are obtained by the evaluation of the derivatives as described above. It is suggested that the highest value of the drawdown derivative observed during the pumping test to estimate the effective T-and S-value should be taken. However, this is only true after having passed well bore storage effects and before having reached the boundaries.

The reason for this heuristic approach is the following. When the water level reaches the position of a fracture, a flattening of the water level is observed. At this stage one would obtain an erroneous effective T-value by using the derivative of this flattened part. The flattening of the drawdown curve is due to the fact that flow conditions have changed from confined to unconfined. At the position of the fracture, the drawdown will be according to the specific yield and not to the storage coefficient of the fracture. Because the specific yield is much higher than the storage coefficient, a flattening of the drawdown curve is observed.

The maximum drawdown derivative coincides with the maximum of the log-drawdown derivative due to the monotonic behavior of the decimal logarithm. The effective S-value curve will thus always show an upward trend in field situations. At early times, the drawdown is according to the storage coefficient of the fracture, and then it changes to the specific yield at the position of the fracture. At late times the S-value changes to the storativity of the matrix.

6.4 JUSTIFICATION BY SYNTHETIC EXAMPLE

The MODFLOW program was used to generate a typical pumping test solution:

- ☐ Two-layer generated pumping test (2020 x 2020-meter square closed boundary) with typical parameter values for fractured aquifers in the Karoo rocks of South Africa with a fracture zone in the bottom layer.
- ☐ Thickness of the first layer = 19 meter and bottom layer = 1 meter. Fracture zone is situated in bottom layer (220 x 220-meter).
- ☐ Abstraction borehole (2 l/s) situated in the center of this fracture zone in the bottom layer.
- ☐ The parameter values for the first layer were taken as:
  - ○ $T_m = 1\ m^2/d$
  - ○ S_m=0.001 (typical matrix values for the Karoo aquifers).
- ☐ The parameter values for the fracture zone were taken as:
  - ○ $T_f = 20\ m^2/day$
  - ○ $S_f = 1x10^{-4}$
  - ○ Vertical $K_z = 0.1$ m/d
  - ○ The remainder of the bottom layer were allocated the same T_m and S_m as top layer.

The Figure below ***(Fig. 6.1)*** shows the Modflow generated values for a period of 2 years. The different derivative graphs could be used with great effect to identify certain specific flow characteristics of fractured-rock aquifers.

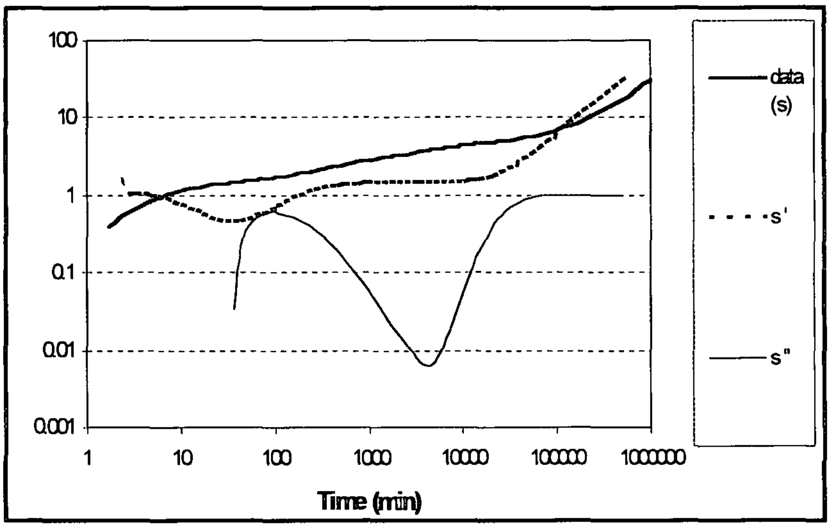


Figure 6.1: Modflow generated data.

The Modflow program was run for a period of 2 years with an abstraction rate of 2 l/s. The generated data values for times up to 3 days (i.e. the typical length of a pumping test) were used in the FC-method to estimate the drawdown and sustainable yield by extrapolating drawdown to 2 years. The correct answer is of course 2 l/s. The table below ***(Table 6.2)*** shows the results:

Parameter	Result	
	Modflow	FC
s (t=t_{EOP}) (m)	3.82	-
s(t=t_{long}) (m)	30.56	29.2
Q_sust (l s^{-1})	2	2.09

Table 6.2: Comparison between Modflow and FC-results for synthetic generated data

The recommended yield estimated with the FC-method is within 4.5 % of the Modflow solution. Further examples of the successful application of the method to various synthetic and real case field studies are available in other literature (Van Tonder *et al.*, 1998).

The most uncertain parameter in the FC method is the choice of the available drawdown that must be used. This issue will be discussed in detail later in this thesis.

6.5 FC PROGRAM IN EXEL

The FC method, contained in the FC program in EXEL was developed by experts in the South African Groundwater field (Van Tonder *et al.*, 1998) and this method was developed especially for the typical South African fractured rock aquifers. This method predicts the sustainable yield much more realistic because it incorporates the possible influences of boundary conditions, the possible influence of other boreholes in the vicinity as well as the possibility of a risk analysis, if it is required. This method is also not sensitive for the storativity value, a parameter that is very difficult to determine when there is no observation borehole data available.

In most of the other methods that is used to determine the sustainable yield, parameters must be calculated separately and then used in the methods. The FC method makes provision for determining most of these parameters and the user is allowed to use them in the software. The diagnostic data plots as well as the derivative plots are also included in the software and data from these plots are used to determine the long-term sustainable yield. The FC method can be seen as a one-stop shop (method) to determine the long-term sustainable yield of a borehole.

6.5.1 ENTERING DATA IN FC PROGRAM

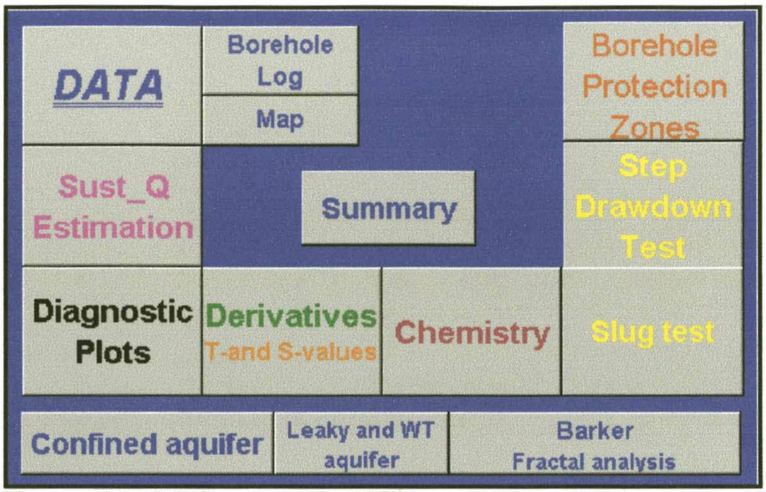
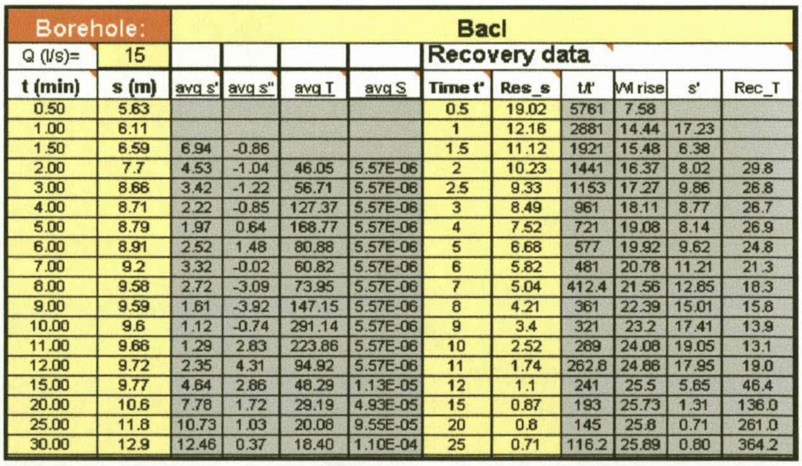


Figure 6.2: Main menu in FC program

From the main menu *(Fig. 6.2)* all the different sub programs (spreadsheets) included in the FC program can be accessed (Van Tonder *et al.* (1999). This is done by pressing the button of the spreadsheet where the user of the program wants to go. In order to use the program, data must first be entered into the relevant spreadsheet.



Borehole:		Bacl									
Q (l/s)=	15					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
0.50	5.63					0.5	19.02	5761	7.58		
1.00	6.11					1	12.16	2881	14.44	17.23	
1.50	6.59	6.94	-0.86			1.5	11.12	1921	15.48	6.38	
2.00	7.7	4.53	-1.04	46.05	5.57E-06	2	10.23	1441	16.37	8.02	29.8
3.00	8.66	3.42	-1.22	56.71	5.57E-06	2.5	9.33	1153	17.27	9.86	26.8
4.00	8.71	2.22	-0.85	127.37	5.57E-06	3	8.49	961	18.11	8.77	26.7
5.00	8.79	1.97	0.64	168.77	5.57E-06	4	7.52	721	19.08	8.14	26.9
6.00	8.91	2.52	1.48	80.88	5.57E-06	5	6.68	577	19.92	9.62	24.8
7.00	9.2	3.32	-0.02	60.82	5.57E-06	6	5.82	481	20.78	11.21	21.3
8.00	9.58	2.72	-3.09	73.95	5.57E-06	7	5.04	412.4	21.56	12.85	18.3
9.00	9.59	1.61	-3.92	147.15	5.57E-06	8	4.21	361	22.39	15.01	15.8
10.00	9.6	1.12	-0.74	291.14	5.57E-06	9	3.4	321	23.2	17.41	13.9
11.00	9.66	1.29	2.83	223.86	5.57E-06	10	2.52	289	24.08	19.05	13.1
12.00	9.72	2.35	4.31	94.92	5.57E-06	11	1.74	262.8	24.86	17.95	19.0
15.00	9.77	4.64	2.86	48.29	1.13E-05	12	1.1	241	25.5	5.65	46.4
20.00	10.6	7.78	1.72	29.19	4.93E-05	15	0.87	193	25.73	1.31	136.0
25.00	11.8	10.73	1.03	20.08	9.55E-05	20	0.8	145	25.8	0.71	261.0
30.00	12.9	12.46	0.37	18.40	1.10E-04	25	0.71	116.2	25.89	0.80	364.2

Figure 6.3: Data entry spreadsheet in FC program

The fields that have to be filled in on the data spreadsheet *(Fig. 6.3 above)* are colored yellow. The first field that has to be filled in is the name of the borehole and then the abstraction rate (Q) in l/s. After the pumping test data had been corrected, the time had been changed to elapsed time (t) in minutes and the water level readings had been changed to drawdown (s) in meters, the data can be entered into the allocated fields in the spreadsheet. It is also possible to import the data into the spreadsheet, *.txt or *.xls file format. When there is recovery data available the data can also be entered into the allocated fields. The time should be elapsed recovery time (t') in minutes and the water levels should be residual drawdown since pumping stopped (res_s), expressed in meters.

6.5.2 DIAGNOSTIC AND DERIVATIVE PLOTS IN FC PROGRAM

- ❑ Once the pumping test data had been entered into the data spreadsheet the program automatically constructs diagnostic data plots ***(Fig. 6.4)***. From the main menu in the program the diagnostic plot button can be pressed to view the different diagnostic data plots.

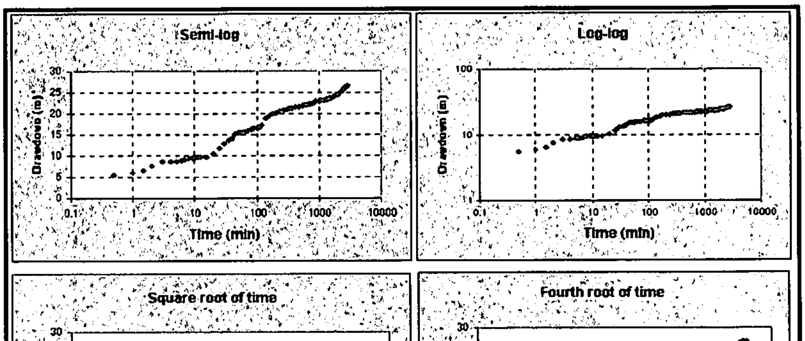


Figure 6.4: Diagnostic data plots in FC program

The diagnostic data plots that the software constructs, include:

- ☐ Semi-log plot (Cooper-Jacob)
- ☐ Log-log plot (Theis)
- ☐ Square root of time plot
- ☐ Fourth root of time plot
- ☐ Cartesian plot
- ☐ Inverse square root of time plot
- ☐ Recovery plot (t/t')
- ☐ Water level rise plot after recovery.

The program also uses the pumping test data to construct the different derivative plots automatically. The figure below ***(Fig. 6.5)*** is an example of the derivative plot constructed in the FC program. To view the derivative plots the appropriate button is pressed in the main menu.

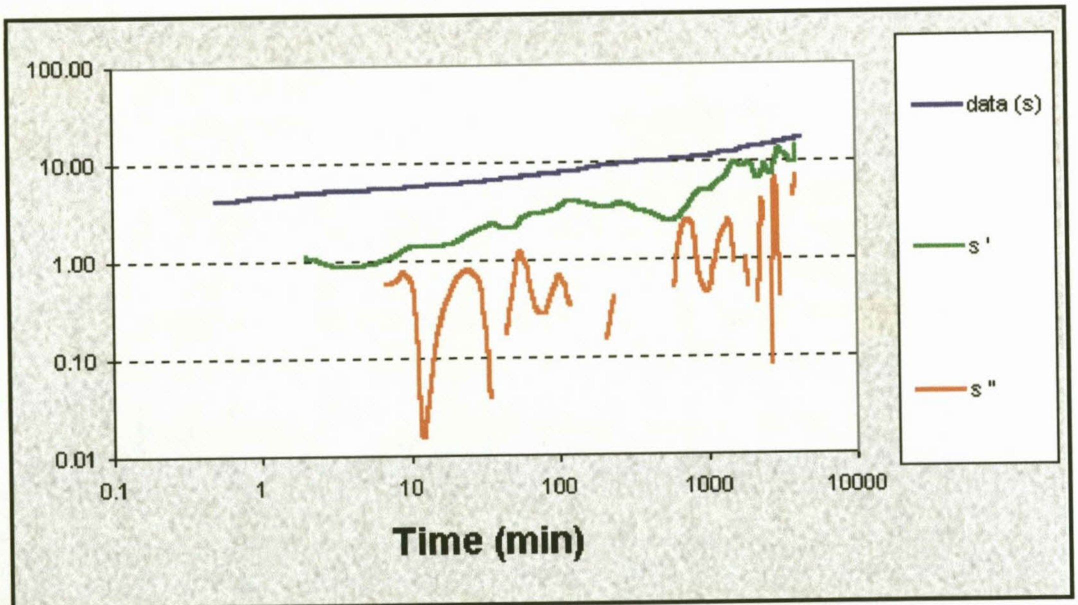
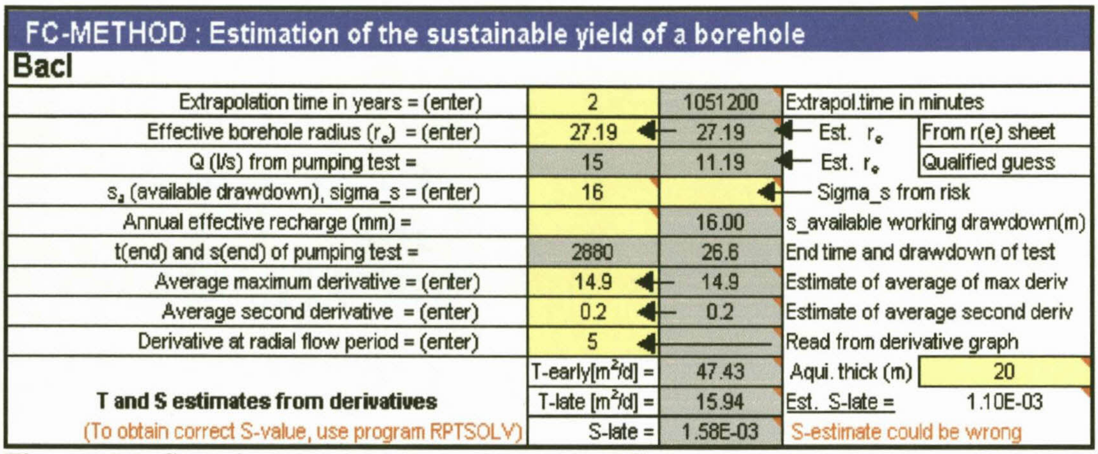


Figure 6.5: Derivative plot in FC program

The blue line in the above plot represents the drawdown versus time data obtained during the pumping test and the green line is the first derivative plot. The red line in the plot represents the second derivative. From the diagnostic data plots and the derivative plots the characteristics associated with the different features on the plots can be identified. The interpretation of these plots is discussed in detail in ***Chapter 4***.

6.5.3 ENTERING VALUES TO DETERMINE SUSTAINABLE YIELD



FC-METHOD : Estimation of the sustainable yield of a borehole

Bacl

Extrapolation time in years = (enter)	2	1051200	Extrapol.time in minutes	
Effective borehole radius (r_e) = (enter)	27.19 ◄—	27.19	◄— Est. r_e	From r(e) sheet
Q (l/s) from pumping test =	15	11.19	◄— Est. r_e	Qualified guess
s_a (available drawdown), sigma_s = (enter)	16	◄	— Sigma_s from risk	
Annual effective recharge (mm) =		16.00	s_available working drawdown(m)	
t(end) and s(end) of pumping test =	2880	26.6	End time and drawdown of test	
Average maximum derivative = (enter)	14.9 ◄—	14.9	Estimate of average of max deriv	
Average second derivative = (enter)	0.2 ◄—	0.2	Estimate of average second deriv	
Derivative at radial flow period = (enter)	5 ◄—	—	Read from derivative graph	
	T-early[m^2/d] =	47.43	Aqui. thick (m)	20
T and S estimates from derivatives	T-late [m^2/d] =	15.94	Est. S-late =	1.10E-03
(To obtain correct S-value, use program RPTSOLV)	S-late =	1.58E-03	S-estimate could be wrong	

Figure 6.6: Sustainable yield spreadsheet in FC program

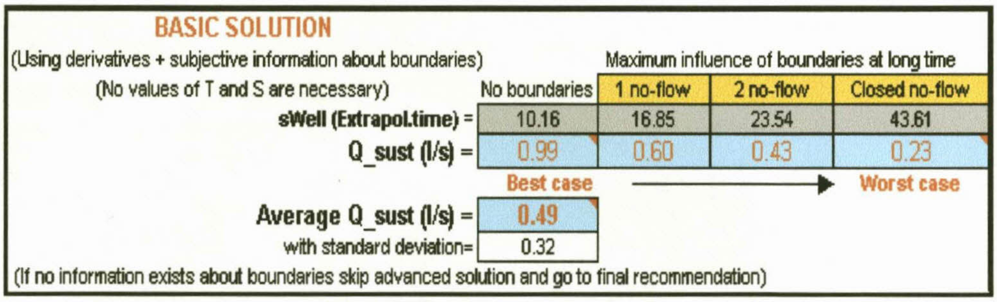
From the main menu the spreadsheet to determine the long-term sustainable yield can be accessed ***(Fig. 6.6)***. This is done by pressing the button named Sust_Q Estimation. In this spreadsheet data should again be entered in the yellow coloured fields. The following fields should be completed:

- ☐ In the first field the extrapolation time in years must be filled in. Usually this is between 1 and 5 years.
- ☐ For the effective borehole radius the recommended value in the grey coloured field next to the yellow field must be used. The program determines this value, but it can be wrong. This value is used to estimate the effective S-value at late time (S-value of the matrix). The program warns the user that the estimate of this S-value can be wrong. Only program RPTSOLV will give the correct estimate for the S-value.
- ☐ The available drawdown (s_a) is the distance between the rest or static water level and the position of the main water strike.
- ☐ The annual effective recharge is entered in meter.
- ☐ For the average maximum derivative the software gives an estimate of the value, but the user must check this value in the derivative plots. This value is used to estimate the effective T-value at late time.

- ☐ The second derivative value is entered into this field, normally close to zero.
- ☐ To enter the derivative at radial flow period the value should be read off in the derivative plot spreadsheet. This is where the derivative plot (green line in plot) shows a horizontal line at early time. The program uses this value to estimate the effective T-value at early time, the end of well bore storage and the effective radius of the borehole. No other calculations are performed with this value.

6.5.4 BASIC SOLUTION

After the values had been entered into the yellow fields in the sustainable yield spreadsheet, the program will estimate probable sustainable yields for the borehole for the period of time selected ***(Fig. 6.7)***. Then the program averages these yields with their standard deviation being provided. If no information regarding real boundaries in the aquifer were available, then the user would accept this average value as first approximation.



