AN APPROACH TO AQUIFER TEST PUMPING IN FRACTURED CRYSTALLINE AQUIFERS WITH A CASE STUDY IN NAMAQUALAND

By

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ABSTRACT

Water resources in South Africa are being stressed. Due to this concern more emphasis should be placed on determining where we can improve our existing methods for the calculation of sustainable yield. Current approaches to calculate aquifer parameters employ general techniques that may not be appropriate to fractured crystalline aquifers. The underlying principles for the methods are based on homogeneous and isotropic aquifer systems of infinite aerial extent.

With the use of pump-testing methods aquifer parameters such as transmissivity (T) and storativity (S) are determined. These parameters are important for calculating the sustainable yield of the aquifer system. A general conceptual model is adopted for the Namaqualand area. The model is based on fractures with high transmissivity and low storativity as well as a matrix component, comprising of micro-fractures/fissures, with lower transmissivity but higher storativity. The hydraulic contrast between fracture and micro-fractured matrix for these fractured, crystalline aquifers influences the hydraulic connectivity and hydraulic gradients observed during pump-testing operations. The model is based on a double porosity system developed for the fractured sandstone aquifers of the Karoo formations. In the case study it illustrates that the model can be applied to the fractured crystalline aquifer.

The drilling of monitoring boreholes is an expensive procedure and therefore it is not always seen as compulsory. This can be one of the reasons why boreholes in semi-arid regions run dry over a short period of time. When no monitoring boreholes exist, parameters such as transmissivity (T) and storativity (S) can only be estimated using a pumping borehole. This can have a negative result on the sustainable yield calculations of the aquifer system. Another important question then is; once a monitoring borehole is drilled, is it hydraulically connected to the pumping borehole? The heterogeneity determines to a great extent the degree of hydraulic connectivity. When there is a monitoring borehole present that is not hydraulically connected one has to revert to using only the pumping borehole. A lot of error can occur in applying these methods to

pumping boreholes because of the distance dependency of the storativity parameter if the usual interpretations are used. In the case study a method is outlined that addresses this specific difficulty. Once the appropriate methods are chosen and a good conceptual understanding of the specific aquifer system has been developed, aquifer parameters can be calculated. For this specific study, the EXCEL based software program, AQUATEST, was used to do the required transmissivity, storativity and total well loss calculations.

In this case study the issues discussed above are addressed. The hydraulic connectivity is illustrated using different scenarios and a method for solving the inaccuracy in determining the storativity (S) component is suggested, which involves the correct determination of the effective radius of a pumping borehole. The total well loss is calculated using AQUATEST, which allows the correct calculation of drawdown within the aquifer at a specific time. Boundary conditions are also applied in AQUATEST, making use of the improved Cooper Jacob method, before the final calculation of transmissivity (T) and storativity (S) parameters.

DECLARATION

I declare that An Approach to Aquifer Test Pumping in Fractured Crystalline Aquifers with a case study in Namaqualand is my own work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

Lindie Ray Hassan May 2002

Signed............................

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1. GENERAL INTRODUCTION

1.1. GROUNDWATER RESOURCES IN SOLVING WATER SUPPLY PROBLEMS

The water supply in South Africa is being stressed and therefore more studies are being conducted on groundwater resources. This source of water is very accessible because it can be extracted directly from the aquifer at various locations. Almost 80 percent of the world's rural population receives a safe water supply only because it comes from a groundwater aquifer, which is usually safe from subsurface pollution. Groundwater is affordable and close to the community who can manage it.

This resource is not only safe water but it's also a very important factor in local development and poverty mitigation. Nearly half of the world's population depends on groundwater sources for drinking water supply and other uses. Generally groundwater is safe to drink if protected against pollution (Braune, 2000).

Historically, groundwater had only contributed 15% of the total bulk water supply. Because of the geology in South Africa, groundwater occurrence in 90% of the country is in hard rock with only secondary openings. Groundwater is contained mainly in fractures and to some extent also in the pores of weathered rock (Braune, 2000).

In the rural areas there is a highly distributed nature of water demand. Regional schemes are in most cases not economically viable. The availability of surface water is decreasing during the droughts or dry periods in urban as well as rural areas.

1.2. RURAL AREAS: PREVIOUS AND CURRENT SITUATIONS

The reason that groundwater received little attention in the past has a lot to do with government priorities and not as such the occurrence of this resource. In the past emphasis was on bulk water supply to the urban, industrial and agricultural sectors. The rural areas were neglected and therefore a lot of problems exist in these areas.