BASIC SOLUTION

(Using derivatives + subjective information about boundaries)

(No values of T and S are necessary)

Maximum influence of boundaries at long time

	No boundaries	1 no-flow	2 no-flow	Closed no-flow
sWell (Extrapol.time) =	10.16	16.85	23.54	43.61
Q_sust (l/s) =	0.99	0.60	0.43	0.23
	Best case	→		**Worst case**
Average Q_sust (l/s) =	**0.49**			
with standard deviation=	0.32			

(If no information exists about boundaries skip advanced solution and go to final recommendation)

Figure 6.7: Basic solution spreadsheet in FC program

6.5.5 ADVANCED SOLUTION

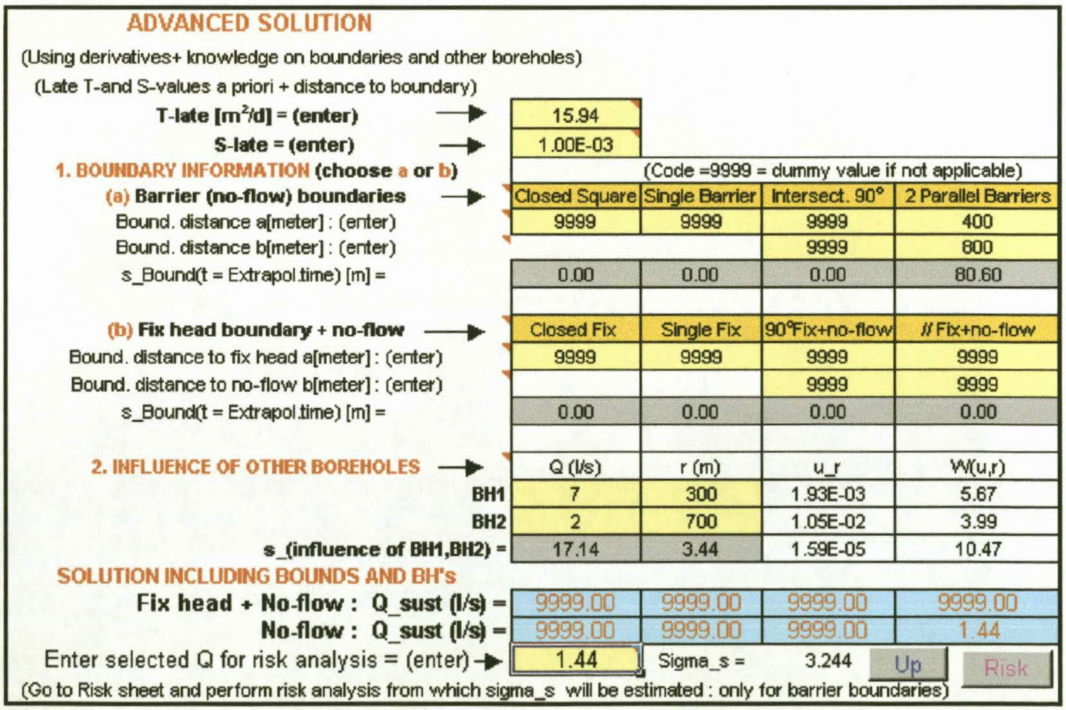
This is where the FC program improves the accuracy of the determination of the long-term sustainable yield. This method makes provision to add additional information which will improve the accuracy of the long-term sustainable yield. Some other methods does not allow for this and as a result, this normally leads to the overestimation of the long-term sustainable yield, resulting in the borehole failing after a period of continuous usage. From there the stigma that groundwater is an unreliable source of water supply and that it can not be used for long-term water supply. The advanced solution can accommodate the following:

6.5.5.1 BOUNDARY CONDITIONS

If information on boundaries is available, the user of the software may include this information in the determination of the long-term sustainable yield calculations by making use of the advanced solution in the program ***(number 1 in Fig. 6.8 below)***. To get to the advanced solution, press the button named Sust_Q Estimation in the main menu. Go to the advanced solution and complete the relevant yellow fields. For this solution the T-late and S-late values are a priority. The user has the choice between two boundary types namely:

- ☐ No-flow boundary types combinations
- ☐ Fixed head boundary combinations.

It is easier to determine and to decide on no-flow boundaries so this option will be used more than the fixed head boundary option. For example, a river may not be a real fixed head boundary because a silty clay layer in the riverbed may reduce leakage to the aquifer.



ADVANCED SOLUTION

(Using derivatives+ knowledge on boundaries and other boreholes)

(Late T-and S-values a priori + distance to boundary)

T-late [m²/d] = (enter) →	15.94			
S-late = (enter) →	1.00E-03			
1. BOUNDARY INFORMATION (choose a or b)	(Code =9999 = dummy value if not applicable)			
(a) Barrier (no-flow) boundaries →	Closed Square	Single Barrier	Intersect. 90°	2 Parallel Barriers
Bound. distance a[meter] : (enter)	9999	9999	9999	400
Bound. distance b[meter] : (enter)			9999	800
s_Bound(t = Extrapol.time) [m] =	0.00	0.00	0.00	80.60
(b) Fix head boundary + no-flow →	Closed Fix	Single Fix	90°Fix+no-flow	// Fix+no-flow
Bound. distance to fix head a[meter] : (enter)	9999	9999	9999	9999
Bound. distance to no-flow b[meter] : (enter)			9999	9999
s_Bound(t = Extrapol.time) [m] =	0.00	0.00	0.00	0.00
2. INFLUENCE OF OTHER BOREHOLES →	Q (l/s)	r (m)	u_r	W(u,r)
BH1	7	300	1.93E-03	5.67
BH2	2	700	1.05E-02	3.99
s_(influence of BH1,BH2) =	17.14	3.44	1.59E-05	10.47
SOLUTION INCLUDING BOUNDS AND BH's				
Fix head + No-flow : Q_sust (l/s) =	9999.00	9999.00	9999.00	9999.00
No-flow : Q_sust (l/s) =	9999.00	9999.00	9999.00	1.44
Enter selected Q for risk analysis = (enter) →	1.44	Sigma_s =	3.244	

(Go to Risk sheet and perform risk analysis from which sigma_s will be estimated : only for barrier boundaries)

Figure 6.8: Advanced solution in FC program

6.5.5.2 INFLUENCE OF OTHER BOREHOLES

During the pumping test or field visit it is easy to obtain information about a borehole or boreholes in the vicinity of the borehole that is pump tested. The boreholes must be in the same aquifer to have an effect on the borehole that is pump tested. The distances as well as the abstraction rates of these boreholes can be obtained and this information can be entered into the FC program ***(number 2 in Fig. 6.8 above).*** The program will take into account the influence of these other boreholes within the selected time.

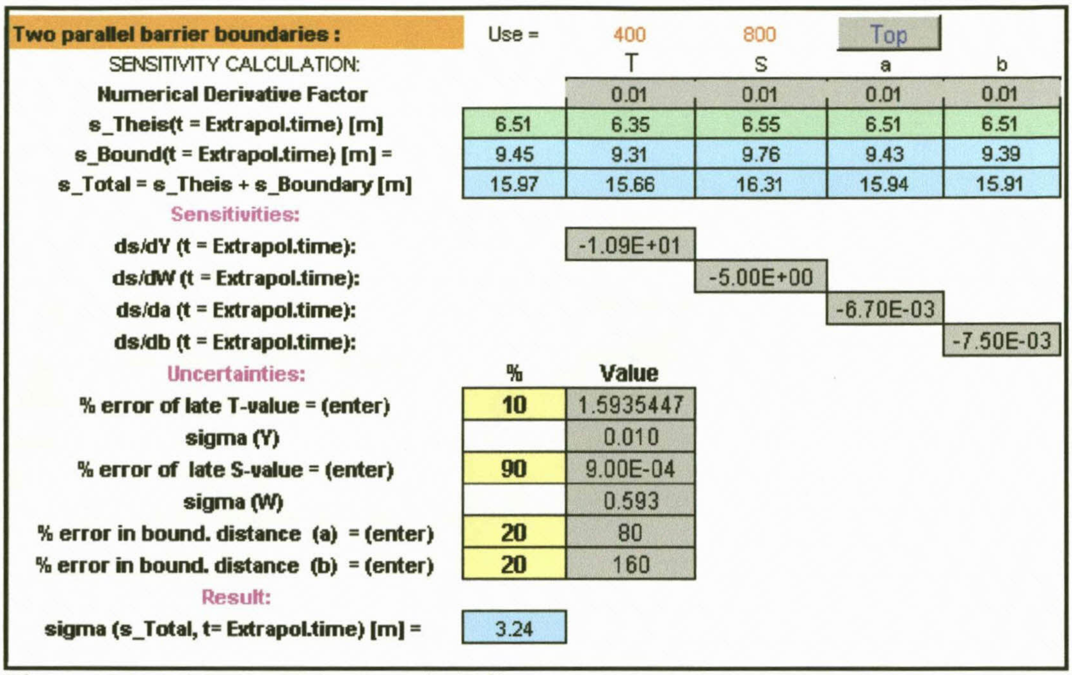
6.5.6 RISK ANALYSIS

If a determined long-term sustainable yield is to be ensured at all cost, then the risk of failure can be minimised even more. This normally is required when water pumped from a borehole is the only source of drinking water for a community. In this case it is very important that the source should be managed properly and the risk of failure must be minimised. This is done by applying is risk analysis to the estimated parameters, resulting in a revised estimation of the assured long-term sustainable yield.

Should a risk analysis be required, a Q-value has to be entered into the relevant field in the advanced solution spreadsheet (close to the bottom of the sheet). After this has been done, the user can proceed to the Risk sheet to continue with the analysis ***(Fig. 6.9)***. This is done by pressing the Risk button at the bottom of the advanced solution.

There are four different scenarios reflecting different boundary conditions. If no probability density function (pdf) is available for the aquifer parameters, it is suggested that the user use the following error percentages:

- ☐ Transmissivity value (T) – use a 33 % error value
- ☐ The boundary distances – use a 33 % error value
- ☐ Storativity value (S) – use up to 100 % error value.



Two parallel barrier boundaries :	Use =	400	800	Top	
SENSITIVITY CALCULATION:		T	S	a	b
Numerical Derivative Factor		0.01	0.01	0.01	0.01
s_Theis(t = Extrapol.time) [m]	6.51	6.35	6.55	6.51	6.51
s_Bound(t = Extrapol.time) [m] =	9.45	9.31	9.76	9.43	9.39
s_Total = s_Theis + s_Boundary [m]	15.97	15.66	16.31	15.94	15.91
Sensitivities:					
ds/dY (t = Extrapol.time):		-1.09E+01			
ds/dW (t = Extrapol.time):			-5.00E+00		
ds/da (t = Extrapol.time):				-6.70E-03	
ds/db (t = Extrapol.time):					-7.50E-03
Uncertainties:	%	Value			
% error of late T-value = (enter)	10	1.5935447			
sigma (Y)		0.010			
% error of late S-value = (enter)	90	9.00E-04			
sigma (W)		0.593			
% error in bound. distance (a) = (enter)	20	80			
% error in bound. distance (b) = (enter)	20	160			
Result:					
sigma (s_Total, t= Extrapol.time) [m] =	3.24				

Figure 6.9: Risk analysis sheet in FC program

After having performed a risk analysis the user may go back to the Sustainable yield spreadsheet (Sust_Q Estimation) and enter this estimated sigma_s value (i.e. the standard deviation) into the field to the right of the initial s_a (available drawdown) cell to obtain the sustainable yield of the borehole with 68.5 % confidence. If a 95 % confidence is required the user must double sigma_s. This change in available drawdown, influenced by the parameter uncertainties as well as yield assurances, will be used by the software to determine a new solution.

The FC program is now ready to recommend a final sustainable yield for the borehole in question by entering the new solution value in the advanced sheet into the yellow field into the final recommendation box. In the example used above a sustainable yield of 1.15 l/s for 24 hours per day can be assured with a 68.5 % confidence and a sustainable yield of 0.86 l/s with a 95 % assurance. This will also be converted to the amount of water that can be abstracted per month.

6.5.7 OTHER RELEVANT CHARTS

The FC program also compiles a graph of the following:

- The effective T-value with time ***(Fig. 6.10)***
- The effective S-value with time ***(Fig. 6.11)***.

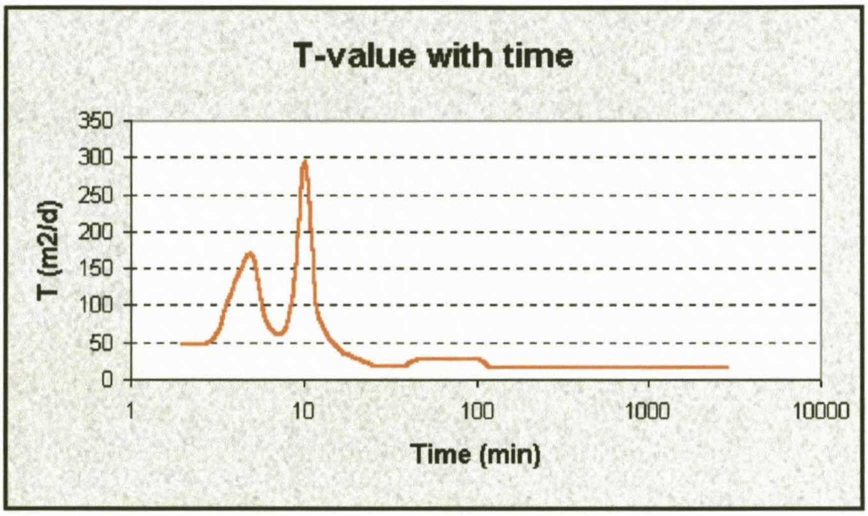


Figure 6.10: Plot of effective T-value with time

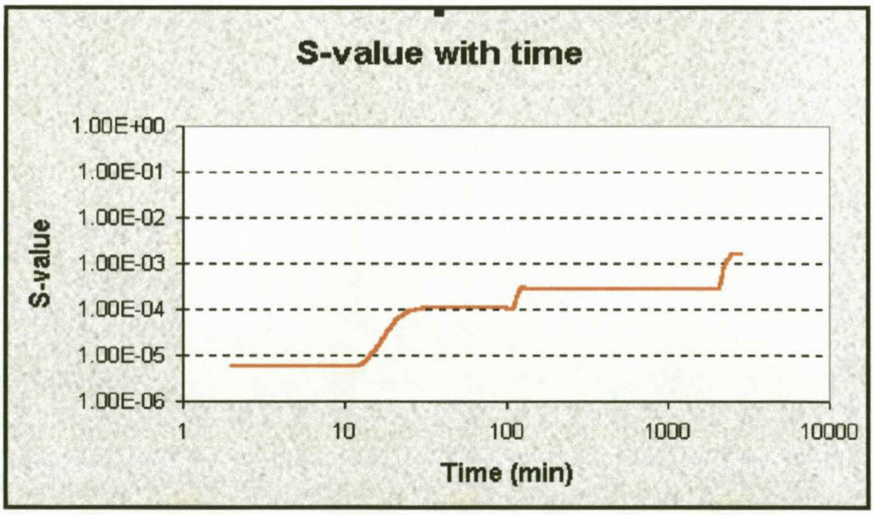
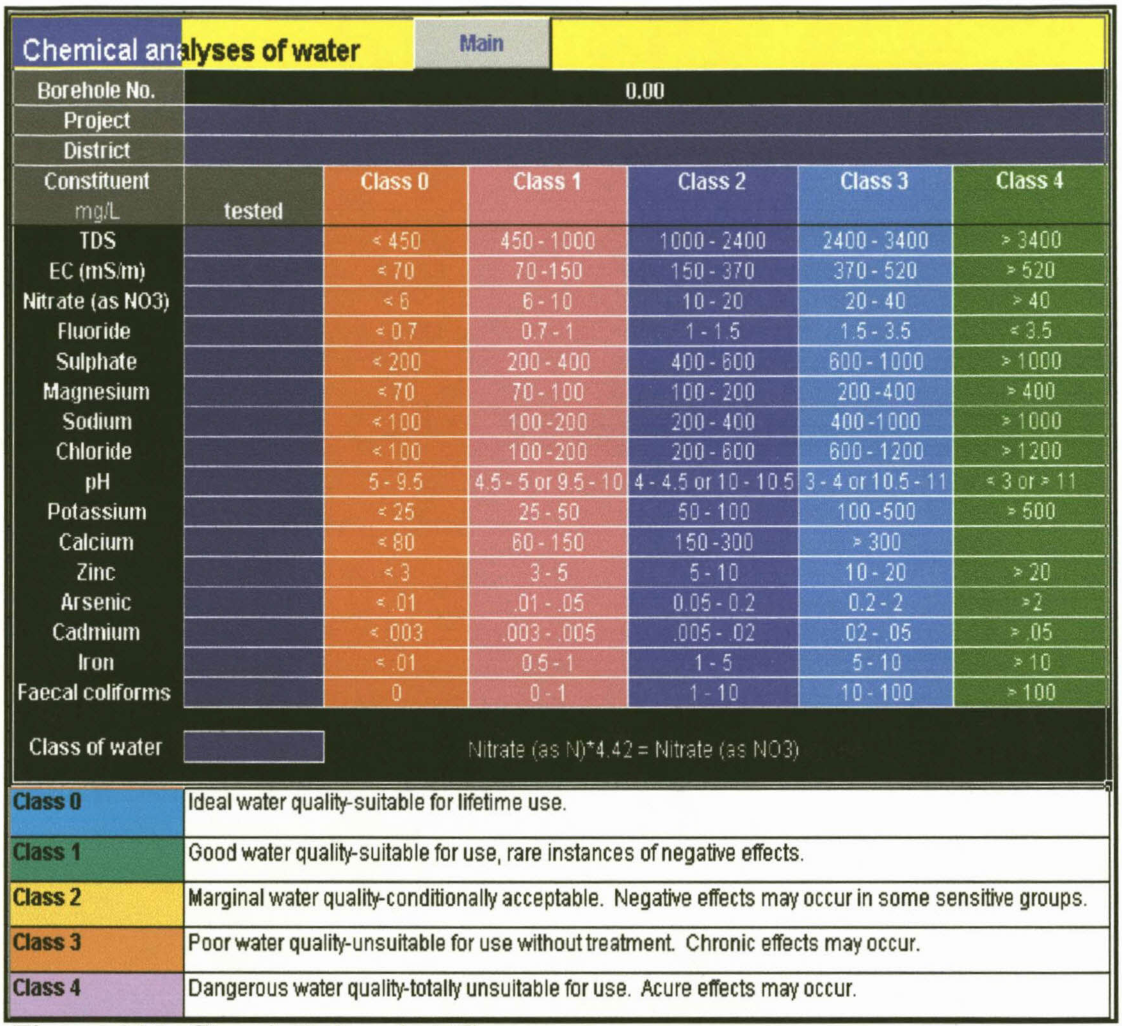


Figure 6.11: Plot of effective S-value with time

6.5.8 CHEMICAL SHEET



Chemical analyses of water

Borehole No. 0.00
Project
District

Constituent mg/L	tested	Class 0	Class 1	Class 2	Class 3	Class 4
TDS		< 450	450 - 1000	1000 - 2400	2400 - 3400	> 3400
EC (mS/m)		< 70	70 -150	150 - 370	370 - 520	> 520
Nitrate (as NO3)		< 6	6 - 10	10 - 20	20 - 40	> 40
Fluoride		< 0.7	0.7 - 1	1 - 1.5	1.5 - 3.5	< 3.5
Sulphate		< 200	200 - 400	400 - 600	600 - 1000	> 1000
Magnesium		< 70	70 - 100	100 - 200	200 -400	> 400
Sodium		< 100	100 -200	200 - 400	400 -1000	> 1000
Chloride		< 100	100 -200	200 - 600	600 - 1200	> 1200
pH		5 - 9.5	4.5 - 5 or 9.5 - 10	4 - 4.5 or 10 - 10.5	3 - 4 or 10.5 - 11	< 3 or > 11
Potassium		< 25	25 - 50	50 - 100	100 -500	> 500
Calcium		< 80	60 - 150	150 -300	> 300	
Zinc		< 3	3 - 5	5 - 10	10 - 20	> 20
Arsenic		< .01	.01 - .05	0.05 - 0.2	0.2 - 2	>2
Cadmium		< .003	.003 - .005	.005 - .02	.02 - .05	> .05
Iron		< .01	0.5 - 1	1 - 5	5 - 10	> 10
Faecal coliforms		0	0 - 1	1 - 10	10 - 100	> 100

Class of water

Nitrate (as N)*4.42 = Nitrate (as NO3)

Class 0	Ideal water quality-suitable for lifetime use.
Class 1	Good water quality-suitable for use, rare instances of negative effects.
Class 2	Marginal water quality-conditionally acceptable. Negative effects may occur in some sensitive groups.
Class 3	Poor water quality-unsuitable for use without treatment. Chronic effects may occur.
Class 4	Dangerous water quality-totally unsuitable for use. Acure effects may occur.

Figure 6.12: Chemical sheet in FC program

The FC program makes provision to enter the values of the hydrogeochemical parameters *(Fig. 6.12)* obtained from taking samples at the borehole that is being pump tested. The suitability of the water quality for the domestic use according to the standards set up by the Department of Water Affairs and Forestry is also included in the program and the tested values can be compared with the standards.

6.5.9 MAP SHEET

The software makes provision for a map to be included for the users reference. This map can be a scanned map of the area or it can be a layout schetch of the area where the borehole is situated.

CHAPTER 7

A GENERALIZED SOLUTION FOR STEP DRAWDOWN TESTS INCLUDING FLOW DIMENSION AND ELASTICITY

7.1 INTRODUCTION

The step-drawdown test was first performed by Jacob (1947), who was primarily interested in finding out what the drawdown in a borehole or well would be if it were pumped at a rate that differs from the rate during the pumping test. For the drawdown in the pumping borehole, he gave the following equation:

$$s_w = B(r_e,t)Q+CQ^2 \qquad (7.1)$$

where $B(r_e,t) = B_1(r_w,t)+B_2$

$B_1(r_w,t)$ = linear aquifer loss coefficient

B_2 = linear well loss coefficient

Q = abstraction rate

C = non-linear well loss coefficient

r_e = effective radius of the well

t = pumping time

The well losses are divided into linear and non-linear head losses. The linear well losses are caused by damage to the aquifer during drilling and completion of the borehole. Examples of linear head losses are losses due to compaction of aquifer material during drilling, losses due to plugging of the aquifer with drilling mud causing a reduction in permeability near the borehole, losses in the gravel pack and head losses in the screen. Examples of non-linear well losses are the friction losses that occur inside the well screen and in the suction pipe where the flow is turbulent and also in the zone adjacent to the well where the flow is usually also turbulent. All these well losses are responsible for the drawdown inside the borehole being much greater than one would expect on theoretical grounds.

Jacob combined the various linear head losses at the well into a single term, r_e, the effective radius of the well (equation (7.1)). He defined this as the distance (measured radially from the axis of the well) at which the theoretical drawdown (based on the log head distribution) equals the drawdown just outside the well. From the data of a step-test, however, it is not possible to determine r_e, because one must also know the storativity of the aquifer, and this (according to Jacob, 1947) can only be obtained from observations in nearby piezometers.

In practice, only the influence of the non-linear well losses on the efficiency can be established, because it is seldom possible to take B_1 and B_2 into account separately. As used in well hydraulics, the concepts of linear and non-linear head loss components (B_2Q+CQ^2) relate to the concepts of skin effect and non-Darcian flow (Ramey, 1982). In well hydraulics, the total drawdown inside a well due to well losses (also indicated as the apparent total skin effect or pseudo skin effect) can be expressed by:

$$B_2Q + CQ^2 = \frac{(Skin + C^1Q)Q}{2\pi T} \tag{7.2}$$

where $C^1 = 2\pi TC =$ non-linear well loss coefficient or high velocity coefficient

Skin $= \xi = 2\pi TB_2 =$ skin factor

Matthews and Russel (1967) relate the effective radius (r_e) of a borehole to the skin factor by the equation:

$$r_e = r_w e^{-skin} \tag{7.3}$$

where r_w = borehole radius

skin = skin factor (ξ)

$$\xi = [\frac{K}{K_s} - 1]\ln[\frac{r_s}{r_w}] \tag{7.4}$$

where K_s = hydraulic conductivity of the zone around borehole with radius r_s.

r_s = radius of zone with a hydraulic conductivity of K_s around well

K = the hydraulic conductivity of the aquifer.

The skin factor can be positive or negative. A positive skin indicates that the drawdown in the borehole is more than expressed by the drawdown in the aquifer (a zone of decreased K is developed around the borehole) and for a negative skin a zone with a higher K is developed around the borehole. A typical case where negative skin is evident is where a borehole intersects a fracture, in this case the effective radius of the borehole is larger than the radius of the borehole and the fracture could be viewed as an extended borehole.

7.2 FIELD METHODS TO ESTIMATE WELL LOSSES

There are two field methods for the estimation of well losses in a borehole. These methods include:

- ☐ the step drawdown test and
- ☐ the multirate test.

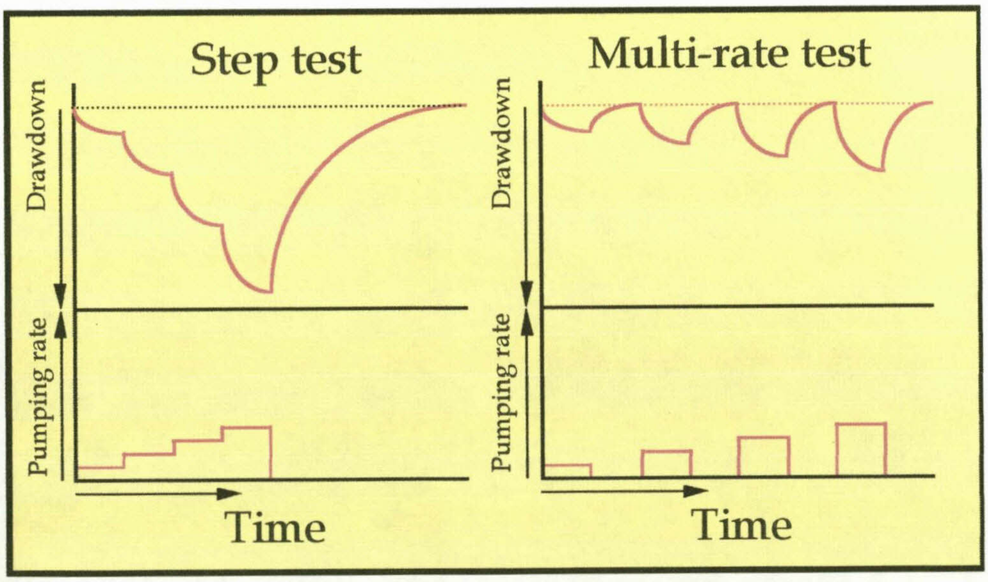


Figure 7.1: Difference between a step drawdown and multirate test

These two methods are described fully in Chapter 3 of this thesis. The figure above ***(Fig. 7.1)*** shows the difference between the two methods. As can be seen in the figure, recovery is allowed between the steps of a multirate test, while in the step drawdown test the pumping rate is increased without allowing recovery to take place. In the case of a multirate test no extrapolation is required, which makes this test less erroneous.

After the step drawdown test or multirate test had been performed in the field the data must be interpreted. The Hantush-Bierschenk method (Kruseman and de Ridder, 1990) can be used to solve for B and C in equation (7.1). To perform the Hantush-Bierschenk method:

- ☐ the field data is plotted on semi-log paper (drawdown versus log time)
- ☐ the curves are extrapolated through the plotted data
- ☐ the increments of drawdown $\Delta s_{w(i)}$ for each step can now be determined
- ☐ calculate the ratio $s_{w(n)} / Q_n$ for each step
- ☐ the values of $s_{w(n)} / Q_n$ versus the corresponding values of Q_n for each step is plotted on a graph
- ☐ a straight line is fitted through the points on the graph and the slope of this line is the value of C
- ☐ the straight line is extended until it intercepts the $Q = 0$ axis and this interception point is the value of B.

7.3 INFORMATION OBTAINED DURING WELL PERFORMANCE TESTS

The data obtained during well performance tests (stepped drawdown or multirate tests) can be used to obtain valuable information on the borehole and aquifer. This include:

- ☐ With B and C known, the drawdown inside the borehole for any realistic discharge (Q) at a certain time (t) can be predicted. The relationship between the drawdown and discharge can be used to choose, empirically, an optimum yield for the borehole.
- ☐ Information on the condition or efficiency of the borehole can be obtained. A general rule to see if a borehole requires development is to compare the estimated C-value with the following criteria:
    - $C < 1e\text{-}7$ implies that the borehole is well developed

  - C > 1e-7 implies well development could possible help to make the well more efficient.
- A step drawdown test could also be used to identify the positions of fractures. A flattening in the water level is an indication of the presence of a fracture.
- A graph of s/Q against Q *(Fig. 7.2)* could be very useful to identify the maximum abstraction rate of a borehole.

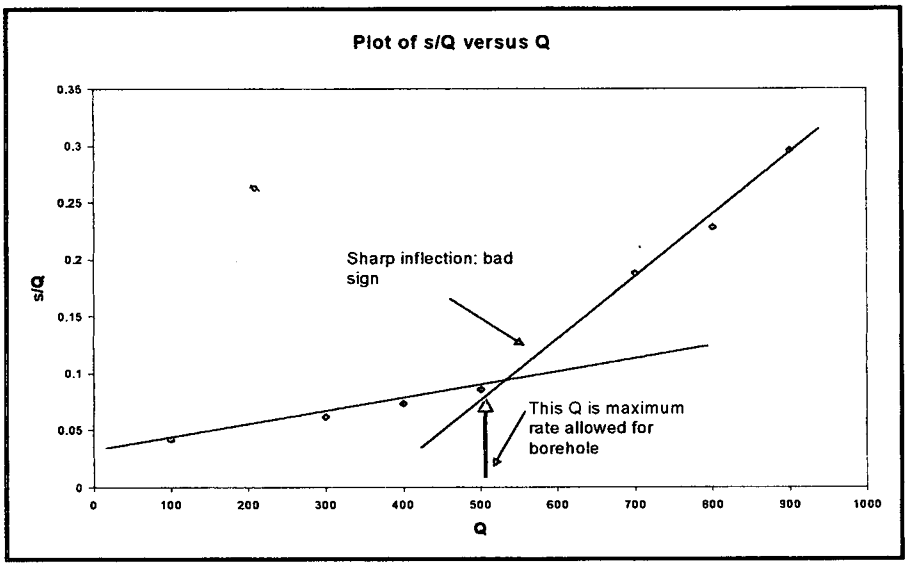


Figure 7.2: Graph of drawdown/Q versus Q could be used to identify a maximum operation rate for a borehole.

7.4 NON-LINEAR RELATIONSHIP BETWEEN DRAWDOWN AND ABSTRACTION RATE

7.4.1 FIELD EXAMPLES

The turbulent flow term CQ^2 in equation (7.1) gives rise to a non-linear relationship between drawdown and abstraction rate Q. There is, however, evidence of a non-linear relationship between drawdown and abstraction rates even in the case of laminar flow. To illustrate this, a typical conceptual model for the Karoo aquifers of South Africa and real examples is used.

The Karoo Sequence of geological formations underlies approximately 50% of the country. The Karoo Sequence consists mainly of sandstones, mudstones, shales and siltstones. The isostatic uplift of Karoo sediments, together with the intrusion of Drakensberg lavas and dolerites, has caused intensive fracturing, particularly in the sandstone layers that are less elastic than the rest of the Sequence.

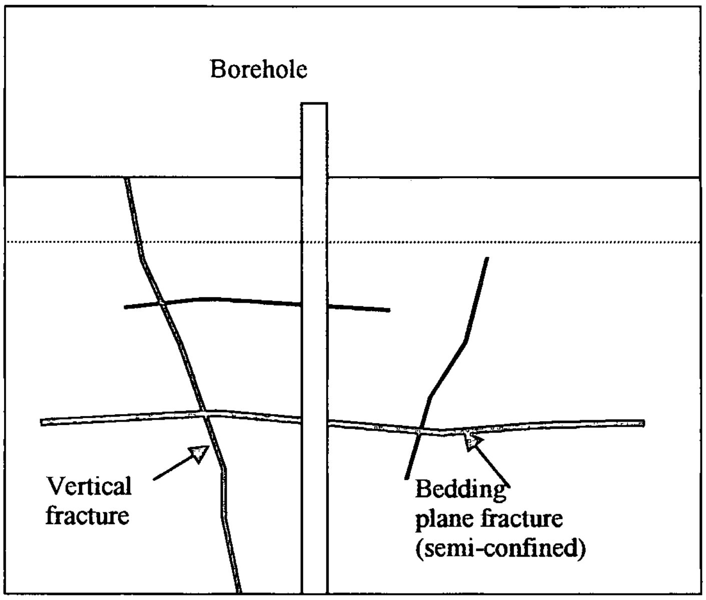


Figure 7.3: A typical conceptual model for a Karoo fractured rock aquifer

The figure above *(Fig. 7.3)* is a typical conceptual model for a shallow fractured Karoo aquifer. There is normally at least one bedding plane fracture, which is usually semi-confined. Vertical fractures intersect the bedding plane fractures. The dotted line indicates the piezometric water level of the bedding plane fracture and the matrix, and the piezometric level of the vertical fracture. When performing a constant rate pumping test on the borehole in Figure 7.3, the following behaviour could usually be seen:

- initially (after well bore storage) the flow towards the borehole will be linear, suggesting that all the water is coming from the bedding plane fracture.
- The flow then becomes bi-linear as water is flowing to the borehole from both the fracture and the rock matrix.
- Finally the water level in the borehole (depending on the abstraction rate) will either remain constant (above the level of the bedding plane fracture) and the flow to the borehole will be pseudo-radial. The water level can also drop below the level of the bedding plane fracture (if the abstraction is more than the rate that water is flowing along the fracture). This characteristic drop in water level is shown in the figure below *(Fig. 7.4)*. A Karoo borehole was pumped at 15 l/s. Each time a fracture was dewatered, a

steepening in the drawdown was observed which indicates a lower total effective T-value for the borehole.

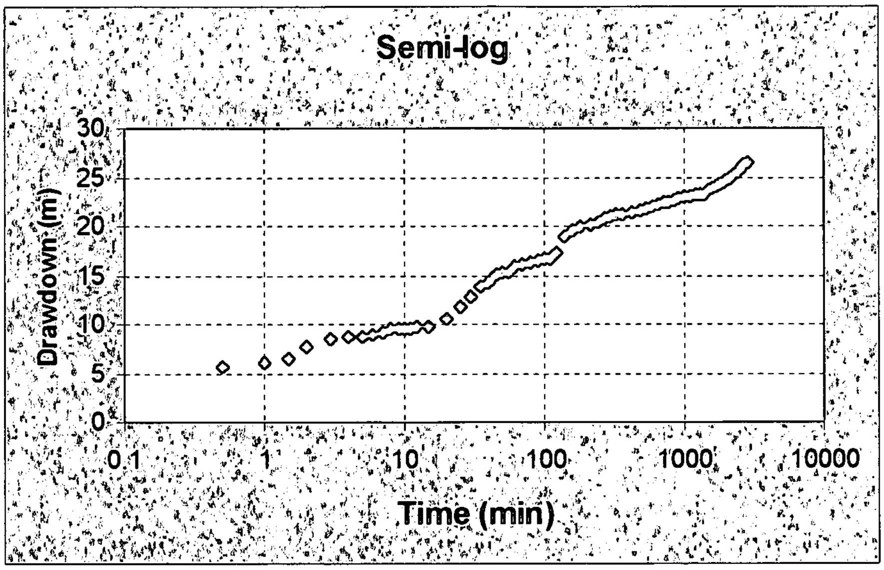


Figure 7.4: Pumping test results from a borehole in the Karoo Sequence. The borehole was pumped at a constant rate of 15 l/s

If fractures were dewatered during a step drawdown test, the estimation of a non-linear well loss coefficient C is in doubt (more fractures will be dewatered at higher rates). Another possibility is that the end of the fracture extent was reached, giving rise to a smaller effective transmissivity (T) value. The value of C obtained in such a case is questionable as the flow is still linear but there exists a non-linear relationship between drawdown and Q. The following example will illustrate the point more clearly.

Two pumping tests were performed in borehole UO5 on the Campus Site at rates 0.5 and 1.25 l/s and measurements were taken in a piezometer in borehole UO6 (5 meters from borehole UO5). This borehole (UO6) is situated in the matrix, 2 meters above the bedding plane fracture that intersects both UO5 and UO6 at 21 meters below surface. The table ***(Table 7.1)*** and figures ***(Fig. 7.5 and Fig. 7.6)*** below show the results.

	Q (l/s)	Drawdown after 1 day in UO5	Drawdown in UO6 piezometer after 1 day
	0.5	1.72	0.024
	1.25	4.82	0.156
Ratio	**2.5**	**2.8**	**6.5**

Table 7.1: Results obtained from a pumping test performed at two rates on borehole UO5. Measurements were taken in UO5 and a piezometer in borehole UO6

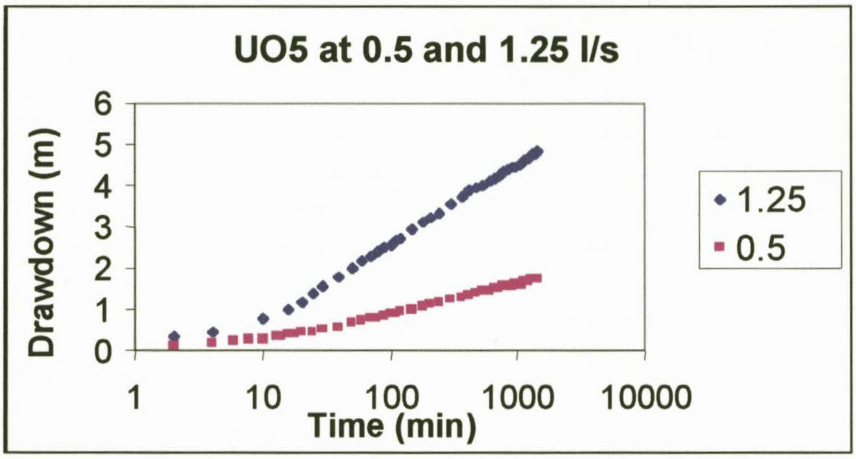


Figure 7.5: Drawdown measured in UO5 at two different rates

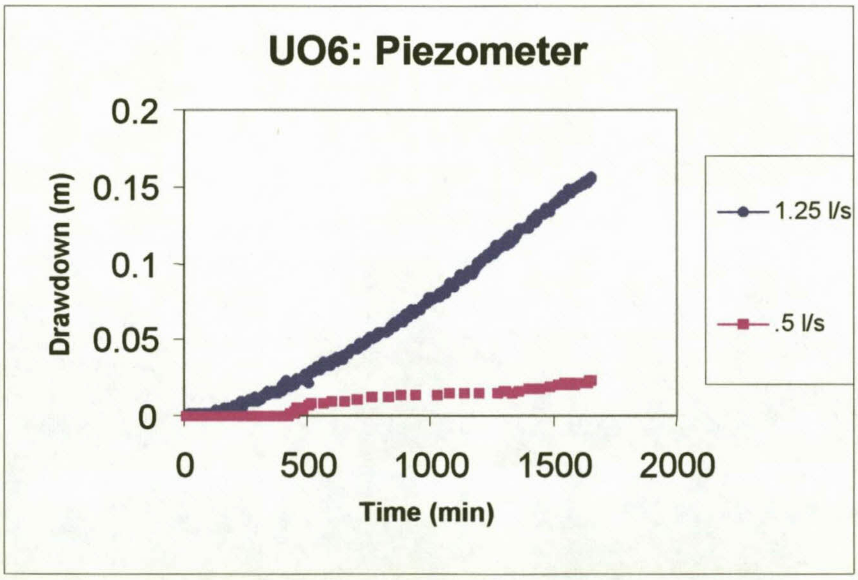


Figure 7.6: Drawdown measured in a piezometer situated in the matrix in borehole UO6 (5 m from UO5) at two different abstraction rates of UO5

The second abstraction rate of 1.25 l/s is a factor 2.5 times higher than the first rate of 0.5 l/s. The drawdown measured in UO5 after 1 day is a factor 2.8 more with the different rates, but comparison of the drawdown in the piezometer (UO6) for the different rates show a factor difference of 6.5 times. Because no fractures were dewatered, there is no reason to believe that the flow from the matrix towards the bedding plane fracture was turbulent. While the ratio between abstraction rates and drawdowns in UO5 were of the same order (2.5 versus 2.8), the ratio of 6.5 obtained for the UO6 piezometer data for the different rates thus clearly shows the non-linear relationship between drawdown and abstraction rate.

Very interesting observations were made in the UO6 piezometer after the pump was switched off:

- ☐ At the rate of 0.5 l/s, the piezometric level still continued to decrease for 5 days
- ☐ At the rate of 1.25 l/s, the piezometric level continued to decrease for 14 days.

There are many examples of pumping tests performed in South Africa on a borehole at different rates which show a non-linear relationship between drawdown and abstraction and only a few of them will be quoted in this thesis.

The tables below ***(Tables 7.2 - 7.5)*** give a summary for four such tests performed with different rates on different boreholes.

	Q (l/s)	**Drawdown (950 minutes)**
	1.5	4.24
	2.0	6.83
Ratio	**1.33**	**0.62**

Table 7.2: Results for the M1 borehole at Meadhurst (mudstone)

	Q (l/s)	Drawdown (420 minutes)
	1.66	1.9
	4.1	8.8
Ratio	**2.47**	**4.6**

Table 7.3: Results for the Khorixas borehole in Namibia (calcrete aquifer)

	Q (l/s)	Drawdown (540 minutes)
	14	5.68
	19	9.98
Ratio	**1.36**	**1.75**

Table 7.4: Results for the Middelburg Zonnebloem 1 borehole (sandstone aquifer)

	Q (l/s)	Drawdown (480 minutes)
	15	4.01
	35	12.43
Ratio	**2.33**	**3.01**

Table 7.5: Results for the Middelburg Zonnebloem 2 borehole (sandstone aquifer)

It is important to mention that the main water strike was not reached during any of the abovementioned examples and that there was no sign of no-flow boundaries that could be detected with a magnetometer within one kilometre around the specific boreholes. It is not implied that the non-linear relationship between drawdown and abstraction rate that is evident from the four quoted examples was not partly due to well losses (turbulent flow) inside the borehole. The implication is only that other factors could also have an influence on this non-linearity principle that was observed during the tests.

This observed non-linearity between drawdown and abstraction rate has the consequence that it is very difficult to extrapolate the future behaviour of the water level in an aquifer if a rate different than that used during the constant rate test is applied.

The figures below *(Figs. 7.7 – 7.10)* show the drawdown graphs obtained for the mentioned four cases at the different abstraction rates.