After 1994 the focus was placed on addressing the people's most basic needs, including water supply and sanitation needs. Because these issues have not been addressed in the rural areas before a lot of work has to be done. Some of the troubles that exists in rural areas:

- No tap water, people collects water directly form windmill or fountains.
- Unhygienic conditions.
- Over-abstraction of resource where there are not enough boreholes to provide the communities with enough water due to poor planning.
- Pipes had to be laid over large distances to transport water, which is an expensive procedure.

1.3. PROBLEMS THAT AFFECT THE AQUIFER SYSTEM

- The degradation of groundwater systems due to pollution of aquifers.
- The economic implications of not resolving groundwater demand and supply management.
- The lack of both professional and public awareness about the sustainable use and economic importance of groundwater resources. In relation to this is the fact that groundwater is being abstracted at unsustainable rates in many areas which leads to the depletion of the resource. This occurs when uncontrolled drilling of wells causes the overall rates of abstraction to exceed the replenishment of the aquifer. This over-abstraction causes many serious problems. Often the yield of the wells is reduced and the cost of pumping increased. In extreme cases this may lead to:
- The wells being abandoned.

- Compaction of underground strata and serious subsidence of the land surface.
- It can also lead to saline water intrusion causing irreversible deterioration of groundwater resources.
- With specific reference to the case study, which is presented later in this thesis, the transmissivity and storativity values calculated for this area are too high for the fractured crystalline aquifer system. As outlined in table 5, later in the thesis, transmissivity values as high as 4720 and 12040 have been calculated.
- This can be one of the important factors that causes the drying up of boreholes in the study area.
- The sustainable rates of abstraction are a very important factor, which can address most of the above mentioned problems. Therefore, this thesis concentrates more on calculating aquifer parameters that enabling one to get a better sustainable yield calculation.

1.4. OBJECTIVES

More emphasis should be placed on determining where we can improve our existing methods for the calculation of aquifer parameters to determine sustainable yield. A good estimation of the aquifer parameters is the basis for understanding the groundwater flow and transport processes and, by doing so, determining how to manage the resource sustainably. However most pumping test data are evaluated using analytical solutions such as Theis or Cooper-Jacob with assumptions, which cannot be applied directly to fractured rock environments. As the estimated parameters are the basis for further investigation, including sustainable management of groundwater resource, a better methodology is required.

The study aims to provide an understanding of the factors or conditions that influence the determination of aquifer parameters through test pumping in fractured crystalline aquifers and to provide information to improve existing models on fractured rocks.

The main aims of this thesis are to evaluate the current techniques used to determine aquifer properties of fractured crystalline aquifers. It is very important to develop a conceptual understanding of the specific aquifer system before attempting to interpret any information. Therefore, conceptual models based on hydraulic connectivity and hydraulic gradients encountered during pump testing are essential. The calculation of aquifer parameters should also be done based on the conceptual understanding of the aquifer system by utilizing relevant pump-testing techniques.

The thesis will also look at specific issues such as using the appropriate software to analyse data for fractured crystalline aquifers by evaluating the current methods; the importance of correct placing of observation boreholes; as well as the calculation of aquifer parameters such as transmissivity, storativity and total well loss.

1.5. RESEARCH REQUIREMENTS AND THESIS LAYOUT

1.5.1. Research Requirements

In relation to the first objective, which is to evaluate current techniques in determining aquifer parameters, the following was included:

- A summary was made of the different methods using Kruseman & De Ridder, 1991 and the M.Sc. thesis of Murray, 1996.
- Methods such as: Theim, Theis, Cooper-Jacob, Bourdet-Gringarten, Kazemi's straight line method, Gringarten-Witherspoon, Huntush-Jacob, Huntush Inflection point (Kruseman & De Ridder, 1991).
- Different parameters needed for aquifer yield and borehole yield assessment were also investigated (Murray,1996).
- Programs such as the FC-method and AQUATEST are being evaluated and used to calculate certain parameters.
- Methods were and are still used in Namaqualand for determining sustainable yields.

In relation to the second objective ,which is to develop conceptual models based on hydraulic conductivity contrast and hydraulic conductivity gradients, during pump testing for the aquifer systems, the following information has to be collected:

- Pump testing data sets of pumping as well as observation boreholes.
- Borehole logs of both.
- Information regarding the flow behavior in fractured rocks: linear, radial, spherical.