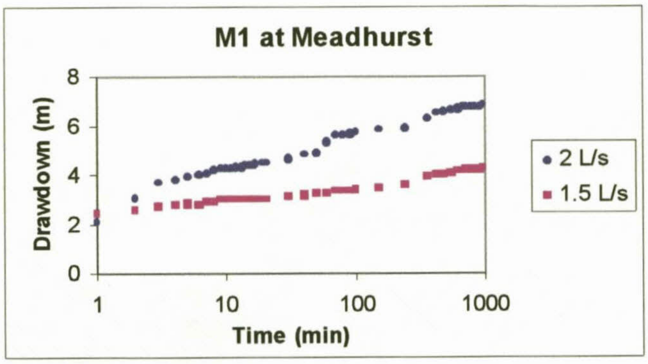


Figure 7.7: Borehole M1 at the Meadhurst Test Site

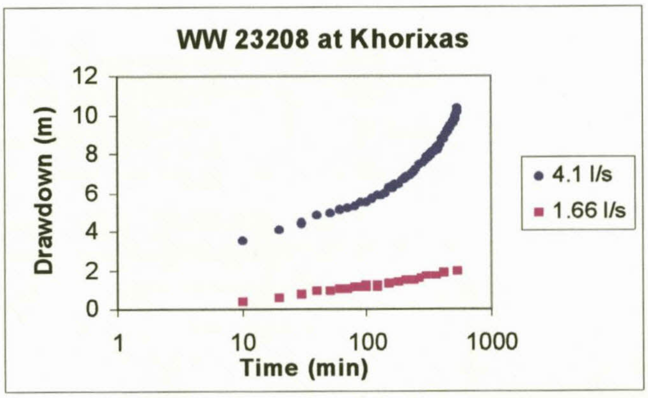


Figure 7.8: The Khorixas borehole in Namibia

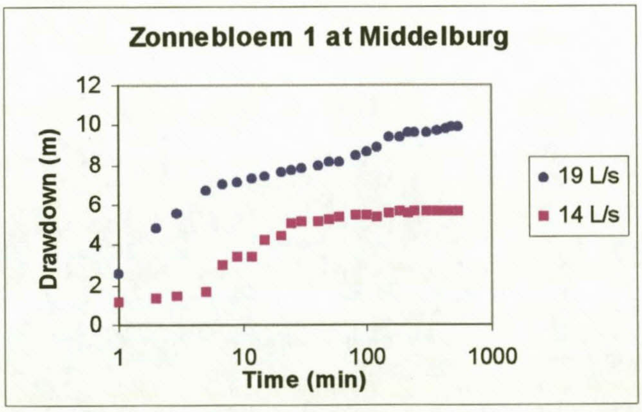


Figure 7.9: The Zonnebloem 1 borehole at Middelburg

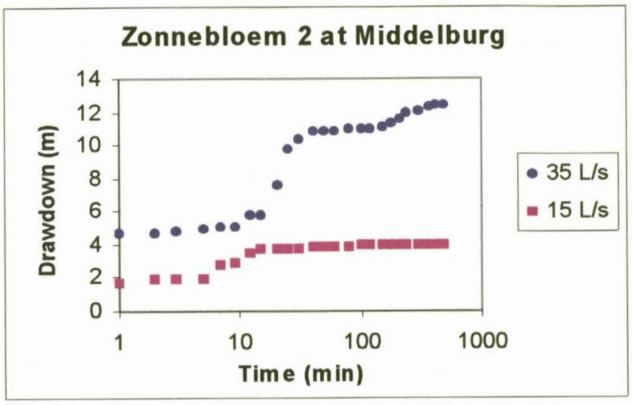


Figure 7.10: The Zonnebloem 2 borehole at Middelburg

7.5 NON-LINEARITY OF DRAWDOWN AND DISCHARGE RATE

Non-linearity between drawdown and discharge rate could be the result of four phenomena:

- ☐ Turbulence (i.e. non-Darcian flow)
- ☐ Dewatering of some discrete fractures
- ☐ Water table aquifer
- ☐ Elasticity

7.5.1 TURBULENCE

The non-linear effect caused by turbulence was discussed in Section 7.1 and equation (7.1) which included the non-linear term CQ^2, that is estimated from a step drawdown test.

It is possible to fragment Equation (7.1) into

$$s_w = CQ^2 \qquad (7.5)$$

generalised as

$$s_w = CQ^n \qquad (7.6)$$

and

$$s_w = BQ \qquad (7.7)$$

Equation (7.6) is valid when $BQ << CQ^n$. The condition holds when the aquifer is fully stressed and the curve converges to a parabolic curve as $Q \rightarrow +\infty$.

Similarly for equation (7.7), which is true when $BQ >> CQ^n$. The condition prevails when $Q < 1$, that is, as Q approaches *0*, then $CQ^n \rightarrow 0$. The graph tends to run parallel to the time axis.

With this information it is clear that an optimum discharge rate (Q) should not push a system into a non-linear domain (over-exploitation) and equally important, the aquifer should not be under utilised.

Turbulence is discussed at particle level where flow is compared to conduit (or void) geometry. Turbulent flow has been observed in pipes transporting fluids, but hardly mentioned when it comes to groundwater. Turbulence is an aspect that is scale dependent and is more pronounced when large conduits are used. This characteristic has made most hydrogeologists comfortable with the principle when fractures and sinkholes are viewed as conduits. By employing computational fluid techniques the concept can be demonstrated.

7.5.2 DEWATERING OF FRACTURES

If a discrete fracture is dewatered during a pumping test, the effective transmissivity value (T-value) becomes smaller with the consequence that the drawdown shows an increase (steeper gradient). If the water level (drawdown1) stays at the position of a fracture for a long time at a specific discharge rate (say Q1), the ratio of drawdown with this discharge rate compared to the drawdown (drawdown2) of a lower discharge rate (say Q2), could result in a smaller drawdown-ratio compared to the discharge rate-ratio. For example if Q1/Q2 = (say) 2, then drawdown1/drawdown2 < 2). In most cases however, the ratio drawdown1/drawdown2 > Q1/Q2.

7.5.3 WATER TABLE AQUIFER

Groundwater flow in a confined aquifer is described by a linear parabolic equation (linear in h). On the other hand, the flow in a water table aquifer is described by a non-linear parabolic differential equation (linear in h^2). The drawdown in a water table aquifer is thus non-linear in the abstraction rate. The most probable reason why we observe a non-linear drawdown to discharge rate (s/Q) relationship in many of the shallow fractured aquifers in South Africa is that the aquifers are not true confined aquifers but a mixture of confined/semi-confined with a water table aquifer overlying the fracture (the matrix). If the drawdown is small compared to the thickness of the formation (i.e. $s << D$), the flow in the aquifer could be described by a linear confined parabolic partial differential equation.

If, however, the drawdown is large compared to the thickness of the formation, the flow must be described by the true water table non-linear partial differential equation. The solution to this problem is not easy and usually the confined partial differential equation is used, but by substituting KD for T (transmissivity). As time progresses (more drawdown) the KD-value (T-value) is becoming smaller and smaller with the consequence that the drawdown per log cycle is becoming larger and larger.

7.5.4 ELASTICITY

The water released from a confined aquifer is in accordance with the elasticity of the formation. Factors that influence the storage coefficient of an aquifer are:

- the specific weight of the water
- aquifer porosity
- aquifer compressibility and
- the compressibility of the water.

If the stress-strain relation relative to the matrix elasticity is linear, the aquifer does not undergo a deformation and is described by the linear law of Hooke (Cloot and Botha, 2000). If the relation is non-linear the aquifer will show deformation according the non-linear law of Hooke.

7.5.4.1 LINEAR LAW OF HOOKE

Cloot and Botha (2000) did some numerical simulations with their elastic numerical model and found very interesting results. An aquifer consisting of three layers was used (a porous middle layer (typical fracture layer) bounded by the top and bottom by aquitards (typical matrix layers). When pumping starts, the perturbations of pressure are developing rapidly in a close vicinity of the borehole and are generating elastic deformations in both horizontal and vertical directions, in different manners however.

The horizontal deformations are developing uniformly throughout the whole depth of the aquifer, while vertical displacements are only generated along the discontinuities existing at the aquitard-aquifer interfaces. For increasing values of time, the perturbations of pressure, as well as the deformations, start to spread into the aquifer. In the case of the radial displacements, the maximum amplitude of deformation starts to travel away from the borehole wall, while the maxima of vertical displacements stay localized on the discontinuities, but the domain of influence is widening on both sides of the interfaces. The interaction between perturbation of pressure and displacement is strengthening and deformations start to affect significantly the heads in the matrix.

The reaction of the piezometric head in both the porous and matrix layer is non-linear but deformation is reversible in this case (i.e. properties of aquifer stay the same).

7.5.4.2 NON-LINEAR LAW OF HOOKE

If the non-linear law of Hooke applies, the stress-strain is first linear (linear deformation) and then, with time it changes to a non-linear relationship (plastic deformation) and at a certain value of the stress the aquifer deforms permanently (permanently damaged). As pumping starts the system behaves along the elastic part of the stress-strain curve and deformations are developing in the same way as in the linear case discussed above. For increasing time the amplitude of the strains become larger in the regions where displacement take place. The strains relative to the radial and vertical displacements quickly exceed the elastic limit and the non-elastic behaviour propagates to the part in the matrix that is closest to the porous-matrix discontinuity. This behaviour enhances the amplitude of the deformations, if compared to the linear case and creating a permanent deformation of the aquifer.

7.6 NON-LINEAR DRAWDOWN-ABSTRACTION OBSERVATION IN THE UO6 PIEZOMETER ON THE CAMPUS TEST SITE

The question can now be asked, which of the four phenomena described above is the reason for the non-linear drawdown-abstraction observation in the UO6 piezometer?

No fractures were dewatered during the pumping test and therefor turbulence could be ruled out. With the aid of tracer tests, it was estimated that the velocity in the matrix of the aquifer on the Campus Test Site is very, very small (< 0.01 m/d) and with such a small velocity the flow in the matrix is supposed to be linear Darcian flow. This leaves us with two possibilities namely:

- ☐ elasticity and
- ☐ the aquifer reacts like a water table aquifer.

Vertical fractures intersect the whole aquifer at some places, which implies that the vertical fracturing zones are phreatic. The ongoing drawdown measured in the UO6 piezometer after the pump was switched off, can only be explained by two factors:

- ☐ elasticity and
- ☐ the abstraction borehole is situated in a limited extent fracture which acts like a semi-closed boundary (which in true in the case of UO5) and the contrast of the fracture-matrix properties are very high (which is also true on the Campus Site).

At this stage it is difficult to choose between the elastic and water table aquifer phenomenon for being the reason of the non-linear drawdown behaviour measured in piezometer UO6. More field tests are required, at different abstraction rates as well as at the same abstraction rate in the same borehole to see if the results obtained can be repeated.

7.7 NON-LINEARITY OF DRAWDOWN WITH TIME

The convergence of drawdown curves to parabolic curves is indicative of non-linearity not only with the abstraction rate (Q), but with time as well. Barker (1988) and Bangoy *et al.*,(1992) mentioned the effect of time in the pass. An equation of the form $s_w = At^n$ was presented (Barker, 1988) where n is equal to the flow dimension of the system.

The effect is difficult to quantify in the field because of the presence of no-flow boundaries (dykes in most cases) or contact zones of different hydraulic properties. The use of fractals and flow dimensions becomes very instrumental in clarifying the phenomenon.

7.8 SUSTAINABLE YIELD ESTIMATION IN THE CASE OF NON-LINEARITY

Helweg (1994) proposed a general solution to the step drawdown test. By replacing the power of 2 in the Jacob equation with p, equation (7.1) becomes:

$$s = BQ + CQ^p \tag{7.8}$$

To solve equation (7.8), an arbitrary fixed time interval (duration of discharge) must be chosen. To generalise the equation it must be modified so that the drawdown of any given discharge and time can be determined.

The BQ-term in equation (7.1) includes time and can be written as:

$$BQ = \frac{2.3Q}{4\pi T}\log\frac{2.25Tt}{r^2S} = [\frac{2.3}{4\pi T}\log\frac{2.25T}{r^2S}]Q + [\frac{2.3}{4\pi T}\log t]Q = AQ + B^1Q\log t \tag{7.9}$$

The coefficient A could also be viewed as the term that includes the skin (ξ), i.e.:

$$A = \frac{\xi}{2\pi T} \tag{7.10}$$

The second term in equation (7.8) can be derived from the Chezy, Darcy-Weisbach and Hazen-Williams equation for head loss in pipes and is summarised by:

$$h_f = \frac{LRQ^p}{D^m} \tag{7.11}$$

where h_f/L = head loss per unit length of pipe

Q = the discharge

D = the pipe diameter

R = coefficient of resistance.

Equation (7.11) is similar to the term CQ^p. The problem now is to include time in the second term of equation (7.9), such that C becomes a function of log t. Drawdown is a function of time and the change in the pseudo pipe diameter attributed to the well screen and surrounding gravel pack is also a function of drawdown. As the drawdown increases the cross-sectional entrance area of the screen will decrease for an unconfined aquifer and consequently we can write:

$$CQ^p = C^1 Q^p \log(t) \tag{7.12}$$

where C^1 = new coefficient that incorporates time.

The general step drawdown equation can now be written as (Helweg, 1994):

$$s(t) = AQ + B^1 Q \log t + C^1 Q^p \log t \tag{7.13}$$

If time is constant equation (7.13) reduces to equation (7.8).

As discussed previously, where it was showed with examples that the relationship between drawdown could be non-linear for Darcian flow and from Barker (1988) where the drawdown is also a power function of time (i.e. a typical fractal flow dimension), the following equation is proposed to addressed these type of non-linearities:

$$s(t) = AQ + B^1 Q^e (\log t)^{G(n/2)} + C^1 Q^p \log t \tag{7.14}$$

where G = Gamma function

n = flow dimension

e = elasticity coefficient (e > 1, if e = 1 no elasticity)

If n = 2 and e = 1, equation (7.14) reduces to the Helweg equation, equation (7.13), because G(2/2) = 1. In the case where n = 1, linear flow is assumed and for any other non-integer value of n, the equation describes fractal flow. The turbulent term in equation (7.14) is similar to the turbulent term in the Helweg equation. The figure below ***(Fig. 7.11)*** shows the values of G(n/2) for different values of the flow dimension n.

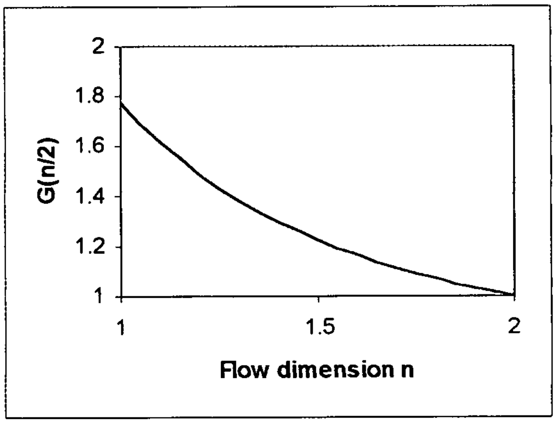


Figure 7.11: Values of G(n/2) for different flow dimension values

The general solution to the step drawdown test (equation (7.14)) implies that the step drawdown test can be conducted in the field without a constant time increment (i.e. the rate can be changed after any time, say 10, 30, 55, 70, etc. minutes). According to Helweg a test with at least three steps are to be conducted and that the final pumping rate of the test must be as high as possible. It is also stated that the drawdown during the last step must reach the pump inlet. It is however proposed that the drawdown must reach the position of the main fracture during the last step and not the pump-inlet, because dewatering the main water strike can cause permanent damage to the borehole.

To estimate the sustainable yield of the borehole, equation (7.14) must be fitted to the step drawdown test data obtained from the field experiment. After the coefficients A, B^1, C^1, p, and n are obtained, a suitable Q must be found from equation (7.14) such that the drawdown after a long time (e.g. 2 years) is equal to the selected prescribed drawdown (i.e. the available drawdown).

The method above is included in the FC-program and is called the non-linear FC-method. It is also possible to estimate a T-and S-value from the generalised step test by using the Birsoy-Summers-method (1980), (Kruseman and de Ridder, 1990). The Cooper Jacob method yielded a T value of 16 m^2/d and S value of 6E-3 for UP16. The Birsoy-Summers-method gave values of 18 m^2/d and 6E-3 for UP16 respectively. Due to the changing of rates a time correction must be performed. The t in the Cooper-Jacob equation is replaced with a correction time $\beta_{t(n)}(t-t_n)$:

$$\beta_{t(n)}(t-t_n)=\prod_{i=1}^{n}(t-t_i)^{\frac{\Delta Q_i}{Q_n}} \tag{7.15}$$

where t_i = time at which the i-th pumping period started

Q_i = constant discharge during the i-th pumping period

ΔQ_i = discharge increment beginning at time t_i.

The application of the method is exactly the same as the Cooper-Jacob method. The only difference is that a graph of s_i/Q_i is drawn against the corrected time. For the estimation of the S-value of the borehole the effective borehole radius must replace the real borehole radius.

7.9 CASE STUDIES

7.9.1 BOREHOLE UP16 ON THE CAMPUS SITE

A step drawdown test was performed on borehole UP16 on the Campus aquifer. The data is included in ***Appendix D.*** The following information applies:

- A bedding plane fracture was intersected in borehole UP16 at a depth of 21 meter below surface
- Water level in UP16 = 13.2 meter

- ☐ The total duration of the test was 120 minutes
- ☐ The pumping rates were changed after 21, 46 and 64 minutes
- ☐ Pumping rates were respectively: 0.61, 1.18, 2.0 and 3.5 l/s.

The figure below *(Fig. 7.12)* shows the data obtained during the pumping test.

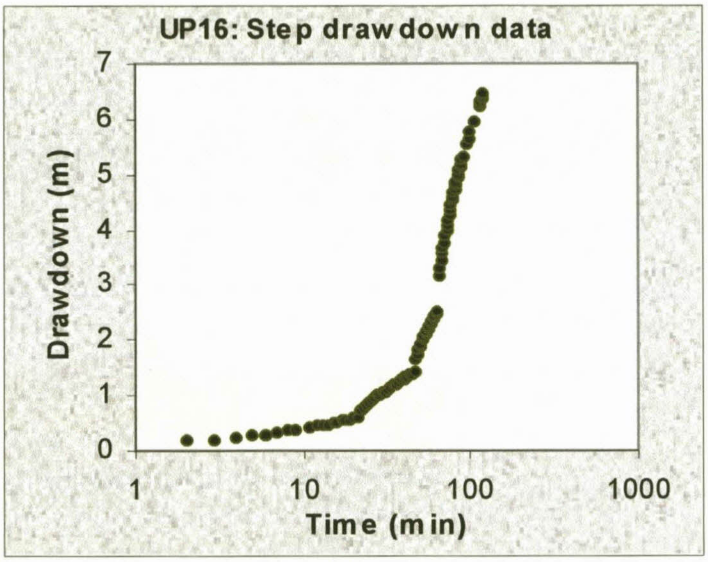


Figure 7.12: Data collected during the step drawdown test on UP16

Equation (7.14) was then fitted to the collected data and the result can be seen in the figure below *(Fig. 7. 13)*.

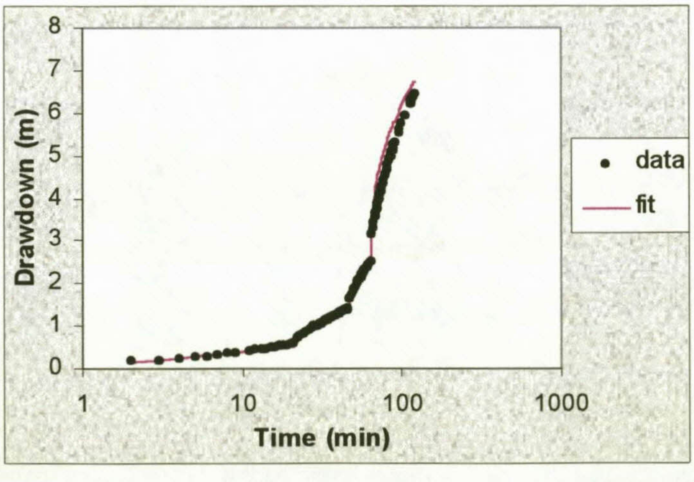


Figure 7.13: Graph showing the measured and fitted data by using equation (7.14)

Fitting the equation (equation (7.14)) to the data yielded the following coefficients ***(Table 7.6)***.

Coefficient	Value
A	0.0013
B	2.0E-3
C	2.1E-7
p	2.42
n	1.63
e	1.3

Table 7.6: Coefficient values obtained by fitting equation (7.14) to UP16 data

By using the fitted coefficients, the Q in equation (7.14) was then used to extrapolate the drawdown for a period of 2 years such that the drawdown would not reach the position of the main water strike or bedding plain fracture (i.e. an available drawdown of 21.0 - 13.2 = 7.8 meter was used). The abstraction rate obtained was 0.5 l/s by including the influence of no-flow boundaries that exists on the Campus Site. The FC-method as was proposed by Van Tonder et al. (1998) yielded a value of 0.48 l/s for the sustainable yield.