In relation to the third objective, which is to determine aquifer parameters based on conceptual understanding of the aquifer system by utilizing relevant pump testing techniques, the following has to be collected:

- Information regading fractured aquifers and crystalline rocks.
- Familiarizing with the software available and developing new software.

And, in relation to the fouth objective, to propose an approach for the sustainable yield determination, all the above information has to be incorporated in pump testing analysis.

1.5.2. Thesis Layout

Chapter 1gives a general overview of groundwater in terms of water supply discussing previous and the current situations. Chapter 2 outlines the typical scenarious of the hydrological settings in South Africa after which it focusses on the description of the crytalline type of aquifer system. Chapter 3 summarizes all the physical properties relating to groundwater that has to be taken into account and also outlines the appropriate methods for the interpretation of pump test data for fractured crystalline aquifers. The test pump procedure is also discussed. The case study is presented in Chapter 4 where the conceptual models are discussed as well as the application of the software AQUATEST to the collected data for the determination of well losses and boundary conditions. The results using AQUATEST is compared to that calculated by the FC program. Chapter 5 provide the recommendations and conclusions on the holistic approach when doing pumptesting.

2. TYPICAL SCENARIOS OF HYDROGEOLOGIC SETTINGS IN SOUTH AFRICA

2.1. GENERAL TYPES OF AQUIFER SYSTEMS

Generally, aquifers have been classified as either confined or unconfined depending on the presence or absence of a water table. Between the above-mentioned two classes there are several intermediate aquifers known as leaky aquifers. Confined aquifers, also known as artesian or pressure aquifers, occur when groundwater is confined between impermeable layers. Unconfined aquifers occur where the water table varies in undulating form, and the slope depends on areas of recharge, discharge and hydraulic properties of the medium. Leaky aquifers are those sections of the geological formations where a permeable stratum is overlain or underlain by a semi-pervious aquitard, or layer (Todd, 1980).

2.2. TYPES OF AQUIFER SYSTEMS BASED ON GEOLOGICAL ENVIRONMENTS.

In South Africa there are five types of aquifer systems based on the geological environment:

Area (sq km's)	Crystalline Basement & Metamorphic Units	Basalt & Dykes	IntraCamrian to Mesozoic sediments		Cenozoic/ Quaternary	Karst
			Eolian/Marine	Alluvial		
1.221.090	Fractured	Fractured	Porous/fractured	Porous	Porous	Karstic
	40%	50%		8%		2%

Table 1: An illustration of the different types of aquifer systems in South Africa

As seen in the above table, 40% of the aquifers is found in Crystalline Basement and Metamorphic Units, which is mostly of a fractured aquifer type. Basalt and Dykes that is also fractured with IntraCambrian to Mesozoic sedimentary systems, consisting of eolian and marine deposits, usually porous and fractured, contributes 50% to the different aquifer systems. IntraCambrian to Mesozoic sedimentary alluvial systems which is mostly porous contributes 8% and Karstic material in Karst environments contributes 2% to the different aquifer systems (Aston, 2000). For this study the crystalline rocks are of most importance.

2.2.1. Fractured Aquifers

In fractured aquifers water storage and transmission occur in secondary porosity in structural aquifers. Secondary porosity is that porosity attributable to fractures, cracks and joints in the rock. Highly variable yields are found in these aquifers. Initially yields may be high, but then show a decrease with continued pumping due to limited storage in some of the fractures.

2.2.2. Karstic Aquifers

The groundwater in Karstic aquifers are found mostly in the underground cavities that are formed at depth in calcium rich rocks as a result of the dissolution of materials such as solid dolomite by carbonic acid present in the groundwater. Yields from successfully placed boreholes are usually high (Aston, 2000).

2.2.3. Alluvial and Eolian Aquifers

Alluvial aquifers consist of unconsolidated material ranging from clayey silts to coarse gravels and boulders that occur along watercourses, in dried up valleys and in existing or old floodplains. Borehole yields are generally high (Ashton, 2000). The term eolian describes wind erosion or deposition. There are two types of wind deposits, loess, which is an unstratified deposit, composed of uniform grains of silt, and dunes or drifts composed of sand. The porosity of loess is very high, 40% to 50% but they are not good transmitters of water because of the poor connectivity of the pore space (Domenico & Schwartz, 1990).

2.2.4. Igneous and Metamorphic rocks

In solid forms igneous and metamorphic rocks are virtually impermeable and therefore serve as poor aquifers. When such rocks occur near the earth surface under weathered conditions they can be developed to sustain small wells for domestic supply (Todd, 1980).

2.3. CRYSTALLINE AQUIFER

In this thesis the focus will be on crystalline aquifers, which is a type of igneous rock and of primary importance to this study.

2.3.1. Porosity

The porosity of a rock is its property of containing pores or voids (Kruseman & de Ridder, 1991). The porosity for dense crystalline rocks can range form near zero to zero. An important distinction is the difference between total porosity, which does not require pore connections, and effective porosity, which is defined as the percentage of interconnected pore space. Many rocks, crystallines in particular have a high total porosity most of which may be unconnected (Domenico & Schwartz, 1990).

Crystalline Rocks	Porosity (%)
Fractured Crystalline rocks	0 – 10
Dense Crystalline rocks	0 – 5
Basalt Crystalline rocks	3 – 35
Weathered Granite	34 – 57
Weathered Gabbro	42 – 45

Table 2: Different porosities for crystalline rocks

2.3.2. Hydraulic conductivity

It is defined as the volume of water that will move through a porous medium in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow (Kruseman & de Ridder, 1991). The range in hydraulic conductivity within a given rock type is greatest for the crystalline rocks as can be seen in the table below (Domenico & Schwartz, 1990).

Crystalline rocks	**Hydraulic conductivity**
Permeable Basalt	4.0 E-7 - 2.0 E-2
Fractured Igneous and Metamorphic rock	8.0 E-9 - 3.0 E-4
Weathered Granite	3.3 E-6 - 5.2 E-5
Weathered Gabbro	5.5 E-7 - 3.8 E-6
Basalt	2.0 E-11 - 4.2 E-7
Unfractured Igneous and Metamorphic rocks	3.0 E-14 - 2.0 E-10

Table 3: Different hydraulic conductivities for various rocks types

3. AQUIFER TEST PUMPING

Test pumping is a crucial tool in determining aquifer parameters, to determine the amount of water that can be abstracted from an aquifer system. There are several methods that have been developed for the calculation of aquifer parameters and for the development of different software packages that are presented later.

3.1. PHYSICAL PROPERTIES

3.1.1 Aquifer Properties

Using pump testing data several hydraulic parameters can be estimated, as is describe by the section below.

3.1.1.1 Hydraulic conductivity (K)

Is defined as the volume of water that will move through a porous medium in unit time under a unit area measured at right angles to the direction of flow (m/d). The hydraulic conductivity of hard rocks depends largely on the density of the fractures and the width of their apertures. Fractures can increase the hydraulic conductivity of solid rocks by several orders of magnitude (Kruseman and de Ridder, 1991).

3.1.1.2 Transmissivity (T)

Is the product of the average hydraulic conductivity (K) and the saturated aquifer thickness (D). Thus, refers to the rate of flow under a unit hydraulic gradient through a cross-section of unit width over the whole saturated thickness of the aquifer. The effective transmissivity, as used for a fractured media is defined as:

$$T = \sqrt{T_{f(x)} * T_{f(y)}} \qquad (3.1)$$

, where f refers to the fractures and x and y to the principal axes of permeability (m^2/d).

Lanchassage et al. (1989) showed that for short duration pumping tests, the local transmissivity values are highly variable in heterogeneous media, while for long duration test an effective mean can be calculated.

3.1.1.3 Storativity (S)

Of a saturated confined aquifer of thickness D is the volume of water released from storage per unit surface area of the aquifer per decline in the component of hydraulic head normal to that surface. In a vertical column of unit area extending through the confined aquifer, the storativity S equal the volume of water released from the aquifer when the peziometric surface drops over a unit distance. Storativity is defined as:

$$S = \rho g D(\alpha + n\beta) \qquad (3.2)$$

where, ρ = mass density of water
g = acceleration due to gravity
α = strain factor
β = compressibility
n = porosity of the water-transmitting medium

It is necessary to use multiple piezometers to obtain sensible S-values in a fissured aquifer (Kirchner and van Tonder, 1995).

3.1.1.4 Compressibility

The compressibility is an important material and fluid property in the analysis of unsteady flow to wells. It describes the change in volume or the strain induced in an aquifer /aquitard under a given stress:

$$\alpha = {(-dVT/VT)}\Big/{d\sigma_e} \qquad (3.3)$$

VT – is the total volume of a given mass of material,
$d\sigma_e$ – is the change in effective stress.