7.9.2 BOREHOLE UP15 ON THE CAMPUS SITE

A step drawdown test was performed on borehole UP15 on the Campus aquifer. The data is included in ***Appendix D.*** The following information applies:

- A bedding plane fracture was intersected in borehole UP15 at a depth of 21 meter below surface
- Water level in UP15 = 13.32 meter
- The total duration of the test was 120 minutes
- The pumping rates were changed after 19, 40 and 60 minutes
- Pumping rates were respectively: 0.572, 1.05, 1.81 and 2.5 l/s.

The figure below *(Fig. 7.14)* shows the data of the test.

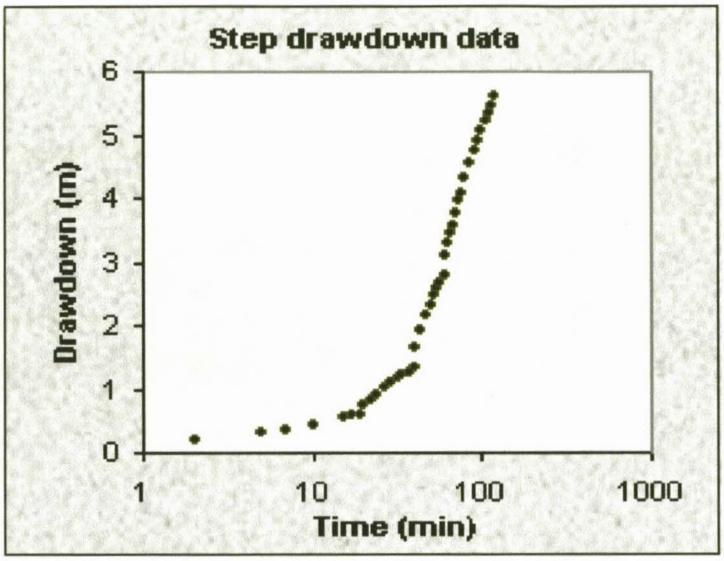


Figure 7.14: Data collected during the step drawdown test on UP15

Equation (7.14) was then fitted to the collected data and the result can be seen in the figure below *(Fig. 7. 15)*.

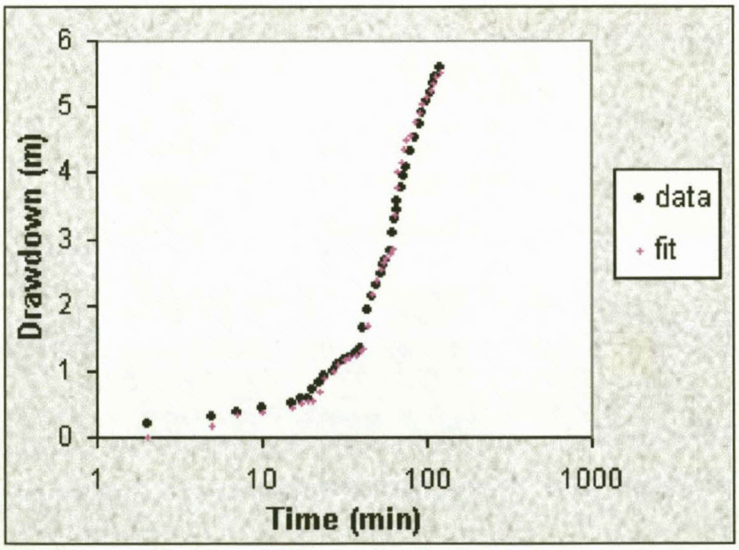


Figure 7.15: Graph showing the measured and fitted data by using equation (7.14)

Fitting the equation (equation (7.14)) to the data yielded the following coefficients *(Table 7.7)*.

Coefficient	**Value**
A	0.00123
B	4.05E-3
C	7.0E-7
p	2.57
n	2.0
e	1.16

Table 7.7: Coefficient values obtained by fitting equation (7.14) to UP15 data

By using the fitted coefficients, the Q in equation (7.14) was then used to extrapolate the drawdown for a period of 2 years such that the drawdown would not reach the position of the main water strike or bedding plain fracture (i.e. an available drawdown of 21.0 - 13.2 = 7.68 meter was used). The abstraction rate obtained was 0.57 l/s by including the influence of no-flow boundaries that exists on the Campus Site. The FC-method as was proposed by Van Tonder et al. (1998) yielded a value of 0.40 l/s for the sustainable yield.

7.10 GENERAL

Non-linearity in drawdown curves should be treated with caution when it comes to assigning of sustainable yields to boreholes. From Section 7.2 the effect of non-linearity can be used as a diagnostic tool making use of the horizontal, linear (straight line) and parabolic plots of drawdown versus time.

The more parallel the drawdown is to the time axis the lesser the imparted stress will be to an aquifer. Highly parabolic curves indicate a very stressed aquifer. Therefore an optimum discharge rate should give a drawdown plot, which is roughly a straight line.

In order to be able to decide on an optimum discharge rate in the field, a step drawdown and at least one constant rate test are recommended. For management purposes a sustainable yield is then decided from an optimum discharge rate. This issue is discussed further in ***Chapter 8***.

CHAPTER 8

PROPOSED GUIDELINES FOR PUMPING TEST EXECUTION AND ANALYSIS IN FRACTURED AQUIFERS

8.1 INTRODUCTION

As stated in Chapter 5, the two main objectives of pumping test analysis are the estimation of aquifer parameters and the estimation of the sustainable yield (long term) of a borehole. The principles for conducting pumping tests and analysing pumping test data will differ, depending on what the objectives and the purpose for doing the pumping test are. In South Africa pumping tests are normally done to estimate the long-term sustainable yield of a borehole so that the water from the borehole can be used to supply water to a community.

The main aim of this chapter is to propose a set of general rules for the practical geohydrologist on how to perform and analyze a pumping test, considering the two objectives. Every borehole in a fractured rock aquifer reacts differently, and therefore it is of no use to give one general recipe on how to conduct and analyze the pumping test that is to be done in it. In the end, the expert analyzing the pumping test is totally responsible for the way in which the test is conducted and analyzed. He or she must use all there practical experience and knowledge to come up with an answer. The aim is also to demonstrate the limitations of analytical analyzing methods. Usually the limitations are due to the assumptions of the method. At the end of this chapter a few typical examples will be discussed.

8.2 PARAMETER ESTIMATION

If the objective of the pumping test is to estimate aquifer parameters that are to be used in for example, a numerical management model, the constant rate pumping test is the most important test that should be conducted and is set as a minimum requirement for parameter estimation. Although a slug test and step drawdown (or multirate) test can also be conducted, it is not of much practical value for parameter estimation. If the interest is setting up a three-dimensional numerical model, a number of piezometers must be installed (to measure pressure heads and vertical K values of each layer) in the vicinity of the pumping borehole. One of the most important factors of a constant rate pumping test in this case, is selecting the abstraction rate during the test. The yield must be chosen in such a way that no main water yielding structures (main fracture) will be dewatered during the test.

The diagram below ***(Fig. 8.1)*** gives an indication of the steps that should be followed when conducting borehole testing for parameters estimation.

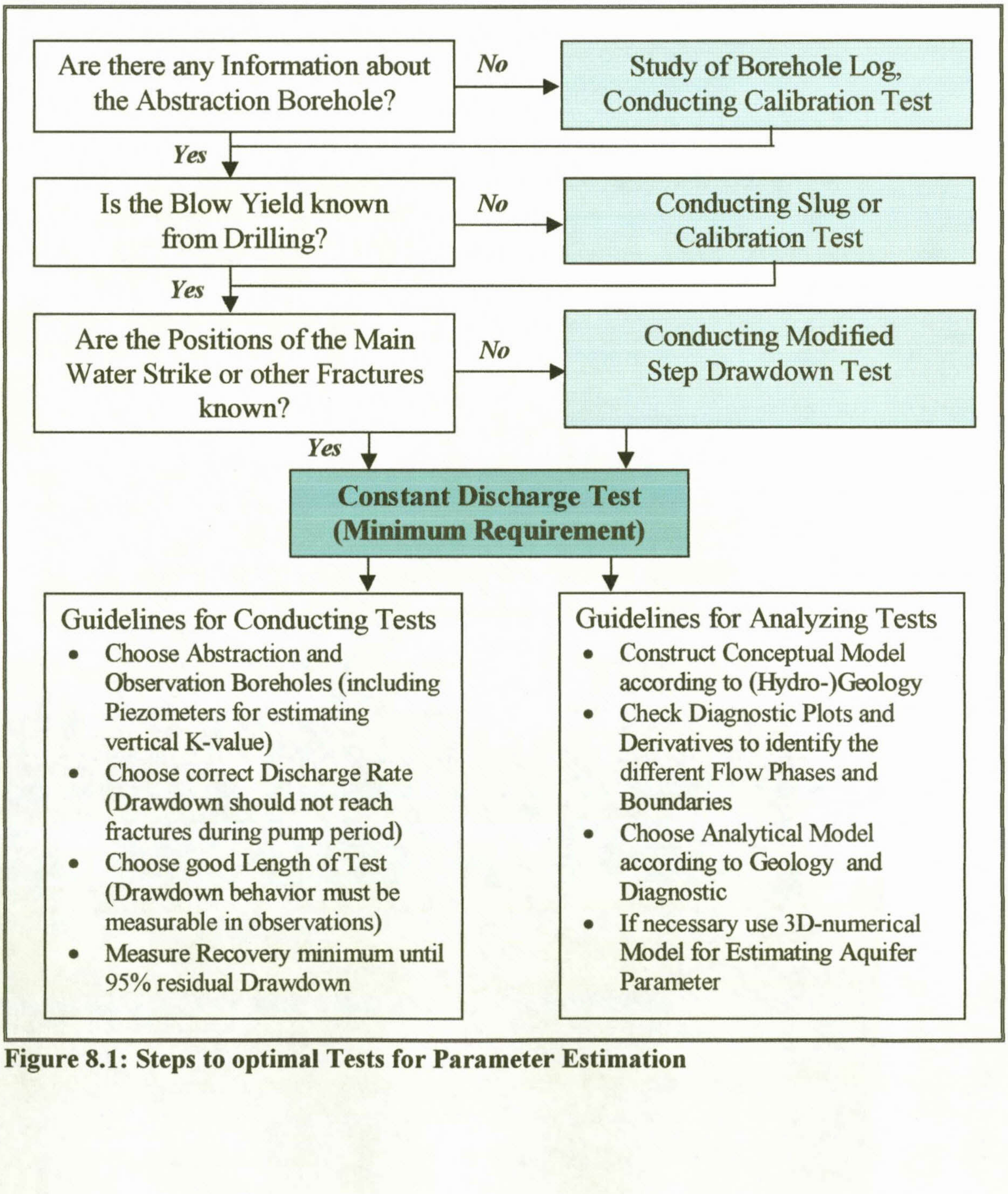


Figure 8.1: Steps to optimal Tests for Parameter Estimation

8.2.1 THE IMPORTANCE OF CORRECT AQUIFER PARAMETER ESTIMATION

It is important to obtain the correct aquifer parameters because of the following reasons:

- ☐ The aquifer parameters are important for management purposes (yield and pollution management). In combination with the geological set up inside the aquifer, the parameters are used for the construction of the correct conceptual model.
- ☐ Usually numerical models are used for well-field management with the objective to optimise pumping rates, subject to certain drawdown constraints.
- ☐ In cases of contaminated groundwater the aquifer parameters are important for risk assessments and planning remedial steps.
- ☐ Depending on the demands, several observation boreholes and piezometers at different depths will be used for measurements.

8.2.2 STEPS AND RULES FOR PARAMETER ESTIMATION

The general rules that should be followed in the determination of aquifer parameters are listed in figure 8.1. The steps are:

- ☐ If no information is available on the maximum yield of the abstraction borehole, a slug test can be performed (Vivier *et al.*, 1995). The recession time after about 90% recovery can then be used to estimate a maximum yield for the borehole:

$$Q\ (L/h) = 117155t^{-0.824} \qquad (8.1)$$

Where t = the 90% recovery of the water level in seconds

Q = abstraction rate in liter/hour.

- ☐ To locate the depth of the main water strike and to determine an abstraction rate that will not allow the water level to reach the position of the main water strike (fracture), a modified minimum one-hour step drawdown test is suggested. This suggested test is slightly different from the known step drawdown test. Usually equal time increments are selected for a stepped drawdown test, but in the proposed test, equal time increments are not important. Start with a very low pumping rate and increase the abstraction rate after any time (e.g. 5 minutes, 15 minutes, 40 minutes or 50 minutes). A flattening of water level will occur at the position of a fracture.

- ☐ For the constant discharge test, which is set as a minimum requirement, choose an abstraction rate so that the drawdown in the abstraction borehole will not reach the position of a fracture. If the position of a fracture is reached the conditions inside the aquifer could change from confined or semi-confined to unconfined which makes the analysis of the data extremely difficult.
- ☐ The duration of the constant rate test must be long enough to ensure interpretable drawdown curves are obtained at the observation points (observation boreholes and piezometers). The minimum proposed duration of pumping should be approximately 8 hours. If the impact of inner (extent of fracture, matrix) or outer boundaries (no-flow or recharge boundaries) is to be estimated, the duration of the constant rate pumping test should be several days.
- ☐ Diagnostic plots (e.g. log-log and derivatives) can assist in identifying the different characteristic flow regimes. These characteristics include wellbore storage, linear flow, bilinear flow, semi-radial flow as well as boundary conditions. This was discussed in detail in Chapter 4.
- ☐ Construct the most suitable conceptual model for the aquifer considering the above characteristics and the geology (it is not always possible to identify the type of flow uniquely and fitting of different models to the data could shed more light).
- ☐ Select the most suitable analytical model (e.g. double porosity, single fracture of infinite or finite conductivity) and use the TPA program (including skin factors and boundary conditions) to fit the measured drawdown and recovery data. Time-drawdown data associated with a flow period representative of typical fractured behavior for the aquifer can only be analyzed using one of the analytical models discussed in Chapter 5 in this thesis. Different models and different methods of interpretation may have to be applied to the various parts of the observed time-drawdown data. A numerical model such as RPTSOLV can also be used to estimate parameter values (storativity).

- If the fractured aquifer reacts as a homogeneous porous aquifer, the Theis or Cooper-Jacob methods can be used to estimate parameters. It should be remembered that the Theis method is only applicable in the case of infinite 'acting' radial flow (i.e. where the derivative is a horizontal line parallel to the time-axis. This is usually at late times of the pumping test, if a boundary was not reached). In this case the estimated T- and S-values are representative of the whole aquifer, without differentiating between the fracture and matrix.
- For more accurate data fits, use a three-dimensional (3D) numerical model (as developed by Chiang *et al.*, 2000). The numerical models are not without problems and the solutions will depend on the conceptual model constructed for the aquifer.
- Measurements during recovery phase must never be omitted and should be analyzed independently.

8.2.3 PITFALLS AND LIMITATIONS

As discussed in Chapter 5, most of the analytical models have inherent problems and limitations. Therefore they have to be used with caution. Some important limitations, which are valid for almost all methods are listed below:

- All analytical models for fractured rock aquifers assume confined conditions (a very strict condition) which is usually violated in pumping tests in South African fractured rock aquifers. Mostly the main fracture-zone (horizontal or vertical) is connected with the surface or a phreatic aquifer above through smaller perpendicular fractures, which implies semi-confined or unconfined conditions in the fracture-zone.
- It is important to make sure of the assumptions underlying each analytical model before applying it to the time-drawdown or time-recovery data.
- When a fracture is dewatered the aquifer system at that point will change from confined (or semi-confined) to unconfined, resulting in the T-value decreasing. The slope in the diagnostic plots before and after reaching the fracture position is normally not the same.
- The T-value estimated with any analytical technique for an observation borehole situated in the matrix or which is badly connected to the fracture will yield a too

high T-value. Here a correct estimation is only possible when using a three-dimensional (3D) numerical model.

- ☐ The estimated S-value will show distance dependency in a single fracture or double porosity aquifer if analyzed with an analytical model. If a single fracture model is used, the fracture half-length must replace the observation distance, if known. For an abstraction borehole situated in a double porosity aquifer, the effective borehole radius must be used as observation distance.
- ☐ If the T-value (or K-value) of a matrix is very small (orders smaller than that of the fracture), the drawdown in matrix piezometers will show a delayed response (i.e. after abstraction has ceased the hydraulic level will still show a drawdown). This behavior can only be seen if the fracture has a limited extent (i.e. acting like a closed boundary). The analyzing of this type of time-drawdown data is not possible using an analytical method. A 3D numerical model must be used.
- ☐ The non-uniqueness of the double porosity analytical model seriously restricts the practical applications of these models when interpreting pumping test data for fractured rock aquifers. Heterogeneous aquifers in which the layers have highly contrasting flow characteristics will react as a double porosity aquifer.
- ☐ Whether outer boundaries will have an impact on the time-drawdown behavior depends on the radius of influence. As a first estimate of the radius of influence of a borehole, the following equation can be used:

$$r_e = 1.5\,(Tt/S)^{0.5} \qquad (8.2)$$

where T = Transmissivity in m^2/d
t = time in days
S =Storativity

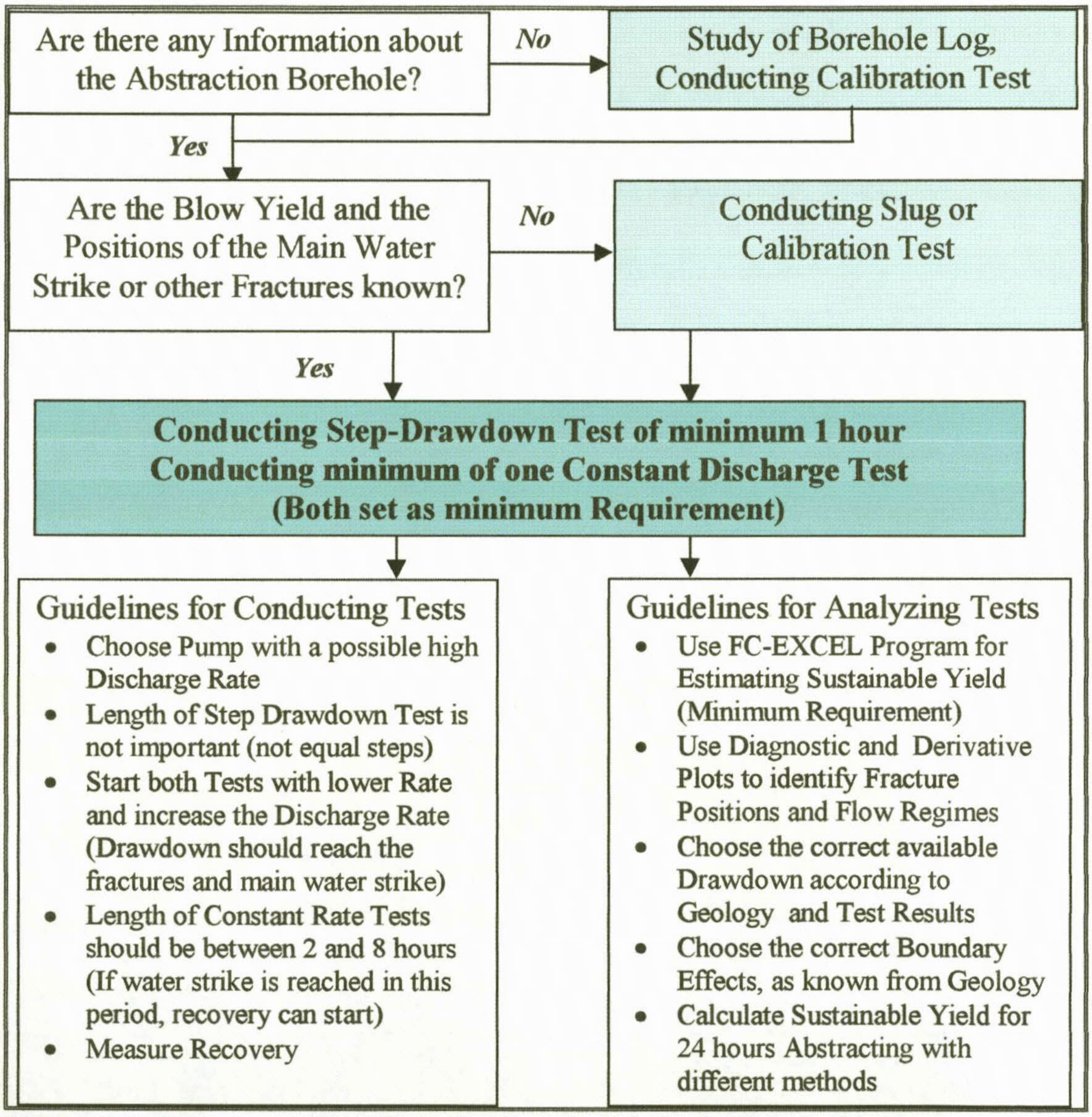
Equation (8.2) can determine whether a no-flow boundary will have an influence on the time-drawdown data. If a no-flow boundary intersects the same fracture as the abstraction borehole, the time-drawdown data will show the influence of the no-flow boundary. The reason for this is because the T-value of the fracture is usually very high (in the order of hundreds or thousand) while the storage coefficient is very small (e.g. in the order of 10^{-5}). If the no-flow boundary does not intersect the same fracture as the abstraction borehole, the influence of the no-flow boundary will normally not be seen in a pumping test as the drawdown wave propagates with the T-value of the formation (which is much smaller than that of the fracture) and the S-value of the formation which is very high (usually in the order of 10^{-3}). The typical radius of influence in a Karoo aquifer with a matrix T-value of 5 m^2/d and S=0.005, is 82 meter after a time of 3 days of pumping. This implies that a no-flow boundary situated 100 meter away from the abstraction borehole will not have an influence on the time-drawdown data. An upward trend in the time-drawdown data after a certain time is normally interpreted as the influence of a no-flow boundary, and this can be incorrect. This is because the end of the fracture zone was attained during the pumping test, causing the steeper drawdown due to the lower T-value of the formation.