Fractured rock has a compressibility that ranges from 10^{-8} to 10^{-10} m^2/N. Similarly the compressibility of water is defined as:

$$\beta = (-dVw/Vw)\Big/_{dp} \qquad (3.4)$$

A change in the water pressure dp induces a change in the volume Vw of the given mass of water. The compressibility of groundwater can be taken constant as 4.4 x 10^{-10} m^2/N.

3.1.2. Flow behaviour in fractured medium

In identifying the flow behaviour one develops a better conceptual understanding of the type of aquifer system and can therefore choose the appropraite method for analysis.

3.1.2.1 Linear Flow

When there is a pressure drop along the fractures and it is linear proportional to the abstraction rate is called linear flow. It illustrates typical geological features such as sub-vertical fractures, faults, or dykes. These features show different flow phases such as:

- Linear fracture flow when feature has a finite conductivity and its embedded in a matrix or low conductive formation, Figure 1 (a).
- Bilinear flow occurs when the matrix is permeable enough and the linear flow is superposed by a perpendicular linear flow from the formation to the fracture, Figure 1 (b).
- Linear flow from the formation to the fracture when fracture cannot store a lot of water.
- Bilinear flow in reservoirs that consist of a continuous fracture network embedded in a porous matrix, double porosity (Van Tonder and Bardenhagen, 2000).

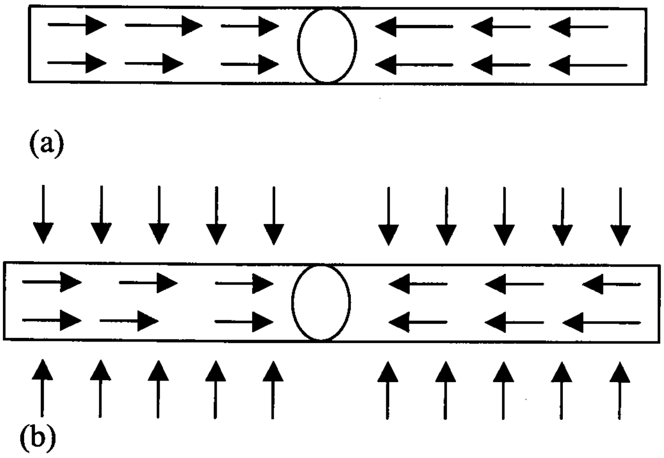


Figure 1: (a) Linear flow; (b) Bilinear flow

3.1.2.2 Radial Flow

Radial flow occurs when the cone of depression is almost circular, is observed in a fully penetrating well in a homogeneous aquifer or any well that can be considered continuum.. The start of the radial flow phase indicates the time at which the aquifer behaves homogeneous. The distance from the pumped well at which the radial flow starts determines the dimension of the REV (Representative elementary volume). The characteristic distance/dimension of the REV for a single fracture embedded in infinite matrix = 5 * fracture halflength (Barker, 1988).

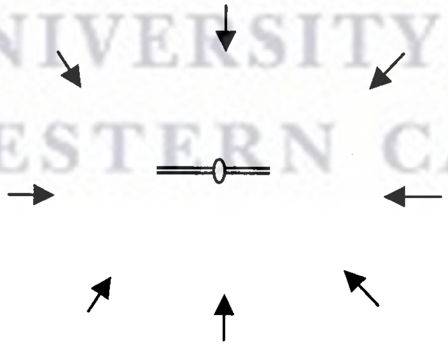


Figure 2: Radial acting flow

3.1.2.3 Spherical Flow

Where the abstraction source is a point in an isotropic medium, the cone of depression becomes a sphere. Spherical flow is observed/occurs within small dimensions and over a short time period. Due to anisotropy the sphere will become an ellipsoid. This type of flow can be considered as a partial penetrating well in a formation with isotropic conductivity (Van Tonder and Bardenhagen, 2000).

3.1.3. Skin Effects

Most boreholes are affected by skin and has to be taken into account when calculating parameters such as transmissivity, storativity and total well losses.

3.1.3.1 Well bore skin

Well bore skin is a thin layer with a very small storage capacity located between borehole wall and aquifer that restricts the inflow to a pumped well. In the presence of well bore skin, an additional drawdown is observed within the well, this effect is known as well losses or skin effect. The sum of both well loss components can be represented by a constant total well skin factor, which is added to a given well function F, to calculate the total drawdown within the pumped well:

$$F(u,\xi) = F(u) + \xi \tag{3.5}$$

Where, u is the argument that describes the relation between aquifer parameters T and S as well as the geometry of the abstraction source over extraction period. In a homogeneous aquifer an ideal well has no well bore skin. This could mean that the effective radius is equal to the drilled, which could be related as follows:

$$R_{eff} = r_w.e^{-\xi} \tag{3.6}$$

Where restricted flow occurs well bore skin exists and the effective radius becomes smaller than the drilled radius. If the permeability around the well is improved a negative well bore skin will be observed and an enlarged effective radius. A positive skin larger than 0.5 cannot be produced. Also, an increased effective radius will be observed in a well situated in a single fracture that acts as a conduit. During radial acting flow phase the skin effect plot as a horizontal line in a lin-log plot which can be used to identify the radial acting flow phase (Ramey, 1982).

3.1.3.2 Partial penetration skin

The theoretical models that are usually being used, assume that the pumped well fully penetrates the aquifer so that the flow towards the well is horizontal. If you have a partially penetrating well this condition is not satisfied in the vicinity of the well. Vertical flow components then exists which gives rise to extra head losses in and near the well (Kruseman & De Ridder, 1991).

This effect can lead to an underestimation of the reservoir's T value, which that might be risky in the design of a dewatering scheme for mining and engineering purposes (Van Tonder and Bardenhagen, 2000).

3.1.3.3 Fracture skin

The fracture skin refers to a thin layer between the fracture and the matrix with a reduced conductivity and very small storage capacity. Such a skin can be created by the effects of mineral precipitation or by clay minerals as a result of weathering. If fracture skin occurs in a single fracture it can cause an additional drawdown similar to that of a well bore skin, whereas in a continuous fractured medium with double porosity it results in a pseudo-steady flow exchange between the fracture and the matrix blocks:

$$\xi_f = \left(\frac{\pi . b_s}{2x_f}\right)\left(\frac{k}{k_s - 1}\right) \tag{3.7}$$

, where b_s is the thickness of the skin; x_f is the fracture halflength; k is the conductivity of the matrix and k_s is the conductivity of the skin (Ramey, 1982).

3.1.3.4 Pseudo skin

When a well is located in the vicinity of a fracture that acts as a conduit it will show less drawdown than would be expected for wells in a homogeneous formation within the

REV, this effect is known as pseudo skin. This effect can be used to determine whether a well is located in a fracture zone, as in principal no negative skin factor or enlarged effective radius is observed in a continuous fractured medium. An exception to this rule is when there is a zone of higher permeability that results in caving processes due to drilling works (Ramey, 1982).

3.1.3.5 Effective Radius

The effective radius refers to the radial distance away from the pumping borehole that is affected by pumping and can be calculated on the basis of:

- The distance between the pumping and the observation boreholes.
- Radius of the pumping borehole, if it is the correct effective radius (Meier et. al., 1998)

This parameter is very important for the estimation of the storativity parameter as will be discussed later in this thesis.

3.1.3.6 Total Well Loss

One very useful indicator of well performance is the total well loss. This is identified as the difference between the observed pumped well drawdown and the theoretical drawdown at the well face, assuming laminar flow in the aquifer. This is one of the most meaningful parameters describing well performance. The performance should be compared between several wells of similar design. It can also be used to compare the performance of a well at different times. The third important role of the total well loss is the prediction of drawdown. The total well loss can be superimposed on the theoretical prediction of the aquifer drawdown for any hydraulic conditions, to determine the well drawdown (Kawecki, 1995).

In theory it is assumed that the aquifer is reasonably homogenoeus with boundaries outside the radius of influence developed during the step test. If there is no well loss, the drawdown in the pumped well is given by:

$$s(r_w,t)=\frac{1}{4\pi T}\sum_{i=1}^{i=n}(Q_i-Q_{I-1})W(u_i) \qquad (3.8)$$

where, the discharge is Q_1 from time t_1, Q_2 from time $t_2 \ldots Q_n$ from the time t_n; $Q_0=0$; t is the time $(t_n<t\leq t_{n+1})$; r_w is the true radius of the pumped well; T is the aquifer transmissivity; $W(u_i)$ is the Theis well function (Theis, 1935), and

$$u_i=\frac{r_w{}^2 S}{4T(t-t_i)} \qquad (3.9)$$

where, S is the storage coefficient. When u_i is small (<0.01), the well function can be approximated by:

$$W(u_i)=\ln\frac{2.25T(t-t_i)}{r_w{}^2 S} \qquad (3.10)$$

Substituting (3.10) in (3.8) gives:

$$s(r_w,t)=\frac{1}{4\pi T}\sum_{i=1}^{i=n}(Q_i-Q_{i-1})\ln\frac{2.25T(t-t_i)}{r_w S} \qquad (3.11)$$