If parameter estimation is to be used for pollution management purposes, it is important to conduct the pumping test in such a way that the parameters for fracture and matrix can be calculated separately. For example, the vertical movement of pollution is controlled mainly by the vertical K-value and the pressure gradient in the vertical direction. The only way to obtain this pressure gradient is by installing piezometers at different depths in a borehole, and to perform a pumping test during which, the hydraulic heads are measured in the piezometers. Analyzing the data can only be done by using a three-dimensional (3D) numerical model, as no analytical method can estimate the vertical K-value.

8.3 SUSTAINABLE YIELD ESTIMATION FOR SINGLE BOREHOLE

If the objective of the pumping test is to estimate the sustainable yield of a single borehole, it is not necessary to use different analytical or numerical models to estimate aquifer parameters. According to the definition of the sustainable yield, it is necessary to only obtain the relationship between the abstraction rate and drawdown in the borehole. Therefore as a minimum requirement for estimating the sustainable yield a minimum of one constant rate test must be conducted, stressing the aquifer. A step drawdown test of minimum one-hour is also set as a minimum requirement. To get prior information, a slug test can also be performed. However it is normally not of much practical value. One of the most important factors to consider when performing a constant rate pumping test is selecting an appropriate abstraction rate. The yield must be chosen so that the main water strike will be reached during the constant rate test.

The diagram below ***(Fig. 8.2)*** gives an indication of the steps that should be followed when conducting borehole testing for sustainable yield estimation.



Are there any Information about the Abstraction Borehole?

Study of Borehole Log, Conducting Calibration Test

Are the Blow Yield and the Positions of the Main Water Strike or other Fractures known?

Conducting Slug or Calibration Test

Conducting Step-Drawdown Test of minimum 1 hour
Conducting minimum of one Constant Discharge Test
(Both set as minimum Requirement)

Guidelines for Conducting Tests

- Choose Pump with a possible high Discharge Rate
- Length of Step Drawdown Test is not important (not equal steps)
- Start both Tests with lower Rate and increase the Discharge Rate (Drawdown should reach the fractures and main water strike)
- Length of Constant Rate Tests should be between 2 and 8 hours (If water strike is reached in this period, recovery can start)
- Measure Recovery

Guidelines for Analyzing Tests

- Use FC-EXCEL Program for Estimating Sustainable Yield (Minimum Requirement)
- Use Diagnostic and Derivative Plots to identify Fracture Positions and Flow Regimes
- Choose the correct available Drawdown according to Geology and Test Results
- Choose the correct Boundary Effects, as known from Geology
- Calculate Sustainable Yield for 24 hours Abstracting with different methods

Figure 8.2: Steps to optimal Tests for Sustainable Yield Estimation

8.3.1 IMPORTANT INFORMATION IN THE ESTIMATION OF THE SUSTAINABLE YIELD OF A BOREHOLE

The following information is important in the estimation of the sustainable yield of a borehole:

- ☐ If single boreholes are used for private purposes, for example irrigation on farms, it is necessary to estimate the sustainable yield of the borehole so that the borehole does not dry up when continuously pumped.
- ☐ In cases like this, only the abstraction borehole is measured. Normally no observation boreholes are available because of the high cost associated with drilling of boreholes. Therefor the only data available is the data obtained in the pumping borehole.

8.3.2 STEPS AND RULES FOR SUSTAINABLE YIELD ESTIMATION

The sustainable yield is defined as the discharge rate that will not cause the water level in the borehole to drop below a prescribed position (usually the position of a major water strike). To estimate the sustainable yield for a single borehole the following general rules should be followed (as listed in figure 8.2):

- ☐ If there is no blow yield information for the borehole available, use a slug test and apply equation (8.1) to get a first estimate of the yield. A calibration test could be performed, but it is not set as a minimum requirement.
- ☐ The conductance of a minimum one-hour step drawdown test is set as a minimum requirement (see point under 8.2 above). As previously discussed under section 8.2, there is no reason for the selected time increments to be constant. The main objective of the test is to identify fracture positions and to choose a suitable rate for the constant rate test. If a non-linear well loss coefficient has to be estimated, the adapted Helweg method (Helweg, 1994) can be used.
- ☐ The only reason why an abstraction borehole can dry up is if the water level in the borehole drops to a level below the main water strike continuously. It is therefor important to stress the aquifer during the constant rate pumping test, ensuring that

the water level reaches the main water strike after some time (this time must not be too short, preferably after more than 2 hours).

- For sustainable yield estimations, at least one short duration constant rate test is proposed as a minimum requirement. The objective is to drop the water level to the position of the main fracture within 8 hours. If this position is reached between 2 and 8 hours, measuring of the recovery phase could start. If not, a higher rate must be chosen for the follow up constant rate pumping test. Many times it is impossible to lower the water level to the main water strike due to the limitations of the pump in a 160 - 165 millimeter drilled borehole. In this case the end drawdown level must be used as available drawdown.
- For estimating the sustainable yield of the borehole, the minimum requirement as set by the Department of Water Affairs and Forestry, is using the FC-program.
- The FC-program will estimate the sustainable yield of the borehole for 24 hours per day by using different methods. If the owner of the borehole only wants to abstract water for 8 hours per day, the rate obtained for 24 hours per day can be revised, as long as this new rate will not cause the water level to drop to the position of the main water strike within 8 hours. The estimated 24 hour sustainable yield is a minimum rate for borehole abstraction.
- The main objective is to recommend an abstraction rate for the borehole so that the water level in the borehole does not reach a specified position after a long time of abstraction (minimum of 1 year and maximum of 5 years for arid regions) without taking recharge into account.
- Monitoring of the water levels inside the borehole during the operation phase is of the utmost importance.

8.3.3 PITFALLS AND LIMITATIONS

There are some limitations when using analytical methods to estimate the sustainable yield. These limitations are:

- The sustainable yield estimate is non-unique, and will depend on the abstraction rate during the constant rate test (the higher the rate the lower the sustainable yield will be, and visa versa). It should also be remembered that the relationship between drawdown and abstraction rate is usually non-linear. This is due to the fact that fractures are dewatered faster at the higher rate and that the effective T-value will be smaller.

- ☐ If the drawdown curve shows an increase in slope, the effective T-value will converge towards the T-value of the matrix, which is normally much smaller than that of the fracture. The increase in slope is normally due to the dewatering of fractures or when the lateral extent of the fracture is reached.
- ☐ It is important to consider the correct choice of the available drawdown in the abstraction borehole. This will be discussed in detail in section 8.4 below.
- ☐ If there are more than one abstraction borehole in the aquifer system, the sum of the sustainable yields for all the boreholes must not be higher than the approximated recharge for the area.

8.4 CHOICE OF AVAILABLE DRAWDOWN

The correct choice of available drawdown is of utmost impotence because the sustainable yield is the relation between this known value and the abstraction rate. Care should therefor be taken in determining this value. The available drawdown inside a borehole should be taken as one of the following:

- ☐ The distance between the static water level and the position of main water strike, if this position was reached during the constant rate test.
- ☐ The distance between the static water level and the position where the drawdown graph shows a sharp increase.
- ☐ The distance between the static water level and the position of the water level at the end of the test if the main water strike was not reached.
- ☐ Also consider the recovery data to decide if the borehole has recovered completely. If the recovery data shows a horizontal flattening at late time, it indicates that the fracture system acts like a semi-closed boundary (i.e. very low formation T-value).
- ☐ For a dolomitic aquifer an available drawdown of 5 meter would normally be a good choice because sinkholes could form if the drawdown inside the aquifer is more.

8.5 PROPOSED DURATION OF A CONSTANT RATE PUMPING TEST

It is important to note that one cannot select the duration of the constant rate pumping test beforehand. It is dangerous and not cost effective to decide beforehand that a test of say, 72 hours duration is required. It is common to see that a contract or tender specifies a 72 hour constant rate pumping test, without any prior knowledge of the aquifer or borehole.

In some cases rigid guidelines are set for the duration of constant rate pumping tests. The criterion set according to the Reconstruction and Development Program rules of South Africa specify that the duration of the constant rate pumping test shall not be less than 12 hours and in some instances it might even last for 72 hours or more (Hobbs and Marais, 1997). According to the South African Bureau of Standards code of practice on the Development, Maintenance and Management of Groundwater Resources (SABS 0299-4:1998 Part 4: Test-pumping of water boreholes) the duration of a constant rate pumping test must be:

- 48 hours for a low yielding borehole if water is to be supplied to a town or village
- 72 hours for a high yielding or main borehole if water is to be supplied to a town or village
- 48 hours if the borehole is to be fitted with an engine driven pump to supply water to a rural village
- 48 hours or more if the water is to be used for irrigation with a high cost consequence if failure occurs.

In some cases it is recommended to run a constant rate pumping test for a minimum length of eight hours when the borehole is to be fitted with a hand, solar or wind driven pump. The test should last for at least forty-eight hours when the borehole is to be equipped with an electrical or diesel driven pump, which is to be operated on a daily basis.

It is proposed that no rigid set of rules should be prescribed, but that the purpose of the pumping test must first be determined. It must be decided whether the constant rate pumping test is required for:

- ☐ parameter estimation or
- ☐ estimation of the long-term sustainable yield.

In parameter estimation the position of the main water strike should first be determined with the modified minimum one-hour step drawdown test. The duration of the constant rate test must be long enough to ensure that interpretable drawdown curves are obtained at the observation points (observation boreholes and piezometers). The minimum proposed duration of pumping should be approximately 8 hours. If the impact of inner (extent of fracture, matrix) or outer boundaries (no-flow or recharge boundaries) is to be estimated, the duration of the constant rate pumping test should be several days.

Whether outer boundaries will have an impact on the time-drawdown behavior depends on the radius of influence. The typical radius of influence in a Karoo aquifer with a matrix T-value of 5 m^2/d and S=0.005, is 82 meter after a time of 3 days of pumping. This implies that a no-flow boundary situated 100 meter away from the abstraction borehole will not have an influence on the time-drawdown data. To continue with a constant rate pumping test for several days to locate possible boundaries situated kilometers away is therefor a futile exercise and a waste of money.

For sustainable yield estimations, the position of the main water strike should first be determined with the modified minimum one-hour step drawdown test. The one hour step drawdown test will also assist in determining the abstraction rate of the constant rate pumping test. After this has been done, at least one short duration constant rate pumping test is proposed. The objective is to drop the water level to the position of the main fracture within 8 hours. If this position is reached between 2 and 8 hours, measuring of the recovery phase could start. If not, a higher rate must be chosen for the next or follow up constant rate pumping test.

8.6 PUMP SELECTION

The best type of pump to be used for constant rate pumping tests is a positive displacement pump like the Mono pump. The yield of this type of pump remains constant and will not change if the water level drops inside the borehole as testing progresses. The main drawback of a positive displacement pump is that it is not easy to specify a pre-selected rate. Submersible (negative displacement) pumps can be used, but the abstraction rate will decrease with an increase in drawdown. It is, however, a simple task to set an exact initial pumping rate, when using a submersible pump. The abstraction rate can be varied by opening and closing a valve.

The maximum yield of the pump must be chosen so that the drawdown, which is necessary to achieve the goal of the pumping test, will be reached in time.

8.7 FIELD EXAMPLES

In order to demonstrate the limitations of analytical analysing methods a few examples will be discussed. Usually these limitations are due to the assumptions made in the methods. The following examples are considered (see Chapter 7):

- ☐ UO5 at the Campus Site
- ☐ M1 at the Meadhurst Site
- ☐ Zonnebloem 1 and Zonnebloem 2 at Middelburg
- ☐ The borehole at Khorixas.

In all the above cases more than one constant rate pumping test was conducted on the borehole. This is to illustrate that the sustainable yield of a borehole is a non-unique value, which will depend on the abstraction rate during the pumping tests. The table below ***(Table 8.1)*** lists the borehole information together with the sustainable yield determined by using the FC- and other methods.

It is clear from Table 8.1 that the sustainable yield increases as the abstraction rate decreases from a constant rate test. The reason for this is that with a higher abstraction rate more information is obtained concerning the effective hydraulic properties of a borehole with depth (fractures were dewatered and the effective T-value becomes smaller). The sustainable yield obtained with a higher abstraction rate, is regarded as the minimum sustainable yield of the borehole. In the case of a deep water strike, which can not be reached during the constant discharge test, the drawdown at the end of the test should be used as available drawdown to estimate the sustainable yield.

Borehole	**Geology**	**Main water strike (b RWL)**	**Q1 (l/s)**	**Sust_Q1 (l/s)**	**Q2 (l/s)**	**Sust_Q2 (l/s)**
M1	Dolerite/ contact	14	1.5	1.4 [0.6*]	2.0	0.80
UO5	Sandstone	10	0.5	0.9 [0.4*]	1.25	0.65
Zon 1	Mudstone	10	14	11.5 [6.9*]	19	5.67
Zon 2	Mudstone	11	15	15.3 [5.6*]	35	9.3
Khorixas	Calcrete	10	1.66	0.38 [0.32*]	4.16	0.36
* = Sustainable yield obtained by using the drawdown at the end of the test as prescribed in section 8.4						

Table 8.1 Borehole information and sustainable yield estimates

In the FC-program developed by Van Tonder *et al.* (1998) the user has the choice to obtain an estimate of the sustainable yield of a borehole with the following methods:

- FC-method (Basic, Advanced and Inflection point solutions)
- Cooper-Jacob method
- Barker-method.

The program is estimating the standard deviation of the estimates obtained with all the methods. In the case of the Advanced FC-program, a risked-based sustainable yield is estimated. To apply the advanced method, the user must know the possible range of the distances to no-flow boundaries and the range of T-and S-value. The program then estimates a 68.5 or 95 % certainty sustainable yield.

To extrapolate the drawdown measured in an abstraction borehole from data of a pumping test of maximum 3 days to a very long period (e.g. 2 years), remains uncertain. The importance of water level monitoring during the actual operational phase of the borehole could not be stressed enough. Monitoring must always be an integral part of aquifer management.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 CONCLUSIONS

From the research it can be concluded that:

1) The real reason why a particular pumping test is to be conducted must be established before the start of the test. The purpose of the pumping test will play an integral part in the actual method of conducting and analysing the test (length and abstraction rate). In South Africa pumping tests are performed for mainly two reasons, to determine the long-term sustainable yield of a borehole or to estimate the aquifer parameters.

2) Because of the composition of the South African aquifer systems (water table aquifer behaviour and elasticity) there is a non-linear relationship between the abstraction rate and the drawdown. At different abstraction rates different fractures will be dewatered and in some cases the end of the fracture extent will be reached. This results in a smaller effective transmissivity (T) value, giving rise to a unique drawdown value per abstraction rate. This non-linearity between drawdown and abstraction rate has the consequence that it is very difficult to extrapolate the behaviour of the water level in an aquifer if a rate different to that used during the constant rate test is applied. This feature should be treated with caution when it comes to the assigning of sustainable yields to boreholes.

3) Incorrect analytical methods are often used to estimate parameter values. Because of assumptions such as homogeneity and infinite areal extent used in developing most of these analytical methods as well as the unique composition and characteristics of South African Karoo aquifers, unrealistic parameter values are produced. These parameter values (such as storativity that is distance dependent if analysed with a wrong model) are then used in

sustainable yield calculations. These incorrect sustainable yield values result in the borehole drying up.

4) Pumping tests should be performed as accurately as possible. An aquifer (groundwater resource) that is to be utilised is not visible to the geohydrologist (can not be seen with the eyes like surface water) and because of this many unknowns and uncertainties exist. This can result in incorrect assumptions and interpretation of data, causing serious problems. In an effort to minimise the uncertainties it is important that the visible or known part of the investigation should be performed properly. It is therefor important that the pumping test and the collection of data during the test should be performed properly.

9.2 RECOMMENDATIONS

1) The purpose or objective of a pumping test should be established before a test is conducted. If the objective of a pumping test is to estimate the parameters of the aquifer the following is recommended:

- ☐ A modified minimum one-hour step drawdown test should be performed to locate the depth of the main water strike as well as to determine an abstraction rate for the constant rate pumping test.
- ☐ A constant rate pumping test, long enough to ensure interpretable drawdown curves at the observation points should be performed. The abstraction rate during this constant rate test is very important because no water yielding structures should be dewatered during the test.
- ☐ The recommended minimum duration of the constant rate pumping test is 8 hours, but depending on the parameters that is to be estimated, it can last for several days.

2) Great care should be taken when analysing pumping test data for parameter estimation. A suitable analytical model should be used, taking into account the unique aquifer conditions in South Africa. In some cases a two-dimensional numerical model such as RPTSOLV, developed for the

conditions in this country, should be used to estimate aquifer parameter values. By applying incorrect analytical methods incorrect, storativity values (S-values) are obtained. When using numerical models such as RPTSOLV, acceptable storativity values are obtained. For more accurate data fits, a three-dimensional numerical model must be used.

3) If the objective of the pumping test is to estimate the long-term sustainable yield of the borehole, the following is recommended:

- ☐ Once again a modified minimum one-hour step drawdown test should be performed to locate the depth of the main water strike as well as to determine an abstraction rate for the constant rate pumping test.
- ☐ The constant rate pumping test should be performed, straining the aquifer in order to drop the water level down to the position of the main water strike within 8-hours.
- ☐ It is recommended that the FC-program be used for the long-term sustainable yield calculation.

4) It is recommended that the non-linearity between drawdown and abstraction rate, causing problems in extrapolating the future behaviour of the water level in an aquifer if a rate different to that used during the constant rate test is applied, be taken into account when assigning sustainable yields to boreholes. If a non-linear well loss coefficient has to be established it is recommended that the revised one-hour step drawdown test be performed.

5) The proper planning and execution of a pumping test will yield reliable data and this data will enable the user to estimate realistic parameter values or long-term sustainable yields. It is therefor recommended that great care should be taken when doing a pumping test and when gathering data during a pumping test.

APPENDIX A

(CONDENSED FIELD GUIDE FOR PUMPING TESTS)

CONDENSED FIELD GUIDE ON PLANNING AND PERFORMING A PUMPING TEST

This is a condensed field guide explaining the different steps involved in planning and executing a pumping test. For more detail on the different steps the thesis should be consulted.

The purpose of the pumping test should be identified in the beginning of the planning stage because this will influence the execution of the test. The objectives can either be to estimate aquifer parameters that are to be used in a numerical management model or it can be to estimate the long-term sustainable yield for the borehole. If the objective of the pumping test is to estimate aquifer parameters the diagram below ***(Diagram 1)*** gives an indication of the steps that should be followed.

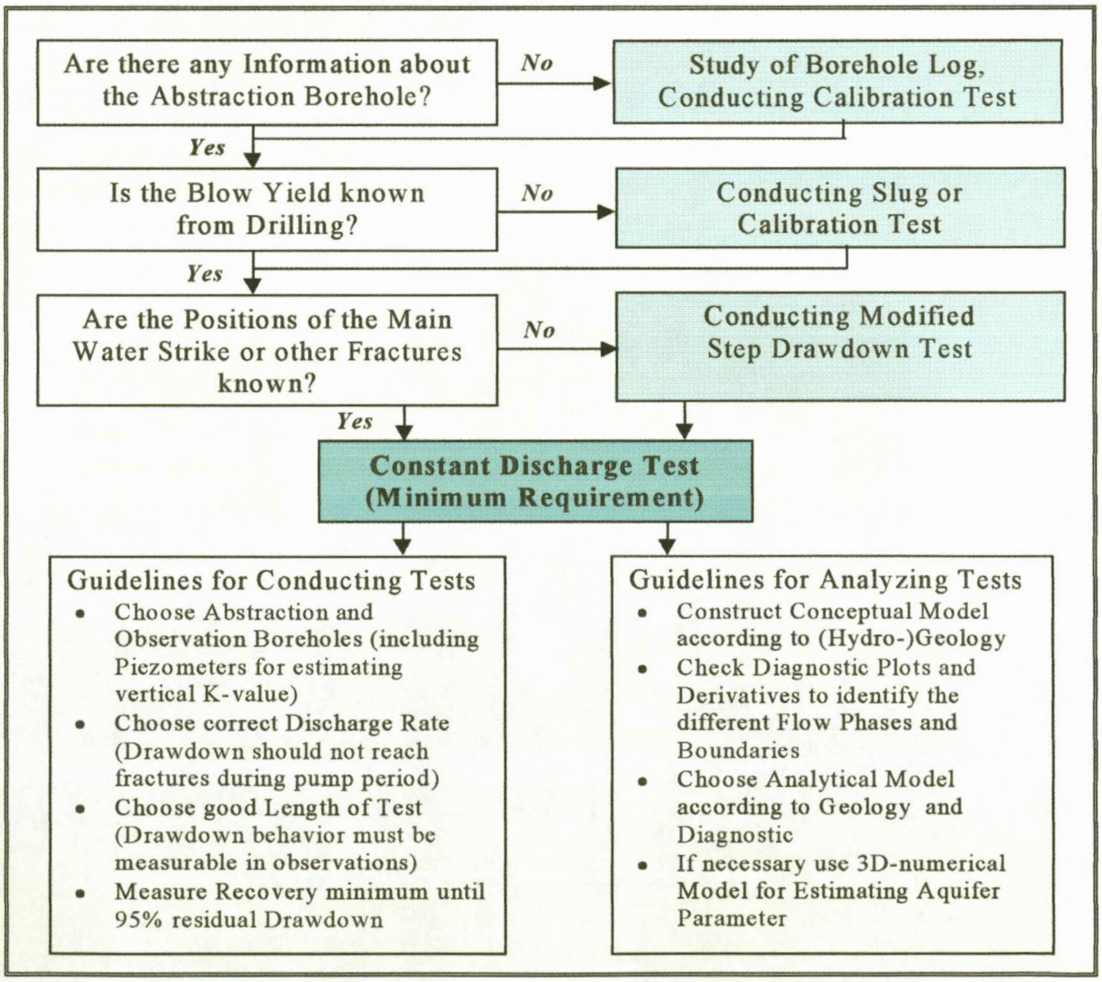
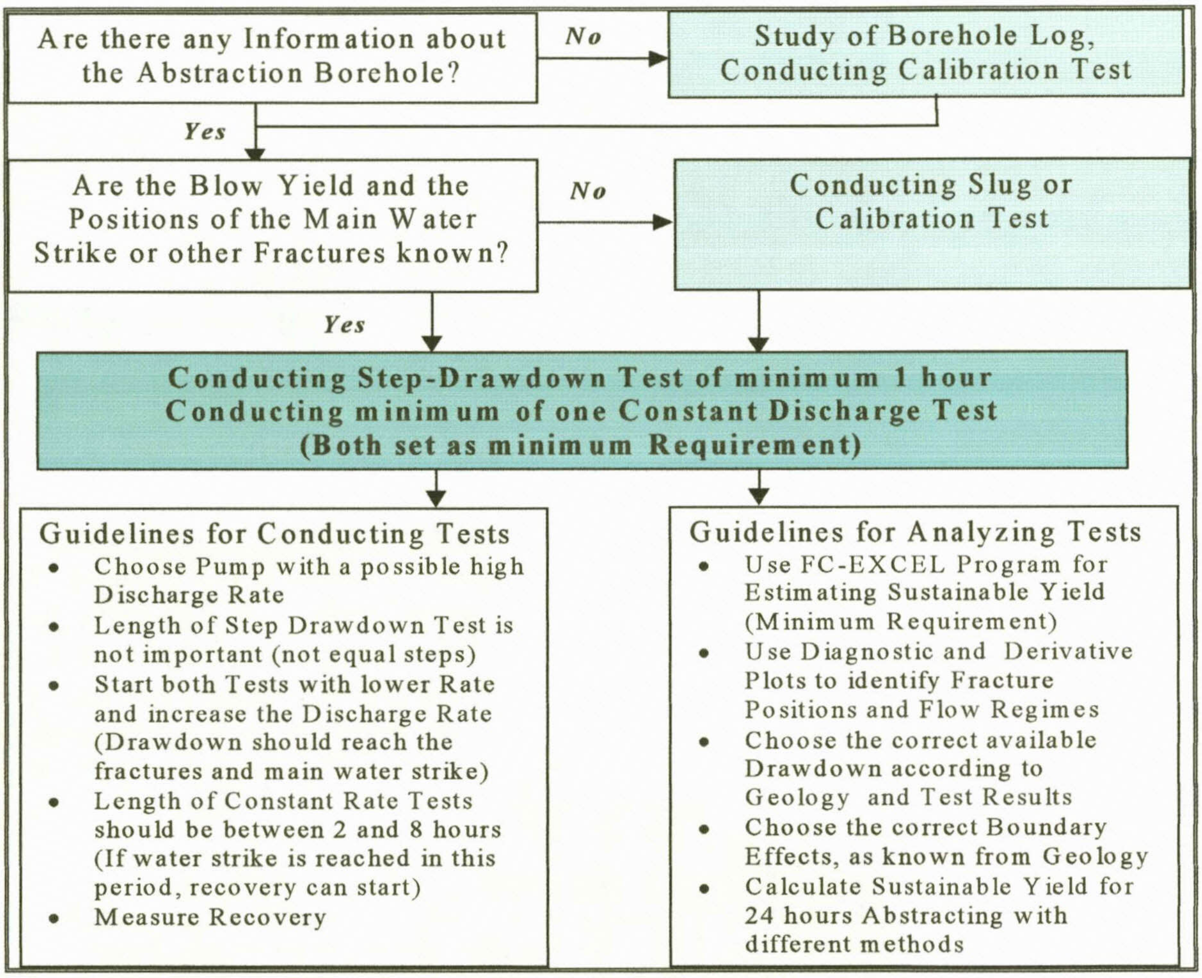


Diagram 1: Steps to follow for parameter estimation

If the objective of the pumping test is to estimate the long-term sustainable yield for a borehole the diagram below ***(Diagram 2)*** gives an indication of the steps that should be followed.



Are there any Information about the Abstraction Borehole?

Study of Borehole Log, Conducting Calibration Test

Are the Blow Yield and the Positions of the Main Water Strike or other Fractures known?

Conducting Slug or Calibration Test

Conducting Step-Drawdown Test of minimum 1 hour
Conducting minimum of one Constant Discharge Test
(Both set as minimum Requirement)

Guidelines for Conducting Tests

- Choose Pump with a possible high Discharge Rate
- Length of Step Drawdown Test is not important (not equal steps)
- Start both Tests with lower Rate and increase the Discharge Rate (Drawdown should reach the fractures and main water strike)
- Length of Constant Rate Tests should be between 2 and 8 hours (If water strike is reached in this period, recovery can start)
- Measure Recovery

Guidelines for Analyzing Tests

- Use FC-EXCEL Program for Estimating Sustainable Yield (Minimum Requirement)
- Use Diagnostic and Derivative Plots to identify Fracture Positions and Flow Regimes
- Choose the correct available Drawdown according to Geology and Test Results
- Choose the correct Boundary Effects, as known from Geology
- Calculate Sustainable Yield for 24 hours Abstracting with different methods

Diagram 2: Steps to follow for long-term sustainable yield estimation

In order to perform a successful pumping test the active participation of different people is required. On the one hand there is the pumping test contractor who is responsible for gathering the field data. There is also the geohydrologist who is responsible for the initial planning of the test as well as the evaluation and interpretation of the field data. This guide will look at each person's responsibilities as well as the necessary interaction between the two parties to ensure the success of the pumping test.

1. BEFORE THE START OF THE PUMPING TEST

1.1 GEOHYDROLOGIST

- ☐ The different tests that are to be performed must be determined before the commencement of the testing and the minimum length of each test must be specified.
- ☐ The geohydrologist must ensure that a proper contract exists between the interested parties. On the one hand the party that requires the pumping test and on the other hand the pumping test contractor that will perform the work. The scope of the work that is to be performed should be described in detail.
- ☐ The geohydrologist must determine the exact position of the pumping test borehole as well as the positions of possible observation boreholes. These positions should be supplied to the pumping test contractor and during a site meeting these positions can be mutually agreed upon.
- ☐ Existing pumping equipment and the removal and reinstallation of this equipment to enable the contractor to perform the pumping test must be described in the contract.
- ☐ As much as possible information regarding the pumping borehole and the aquifer must be gathered by the geohydrologist prior to the beginning of the pumping test. Information on borehole logs, maps and aerial photographs, existing pumping tests, blow yields, possible abstraction rates, positions of fractures as well as the depth of the borehole should be obtained in order to assist the pumping test contractor.

1.2 THE PUMP TEST CONTRACTOR

- ☐ Enter into a proper contract to ensure payment and correct information. Issues such as the removal and reinstallation of existing equipment must be included in the contract.
- ☐ Obtain as much as possible information regarding the geology, borehole logs, blow yields, possible abstraction rates, positions of fractures as well as the depth of the borehole from the geohydrologist.
- ☐ Get permission from the owner of the property to perform the pumping test.

- ☐ Gather the equipment to do the pumping test. A list of the equipment is included in *Appendix B*.
- ☐ Ensure that a pump, capable of pumping sufficient volumes of water for long enough periods of time, is available to perform the testing.

2. ARRIVAL ON SITE ACTIONS

2.1 PUMP TEST CONTRACTOR

- ☐ Arrange a site meeting with the geohydrologist. Locate the correct borehole that is to be pump tested as well as the identified observation boreholes. If no observation boreholes had been specified, locate possible observation boreholes in the vicinity of the pumping borehole.
- ☐ Remove existing pumping equipment from the pump testing borehole and make notes about the condition and type of equipment as well as the depth of installation.
- ☐ Determine the depth and diameter of the pumping as well as the observation boreholes.
- ☐ Measure the distances from the pumping borehole to the different observation boreholes as well as the collar heights above the natural ground level.
- ☐ Measure the static water levels in the pumping as well as the observation boreholes.
- ☐ If no information regarding the blow yield is available, perform a slug test to get a first estimate of the possible maximum yield of the pumping borehole. If the possible maximum yield is found to be less than 0.3 l/s, the geohydrologist must be contacted and a decision whether to stop or continue with testing must be taken.
- ☐ If testing is to continue, the pumping equipment should now be installed into the pumping borehole. The intake of the pump should be placed at the correct depth.
- ☐ Discharge piping must be attached to the pump to ensure that the water pumped from the borehole is discharged away from the borehole. The correct length of discharge piping must be used.

- Equipment to measure the amount of water that is pumped from the pumping borehole should be installed. The discharge from the pump should be measured and recorded at regular intervals.
- In some cases electronic data logging equipment is prescribed to do water level measurements. If prescribed, this equipment should now be installed. If not required, water level measurements can be taken with a dip tape and a stopwatch.
- The actual testing can now start.

3. DURING TESTING

3.1 PUMP TEST CONTRACTOR

- If the objective of the pumping test is to determine parameter values for the aquifer, the pumping test contractor will proceed as follow.
    - As mentioned before, a slug test will be performed to give a first estimate of the possible maximum yield for the borehole.
    - To perform a proper constant rate pumping test the correct pumping rate should be chosen. The pumping rate should allow for sufficient drawdown during the constant rate test, without allowing the water level to reach the position of the main fracture. To determine the optimum abstraction rate the pump test contractor will perform a short calibration test.
    - If the position of the main water strike or fracture is not known, a revised minimum one-hour step drawdown test will be performed. No equal time steps are required and the pumping rates can be increased at any time during the test. A flattening of the water level indicates the positions of the fractures.
    - Next a constant rate pumping test must be performed. The abstraction rate should not allow the water level to reach the position of the main water strike.
    - The duration of the constant rate pumping test must be long enough to ensure that interpretable drawdown curves are obtained at the observation points (observation boreholes). The minimum proposed duration of pumping should be approximately 8 hours. If the impact of inner boundaries (extent of fracture, matrix) or outer boundaries (no-flow or

  recharge boundaries) is to be estimated, the duration of the constant rate pumping test should be several days.
  - Measure the recovery inside the abstraction borehole until the water level has recovered to 95 percent of the original static water level. A recovery test is an independent test without any external interference's and it can yield important information.
- If the objective of the pumping test is to determine the long-term sustainable yield for a specific borehole, the pumping test contractor will proceed as follow.
  - As mentioned before, a slug test will be performed to give a first estimate of the possible maximum yield for the borehole.
  - To perform a proper constant rate pumping test the correct pumping rate should be chosen. In this case the pumping rate should allow for as much as possible drawdown during the constant rate test, ensuring that the water level will reach a position below the main fracture. To determine the optimum abstraction rate the pump test contractor will perform a short calibration test.
  - If the position of the main water strike or fracture is not known, a revised minimum one-hour step drawdown test will be performed. No equal time steps are required and the pumping rates can be increased at any time during the test. The main objective of this test is to identify fracture positions and to choose a suitable rate for the constant rate pumping test. A flattening of the water level indicates the positions of the fractures.
  - The pump test contractor will now proceed with a short duration constant rate test. The objective is to drop the water level to the position of the main fracture within 8 hours. If this position is reached between 2 and 8 hours, measuring of the recovery phase could start. If not, a higher pumping rate must be chosen for the follow up constant rate pumping test. Many times it is impossible to lower the water level to the main water strike due to the limitations of the pump in a 160 - 165 millimeter drilled borehole. In this case the end drawdown level must be used as available drawdown.
  - Measure the recovery inside the abstraction borehole until the water level has recovered to 95 percent of the original static water level. A recovery test is an independent test without any external interference's and it can yield important information.

- Proper water level measurements should be taken in both the abstraction and observation boreholes during testing. These measurements should be recorded on the prescribed data sheets and the information should be handed to the geohydrologist after the completion of the tests. The discharge rate from the pump should also be measured regularly.
- Additional information such as other pumping activities or abstractions during testing, irrigation activities prior to testing, change in water color and temperature as well as visible boundaries should be recorded. As much as possible information should be supplied by the pump test contractor.
- If specified in the contract, the pump test contractor must take water samples. The samples should be taken close to the end of testing and the samples should be handed over to the geohydrologist.

3.2. GEOHYDROLOGIST

- The geohydrologist can visit the test site while the contractor is busy with the testing. Control water level measurements against time as well as discharge measurements from the pump can be taken.
- The pumping test contractor must consult the geohydrologist on important issues such as the length and abstraction rate for the constant rate pumping test.
- The positions of the main fractures can be verified once the modified step drawdown test had been performed. This should be done in conjunction with the geohydrologist.

4. AFTER THE PUMPING TEST HAD BEEN PERFORMED

4.1 PUMP TEST CONTRACTOR

- The pump testing and water level measuring equipment must be removed from the boreholes.
- If it is the responsibility of the pump test contractor, the pumping equipment that was installed on the boreholes prior to testing should be reinstalled to the same condition before removal.

- The terrain should be properly cleaned and it should be left in the same condition as during the start of the testing.
- The information gathered during the pumping test should be submitted, with a detailed account for the work done, to the geohydrologist.

4.2 GEOHYDROLOGIST

- The geohydrologist must obtain the results of the different pumping tests from the pumping test contractor.
- The raw data should be checked, edited and prepared before the tests can be analyzed.
- If the objective of the pumping test is to obtain parameter values for the aquifer the geohydrologist must:
  - Construct a conceptual model according to the geology as well as hydrologic conditions influencing the aquifer.
  - Construct and check the diagnostic and derivatives plots to identify the different flow phases and boundary conditions present in the aquifer.
  - Choose an analytical model according to the geology and diagnostic results.
  - If necessary, use a three-dimensional numerical model to estimate the aquifer parameter values.
- If the objective of the pumping test is to estimate a long-term sustainable yield for a specific borehole the geohydrologist must:
  - Use the FC-EXCEL Program for estimating the sustainable yield.
  - Use diagnostic and derivative plots to identify fracture positions and flow regimes.
  - Choose the correct available drawdown inside the borehole according to the geology and test results.
  - Choose the correct boundary effects, as obtained from the geology and diagnostic results.
  - Calculate a sustainable yield for 24 hours abstracting with different methods.

APPENDIX B

(CHECKLIST FOR PUMPING TEST AND OTHER EQUIPMENT)

CHECKLIST FOR PUMP TEST EQUIPMENT

NO	DESCRIPTION	QUANTITY	PACKED
1	Global Positioning System (GPS)		
2	Survey equipment (Theodilite, range rods)		
3	Compass		
4	Camera		
5	Electric lead		
6	Adapter plugs		
7	Flat screwdriver		
8	Phillips screwdriver		
9	Generator		
10	Jerry cans		
11	Fuel (Petrol or diesel)		
12	Oil		
13	Funnel		
14	Pump – Small capacity		
15	Vertical delivery pipes for small pump		
16	Horizontal delivery pipes for small pump		
17	Hose clamps for small pump		
18	Valve to reduce delivery from small pump		
19	Pump – Large capacity		
20	Vertical delivery pipes for large pump		
21	Horizontal delivery pipes for large pump		
22	Hose clamps for large pump		
23	Valve to reduce delivery from large pump		
24	Twenty litre bucket		
25	Fifty litre bucket		
26	Stopwatch		
27	Flowmeter		
28	Flowmeter fittings		
29	Tripod frame		
30	Block and tackle		
31	Winch		
32	Additional chain		
33	Slug test cylinder		
34	Bailer		
35	Ski rope (100 meters)		
36	Pressure probe (s)		
37	Data logger		
38	Data cable		
39	Solar panel		
40	Battery for data logging equipment		
41	Dipmeter		
42	Extra batteries for dipmeter		
43	Five meter tape measure		
44	Fifty meter tape measure		
45	Hundred meter tape measure		

46	Shifting spanner		
47	Baboon wrench		
48	Pliers		
49	Hammer		
50	Open-ring spanners		
51	Thin wire		
52	Cable ties		
53	Spade		
54	Tree saw		
55	Water sample bottles		
56	Marker pen		
57	Thread tape		
58	Masking tape		
59	Flood light		
60	Flash light		
61	Pen		
62	Data sheets – Constant rate test		
63	Data sheets – Calibration test		
64	Data sheets – Stepped drawdown test		
65	Data sheets – Multi rate test		
66	Writing paper		
67	Laptop computer		
68			
69			
70			
71			
72			
73			
74			
75			

CHECKLIST FOR OTHER EQUIPMENT

NO	DESCRIPTION	QUANTITY	PACKED
1	Tent		
2	Tent pegs		
3	Camping beds		
4	Mattress		
5	Matches		
6	Fire wood		
7	Charcoal		
8	Chair		
9	Table		
10	Water container		
11	Water		
12	Gas braai		
13	Umbrella		
14	Hat		
15	Suntan lotion		
16	Bedding		
17	Mosquito repellent		
18	Alarm clock		
19	Pots and pans		
20	Kettle		
21	First aid kit		
22			
23			
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APPENDIX C

(DATA SHEETS FOR PUMPING TESTS)

CALIBRATION TEST DATA SHEET

General Information	Pumping Borehole Information	Remarks
Project No:	Depth of Pump (m):	
Borehole No:	Collor Height (m):	
Site Name:	BH diameter (m):	
Farm Name:	Depth of BH (m):	
Coordinates	Static W/L (m):	
Latitude:		
Longitude:		

Discharge rate 1

Date: Time:

Static W/L (m):

Time	Drawdown	Yield	Time	Recovery
(min)	s (m)	(l/s)	(min)	s' (m)
1			1	
2			2	
3			3	
4			4	
5			5	
6			6	
7			7	
8			8	
9			9	
10			10	
11			11	
12			12	
13			13	
14			14	
15			15	
			20	
			30	
			40	
			50	
			60	
			70	
			80	
			90	
			100	

Discharge rate 2

Date: Time:

Static W/L (m):

Time	Drawdown	Yield	Time	Recovery
(min)	s (m)	(l/s)	(min)	s' (m)
1			1	
2			2	
3			3	
4			4	
5			5	
6			6	
7			7	
8			8	
9			9	
10			10	
11			11	
12			12	
13			13	
14			14	
15			15	
			20	
			30	
			40	
			50	
			60	
			70	
			80	
			90	
			100	

Discharge rate 3

Date: Time:

Static W/L (m):

Time	Drawdown	Yield	Time	Recovery
(min)	s (m)	(l/s)	(min)	s' (m)
1			1	
2			2	
3			3	
4			4	
5			5	
6			6	
7			7	
8			8	
9			9	
10			10	
11			11	
12			12	
13			13	
14			14	
15			15	
			20	
			30	
			40	
			50	
			60	
			70	
			80	
			90	
			100	

Discharge rate 4

Date: Time:

Static W/L (m):

Time	Drawdown	Yield	Time	Recovery
(min)	s (m)	(l/s)	(min)	s' (m)
1			1	
2			2	
3			3	
4			4	
5			5	
6			6	
7			7	
8			8	
9			9	
10			10	
11			11	
12			12	
13			13	
14			14	
15			15	
			20	
			30	
			40	
			50	
			60	
			70	
			80	
			90	
			100	

Discharge rate 5

Date: Time:

Static W/L (m):

Time	Drawdown	Yield	Time	Recovery
(min)	s (m)	(l/s)	(min)	s' (m)
1			1	
2			2	
3			3	
4			4	
5			5	
6			6	
7			7	
8			8	
9			9	
10			10	
11			11	
12			12	
13			13	
14			14	
15			15	
			20	
			30	
			40	
			50	
			60	
			70	
			80	
			90	
			100	

Discharge rate 6

Date: Time:

Static W/L (m):

Time	Drawdown	Yield	Time	Recovery
(min)	s (m)	(l/s)	(min)	s' (m)
1			1	
2			2	
3			3	
4			4	
5			5	
6			6	
7			7	
8			8	
9			9	
10			10	
11			11	
12			12	
13			13	
14			14	
15			15	
			20	
			30	
			40	
			50	
			60	
			70	
			80	
			90	
			100	

CONSTANT DISCHARGE TEST DATA SHEET

General Information

Project No:
Borehole No:
Site Name:
Farm Name:
Latitude:
Longitude:

Test Started

Date:
Time:

Test Ended

Date:
Time:
Duration (min):
Planned Yield:

Remarks

Pumping Borehole Information

Depth of Pump (m):
Collor Height (m):
BH diameter (m):
Depth of BH (m):
Static W/L (m):

Observation Borehole Information

Observation BH 1	**Observation BH 2**	**Observation BH 3**
Number:	Number:	Number:
Distance:	Distance:	Distance:
Static W/L (m):	Static W/L (m):	Static W/L (m):

Time (min)	Drawdown s (m)	Yield (l/s)	Time (min)	Recovery s' (m)	Time (min)	Drawdown (m)	Time (min)	Drawdown (m)	Time (min)	Drawdown (m)
1			1		1		1		1	
2			2		2		2		2	
3			3		3		3		3	
4			4		4		4		4	
5			5		5		5		5	
6			6		6		6		6	
7			7		7		7		7	
8			8		8		8		8	
9			9		9		9		9	
10			10		10		10		10	
11			11		11		11		11	
12			12		12		12		12	
13			13		13		13		13	
14			14		14		14		14	
15			15		15		15		15	
16			16		16		16		16	
17			17		17		17		17	
18			18		18		18		18	
19			19		19		19		19	
20			20		20		20		20	
25			25		25		25		25	
30			30		30		30		30	
40			40		40		40		40	
50			50		50		50		50	
60			60		60		60		60	
75			75		75		75		75	
90			90		90		90		90	
120			120		120		120		120	
150			150		150		150		150	
180			180		180		180		180	
240			240		240		240		240	
300			300		300		300		300	
360			360		360		360		360	
420			420		420		420		420	
480			480		480		480		480	
600			600		600		600		600	
720			720		720		720		720	
900			900		900		900		900	
1080			1080		1080		1080		1080	
1440			1440		1440		1440		1440	
1800			1800		1800		1800		1800	
2160			2160		2160		2160		2160	
2520			2520		2520		2520		2520	
2880			2880		2880		2880		2880	
3600			3600		3600		3600		3600	
4320			4320		4320		4320		4320	

STEPPED DISCHARGE TEST DATA SHEET

General Information

Project No:
Borehole No:
Site Name:
Farm Name:

Pumping Borehole Information

Depth of Pump (m):
Collor Height (m):
BH diameter (m):
Depth of BH (m):

Remarks

Discharge rate 1

Date: Time:

Static W/L (m):

Time (min)	Drawdown s (m)	Yield (l/s)	Time (min)	Recovery s' (m)
1			1	
2			2	
3			3	
4			4	
5			5	
6			6	
7			7	
8			8	
9			9	
10			10	
11			11	
12			12	
13			13	
14			14	
15			15	
16			16	
17			17	
18			18	
19			19	
20			20	
30			30	
40			40	
50			50	
60			60	
70			70	
80			80	
90			90	
100			100	
110			110	
120			120	

Discharge rate 2

Date: Time:

Static W/L (m):

Time (min)	Drawdown s (m)	Yield (l/s)	Time (min)	Recovery s' (m)
1			1	
2			2	
3			3	
4			4	
5			5	
6			6	
7			7	
8			8	
9			9	
10			10	
11			11	
12			12	
13			13	
14			14	
15			15	
16			16	
17			17	
18			18	
19			19	
20			20	
30			30	
40			40	
50			50	
60			60	
70			70	
80			80	
90			90	
100			100	
110			110	
120			120	

Discharge rate 3

Date: Time:

Static W/L (m):

Time (min)	Drawdown s (m)	Yield (l/s)	Time (min)	Recovery s' (m)
1			1	
2			2	
3			3	
4			4	
5			5	
6			6	
7			7	
8			8	
9			9	
10			10	
11			11	
12			12	
13			13	
14			14	
15			15	
16			16	
17			17	
18			18	
19			19	
20			20	
30			30	
40			40	
50			50	
60			60	
70			70	
80			80	
90			90	
100			100	
110			110	
120			120	

Discharge rate 4

Date: Time:

Static W/L (m):

Time (min)	Drawdown s (m)	Yield (l/s)	Time (min)	Recovery s' (m)
1			1	
2			2	
3			3	
4			4	
5			5	
6			6	
7			7	
8			8	
9			9	
10			10	
11			11	
12			12	
13			13	
14			14	
15			15	
16			16	
17			17	
18			18	
19			19	
20			20	
30			30	
40			40	
50			50	
60			60	
70			70	
80			80	
90			90	
100			100	
110			110	
120			120	

Discharge rate 5

Date: Time:

Static W/L (m):

Time (min)	Drawdown s (m)	Yield (l/s)	Time (min)	Recovery s' (m)
1			1	
2			2	
3			3	
4			4	
5			5	
6			6	
7			7	
8			8	
9			9	
10			10	
11			11	
12			12	
13			13	
14			14	
15			15	
16			16	
17			17	
18			18	
19			19	
20			20	
30			30	
40			40	
50			50	
60			60	
70			70	
80			80	
90			90	
100			100	
110			110	
120			120	

Discharge rate 6

Date: Time:

Static W/L (m):

Time (min)	Drawdown s (m)	Yield (l/s)	Time (min)	Recovery s' (m)
1			1	
2			2	
3			3	
4			4	
5			5	
6			6	
7			7	
8			8	
9			9	
10			10	
11			11	
12			12	
13			13	
14			14	
15			15	
16			16	
17			17	
18			18	
19			19	
20			20	
30			30	
40			40	
50			50	
60			60	
70			70	
80			80	
90			90	
100			100	
110			110	
120			120	

MULTI RATE TEST DATA SHEET

General Information	Pumping Borehole Information	Remarks
Project No:	Depth of Pump (m):	
Borehole No:	Collor Height (m):	
Site Name:	BH diameter (m):	
Farm Name:	Depth of BH (m):	

Discharge rate 1

Date: Time:

Static W/L (m):

Time (min)	Drawdown s (m)	Yield (l/s)	Time (min)	Recovery s' (m)
1			1	
2			2	
3			3	
4			4	
5			5	
6			6	
7			7	
8			8	
9			9	
10			10	
11			11	
12			12	
13			13	
14			14	
15			15	
16			16	
17			17	
18			18	
19			19	
20			20	
30			30	
40			40	
50			50	
60			60	
70			70	
80			80	
90			90	
100			100	
110			110	
120			120	

Discharge rate 2

Date: Time:

Static W/L (m):

Time (min)	Drawdown s (m)	Yield (l/s)	Time (min)	Recovery s' (m)
1			1	
2			2	
3			3	
4			4	
5			5	
6			6	
7			7	
8			8	
9			9	
10			10	
11			11	
12			12	
13			13	
14			14	
15			15	
16			16	
17			17	
18			18	
19			19	
20			20	
30			30	
40			40	
50			50	
60			60	
70			70	
80			80	
90			90	
100			100	
110			110	
120			120	

Discharge rate 3

Date: Time:

Static W/L (m):

Time (min)	Drawdown s (m)	Yield (l/s)	Time (min)	Recovery s' (m)
1			1	
2			2	
3			3	
4			4	
5			5	
6			6	
7			7	
8			8	
9			9	
10			10	
11			11	
12			12	
13			13	
14			14	
15			15	
16			16	
17			17	
18			18	
19			19	
20			20	
30			30	
40			40	
50			50	
60			60	
70			70	
80			80	
90			90	
100			100	
110			110	
120			120	

Discharge rate 4

Date: Time:

Static W/L (m):

Time (min)	Drawdown s (m)	Yield (l/s)	Time (min)	Recovery s' (m)
1			1	
2			2	
3			3	
4			4	
5			5	
6			6	
7			7	
8			8	
9			9	
10			10	
11			11	
12			12	
13			13	
14			14	
15			15	
16			16	
17			17	
18			18	
19			19	
20			20	
30			30	
40			40	
50			50	
60			60	
70			70	
80			80	
90			90	
100			100	
110			110	
120			120	

Discharge rate 5

Date: Time:

Static W/L (m):

Time (min)	Drawdown s (m)	Yield (l/s)	Time (min)	Recovery s' (m)
1			1	
2			2	
3			3	
4			4	
5			5	
6			6	
7			7	
8			8	
9			9	
10			10	
11			11	
12			12	
13			13	
14			14	
15			15	
16			16	
17			17	
18			18	
19			19	
20			20	
30			30	
40			40	
50			50	
60			60	
70			70	
80			80	
90			90	
100			100	
110			110	
120			120	

Discharge rate 6

Date: Time:

Static W/L (m):

Time (min)	Drawdown s (m)	Yield (l/s)	Time (min)	Recovery s' (m)
1			1	
2			2	
3			3	
4			4	
5			5	
6			6	
7			7	
8			8	
9			9	
10			10	
11			11	
12			12	
13			13	
14			14	
15			15	
16			16	
17			17	
18			18	
19			19	
20			20	
30			30	
40			40	
50			50	
60			60	
70			70	
80			80	
90			90	
100			100	
110			110	
120			120	

APPENDIX D

(REVISED STEP DRAWDOWN DATA FOR UP15 AND UP16)

STEPPED DISCHARGE TEST DATA SHEET

220

General Infomation

Project No:
Borehole No: UP16
Site Name: Campus Test Site
Farm Name:

Pumping Borehole Information

Depth of Pump (m):
Collor Height (m):
BH diameter (m):
Depth of BH (m):

Remarks

Discharge rate 1

Date: 20/08/2000 Time: 14:07
Static W/L (m): 13.2 m

Time (min)	Drawdown s (m)	Yield (l/s)	Time (min)	Recovery s' (m)
0	0	0.61		
2	0.17	0.61		
3	0.19	0.61		
4	0.23	0.61		
5	0.265	0.61		
6	0.295	0.61		
7	0.32	0.61		
8	0.35	0.61		
9	0.375	0.61		
11	0.425	0.61		
12	0.45	0.61		
13	0.46	0.61		
14	0.48	0.61		
15	0.5	0.61		
16	0.52	0.61		
17	0.535	0.61		
18	0.55	0.61		
19	0.565	0.61		
20	0.585	0.61		
21	0.6	0.61		

Discharge rate 2

Date: Time:
Static W/L (m):

Time (min)	Drawdown s (m)	Yield (l/s)	Time (min)	Recovery s' (m)
22	0.73	1.18		
23	0.78	1.18		
24	0.83	1.18		
25	0.87	1.18		
26	0.91	1.18		
27	0.96	1.18		
28	0.99	1.18		
29	1.01	1.18		
30	1.045	1.18		
31	1.07	1.18		
32	1.1	1.18		
33	1.135	1.18		
34	1.16	1.18		
35	1.18	1.18		
36	1.2	1.18		
37	1.23	1.18		
38	1.25	1.18		
39	1.275	1.18		
40	1.29	1.18		
41	1.315	1.18		
42	1.335	1.18		
43	1.355	1.18		
44	1.37	1.18		
45	1.39	1.18		
46	1.41	1.18		

Discharge rate 3

Date: Time:
Static W/L (m):

Time (min)	Drawdown s (m)	Yield (l/s)	Time (min)	Recovery s' (m)
47	1.66	2		
48	1.74	2		
49	1.81	2		
50	1.875	2		
51	1.94	2		
52	1.995	2		
53	2.05	2		
54	2.1	2		
55	2.15	2		
56	2.2	2		
57	2.255	2		
58	2.29	2		
59	2.325	2		
60	2.37	2		
61	2.405	2		
62	2.45	2		
63	2.49	2		
64	2.52	2		

Discharge rate 4

Date: Time:
Static W/L (m):

Time (min)	Drawdown s (m)	Yield (l/s)	Time (min)	Recovery s' (m)
65	3.15	3.5		
66	3.3	3.5		
67	3.44	3.5		
68	3.56	3.5		
69	3.67	3.5		
70	3.77	3.5		
71	3.87	3.5		
72	3.97	3.5		
73	4.085	3.5		
74	4.175	3.5		
75	4.26	3.5		
76	4.35	3.5		
77	4.43	3.5		
78	4.51	3.5		
79	4.585	3.5		
80	4.66	3.5		
81	4.73	3.5		
82	4.8	3.5		
83	4.87	3.5		
84	4.94	3.5		
85	5	3.5		
86	5.06	3.5		
87	5.12	3.5		
88	5.18	3.5		
89	5.24	3.5		
90	5.29	3.5		
95	5.54	3.5		
97	5.64	3.5		
100	5.76	3.5		
105	5.96	3.5		

Discharge rate 4

Date: Time:
Static W/L (m):

Time (min)	Drawdown s (m)	Yield (l/s)	Time (min)	Recovery s' (m)
113	6.22	3.5		
114	6.27	3.5		
115	6.29	3.5		
116	6.31	3.5		
117	6.34	3.5		
118	6.37	3.5		
119	6.4	3.5		
120	6.43	3.5		

Discharge rate 6

Date: Time:
Static W/L (m):

Time (min)	Drawdown s (m)	Yield (l/s)	Time (min)	Recovery s' (m)

STEPPED DISCHARGE TEST DATA SHEET

General Information

Project No:
Borehole No: UP15
Site Name: Campus Test Site
Farm Name:

Pumping Borehole Information

Depth of Pump (m):
Collor Height (m):
BH diameter (m):
Depth of BH (m):

Remarks

Discharge rate 1

Date: 25/08/2000 Time: 14:28
Static W/L (m): 13.32 m

Time (min)	Drawdown s (m)	Yield (l/s)	Time (min)	Recovery s' (m)
2	0.21	0.572		
5	0.32	0.572		
7	0.37	0.572		
10	0.43	0.572		
15	0.53	0.572		
17	0.57	0.572		
19	0.59	0.572		

Discharge rate 2

Date: Time:
Static W/L (m):

Time (min)	Drawdown s (m)	Yield (l/s)	Time (min)	Recovery s' (m)
20	0.735	1.05		
22	0.83	1.05		
24	0.91	1.05		
27	1.01	1.05		
29	1.08	1.05		
32	1.16	1.05		
34	1.21	1.05		
37	1.27	1.05		
40	1.33	1.05		

Discharge rate 3

Date: Time:
Static W/L (m):

Time (min)	Drawdown s (m)	Yield (l/s)	Time (min)	Recovery s' (m)
41	1.64	1.81		
44	1.93	1.81		
47	2.14	1.81		
50	2.31	1.81		
53	2.48	1.81		
55	2.59	1.81		
57	2.67	1.81		
60	2.8	1.81		

Discharge rate 4

Date: Time:
Static W/L (m):

Time (min)	Drawdown s (m)	Yield (l/s)	Time (min)	Recovery s' (m)
61	3.1	2.5		
63	3.3	2.5		
65	3.44	2.5		
67	3.58	2.5		
70	3.78	2.5		
73	3.95	2.5		
75	4.07	2.5		
80	4.32	2.5		
85	4.54	2.5		
90	4.74	2.5		
95	4.91	2.5		
100	5.06	2.5		
105	5.21	2.5		
110	5.34	2.5		
115	5.46	2.5		
120	5.59	2.5		

Discharge rate 5

Date: Time:
Static W/L (m):

Time (min)	Drawdown s (m)	Yield (l/s)	Time (min)	Recovery s' (m)

Discharge rate 6

Date: Time:
Static W/L (m):

Time (min)	Drawdown s (m)	Yield (l/s)	Time (min)	Recovery s' (m)

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SUMMARY

With the depletion of surface water resources in South Africa the utilisation of groundwater as the only potable water resource for communities in some rural areas is quickly becoming a reality. Failure of this resource will cause serious problems and it may even lead to loss of life. To prevent failure and to ensure the sustainability of this new resource, pumping tests are performed to determine the long-term sustainable yield of borehole. This is the main reason why pumping tests are performed in South Africa, but in some instances pumping tests are performed to determine parameter values for aquifers.

This research focussed on presenting guidelines on the proper planning and execution of the different types of pumping tests. To perform a proper pumping test involves big financial costs and therefor it is important to ensure that the correct information is obtained during such a test. Recommendations regarding the lengths of pumping tests as well as the abstraction rates during pumping tests are also made in this research.

Before the interpretation of pumping test data it is important to obtain a better understanding of the basic concepts and characteristics involved in groundwater hydraulics. These concepts, together with the interpretation of diagnostic and derivative data plots are discussed in detail and it will provide the reader with enough knowledge to identify and understand the different flow regimes present in an aquifer.

This research looks at the different steps involved in the interpretation of pumping test data and these steps are illustrated by means of worked examples. The different analytical methods to determine parameter values for an aquifer are also discussed in this thesis and the assumptions made in developing these methods are pointed out to the reader. In most cases these assumptions result in incorrect parameter value estimates. Numerical models, developed for the unique aquifer systems of South Africa, yielding the correct parameter values, are also discussed.

Well losses can be divided into linear and non-linear losses. Non-linear well losses are mainly caused by turbulent flow inside the aquifer and borehole. This research

however shows a non-linear relationship between drawdown and abstraction rate while the flow inside the aquifer is still linear. The non-linearity between drawdown and abstraction rate is corroborated by means of several examples and this non-linearity can only be the result of the unique composition of aquifers in this country. Different abstraction rates result in different fractures being dewatered and fracture extents that are reached, causing a smaller effective T-value. The consequence of this non-linearity is that it is very difficult to extrapolate the future water levels in an aquifer. To estimate a sustainable yield in the case of non-linearity this research recommends a revised step drawdown test. This 100-minute test, conducted without constant time intervals, will also point out the positions of the main water strikes.

A method, developed in South Africa, with which the long-term sustainable yield can be determined, is also discussed in detail and it is explained by means of a step by step worked example. Included in this method is the effect of boundary conditions as well as a risk analysis.

OPSOMMING

Met die uitputting van oppervlak waterbronne in Suid-Afrika word die gebruik van grondwater bronne as die enigste bruikbare waterbron vir sommige landelike gemeenskappe 'n realiteit. Indien hierdie bron onvoldoende is, kan dit ernstige probleme en selfs lewensverlies tot gevolg hê. Om die swigting van boorgate te vehoed en om die volhoubaarheid van hierdie bron te verseker, word pomptoetse gedoen om die langtermyn lewerings van boorgate korrek te bereken. Dit is dan ook die hoof doelwit van die meeste pomptoetse wat in Suid-Afrika gedoen word, maar in sommige gevalle word pomptoetse ook gedoen om parameters vir akwifere te bepaal.

Hierdie navorsing fokus op die onwikkeling van riglyne vir die behoorlike beplanning en uitvoering van die verskillende tipes pomptoetse. Groot kostes word aangegaan om pomtoetse uit te voer en daarom is dit belangrik dat akkurate inligting tydens so 'n pomptoets bekom word. Aanbevelings rondom die tydsduur van pomptoetse sowel as ontrekkingstempo's tydens pomptoetse, word ook gemaak.

Voordat pomptoetse ontleed word, is dit belangrik om 'n goeie kennis van die basiese begrippe en eienskappe wat by grondwater betrokke is, op te doen. Hierdie begrippe, saam met die ontleding van afgeleide grafieke word breedvoerig bespreek en dit sal die leser toerus met voldoende kennis om die verskillende vloeipatrone in akwifeer te kan identifiseer.

Die navorsing kyk na die veskillende stappe wat by die ontleding van pomptoetse betrokke is en hierdie stappe word aan die hand van voorbeelde verduidelik. Die verskillende analitiese metodes wat gebruik word om parameters te bepaal, word ook bespreek en die aannames wat by die ontwikkeling van die verskillende metodes gemaak is, word uitgelig. In die meeste gevalle het hierdie aannames tot gevolg dat foutiewe parameter waardes verkry word. Numeriese metodes, wat vir die unieke akwifeer toestande in Suid-Afrika ontwikkel is en wat korrekte parameter waardes lewer, word ook bespreek.

Boorgat verliese kan in lineêre en nie-lineêre verliese verdeel en nie-lineêre verliese is die gevolg van turbulente vloeie in die boorgat en akwifeer. Hierdie navorsing bewys

egter dat daar 'n nie-lineêre verband tussen die afttrekking in die boorgat en die ontrekkingstempo bestaan, selfs al is die vloei in die boorgat en die akwifeer lineêr. Hierdie waarneming word met behulp van verskeie voorbeelde gestaaf. Hierdie nie-lineariteit is die gevolg van die unieke samestelling van akwifere in Suid-Afrika. Verskillende ontrekkingstempo's het tot gevolg dat verskillende frakture ontwater word en in sommige gevalle word die einde van frakture bereik. Dit het tot gevolg dat die effektiewe T-waarde kleiner word. As gevolg van hierdie nie-lineariteit word die vooruitskatting van toekomstige watervlakke in akwifere bemoeilik. Om die volhoubare lewering in die geval van nie-lineariteit te bereken, word 'n hersiene staptoets in die navorsing aanbeveel. Hierdie 100-minuut toets, waarvan die tydsintervalle nie gelyk hoef te wees nie, sal ook die posisies van die hoof frakture aandui.

'n Metode wat in Suid-Afrika ontwikkel is en wat gebruik word om die langtermyn volhoubare lewering van 'n boorgat te bereken, word volledig bespreek. Die metode word aan die hand van 'n uitgewerkte voorbeeld verduidelik. Ingesluit in die metode is die uitwerking van grenstoestande sowel as 'n risiko analise.

KEY TERMS

1. Pumping test analysis
2. Double porosity systems
3. Parameter estimation
4. Long term sustainable yield calculation
5. Abstraction rate
6. Available drawdown
7. Length of pumping tests
8. Non-linearity between drawdown and abstraction rate
9. Two-dimensional numerical model
10. Revised step drawdown test