A condition for this equation is that $u_n<0.01$, this condition is satisfied less than a second after the start of step n in a typical confined aquifer making equation 3.11 valid at all practical times. The total well loss is given by:

$$L_w=s_w(t)-s(r_w,t) \qquad (3.12)$$

where, L_w, is the total well loss, and $s_w(t)$ is the observed drawdown in the pumped well at time t.

The total well loss cannot be calculated exactly by the previous equations because not all the terms are generally known. The well radius, r_w, is likely to be unknown. If the well is not screened, the well radius is equal to the open hole radius. Another possible unknown is the aquifer storage coefficient which can only be determined if an observation well is available. The transmissivity is known because it can be calculated from the pumped well data. Although L_w cannot be calculated exactly, it is possible to calculate a range for the total well loss corresponding to the reasonable range for r_w and S. If r_w increases from r_{w1} to r_{w2} and S increases from S_1 to S_2, then the drawdown changes by Δs given by:

$$\Delta L_w = \Delta B_2 Qn + CQn^2 \tag{3.13}$$

Since B_2 is the parameter associated with Qn, and L_w depends only on Qn and not Qn^2 it follows that $\Delta C = 0$ and:

$$\Delta B_2 = \frac{1}{4\pi T} \ln \frac{r_{w2}{}^2 S_2}{r_{w1}{}^2 S_1} \tag{3.14}$$

i.e. the parameter C is not affected by the uncertainty in r_w and S.

The range of L_w is $\pm \Delta L_w / 2$, similarly the range for the parameter B_2 is $\pm \Delta B_2 / 2$. These formulae are applied to the data, using AQUATEST, later in the case study. AQUATEST is an excel based spreadsheet that has been developed for determining aquifer parameters such as transmissivity and storativity.

3.1.4. Aquifer Conditions

As can be seen from above there are various conditions and elements that affect the calculations of T and S values. Aquifer conditions are important with regard to pump testing and has to be taken into account.

3.1.4.1 Fracture Dewatering

Fracture dewatering should be avoided at all times because of the danger of mineral precipitation that can lead to fracture and well clogging. This effects is directly related to the water chemistry. The dewatering of a continuous fracture network (homogeneous aquifer) can lead to a gradual change, in time, in the physical conditions due to the reduction of the down-hole influx area. The dewatering in a discontinuous fracture network will cause a sudden drop in the water level in the borehole when the fracture is reached. Physical conditions in the vertical direction change instantaneously due to:

- The aquifer above the dewatered fracture becoming a purged aquifer that releases water into the fracture and borehole.
- Unconfined conditions in dewatered fracture.
- Turbulent flow in dewatered fracture and along.
- Reduced influx area.

The drawdown scenario can be described as follows:

- When the water level reaches the water strike the flow in the dewatered fracture will change from confined to unconfined.
- If the storage capacity of the fracture is small compared to the discharge rate the drawdown will continuously drop below the main water strike, until a new pressure difference develop between the fracture and the matrix is sustained.
- Radial flow is observed both before and after the dewatering of the fracture, the drawdown curve after the dewatering (example the fracture in a lin-log plot) will show an increased slope compared to the initial one.
- The determination of aquifer parameters using such disturbed curves is sometimes possible if conventional methods are applied to parts of the curves.

3.1.4.2 Boundary Conditions

Pumping tests sometimes have to be performed close to a bounded aquifer, in which case the general assumption that the aquifer is of infinite areal extent is no longer valid. To analyse the flow in bounded aquifers, we apply the principal of superposition i.e. the drawdown caused by two or more wells is the sum of the drawdown caused by each separate well. Thus by introducing imaginary wells we can transform bounded aquifer of finite extent, into one of seemingly infinite areal extent, which allows the use of methods available (Kruseman & De Ridder, 1991).

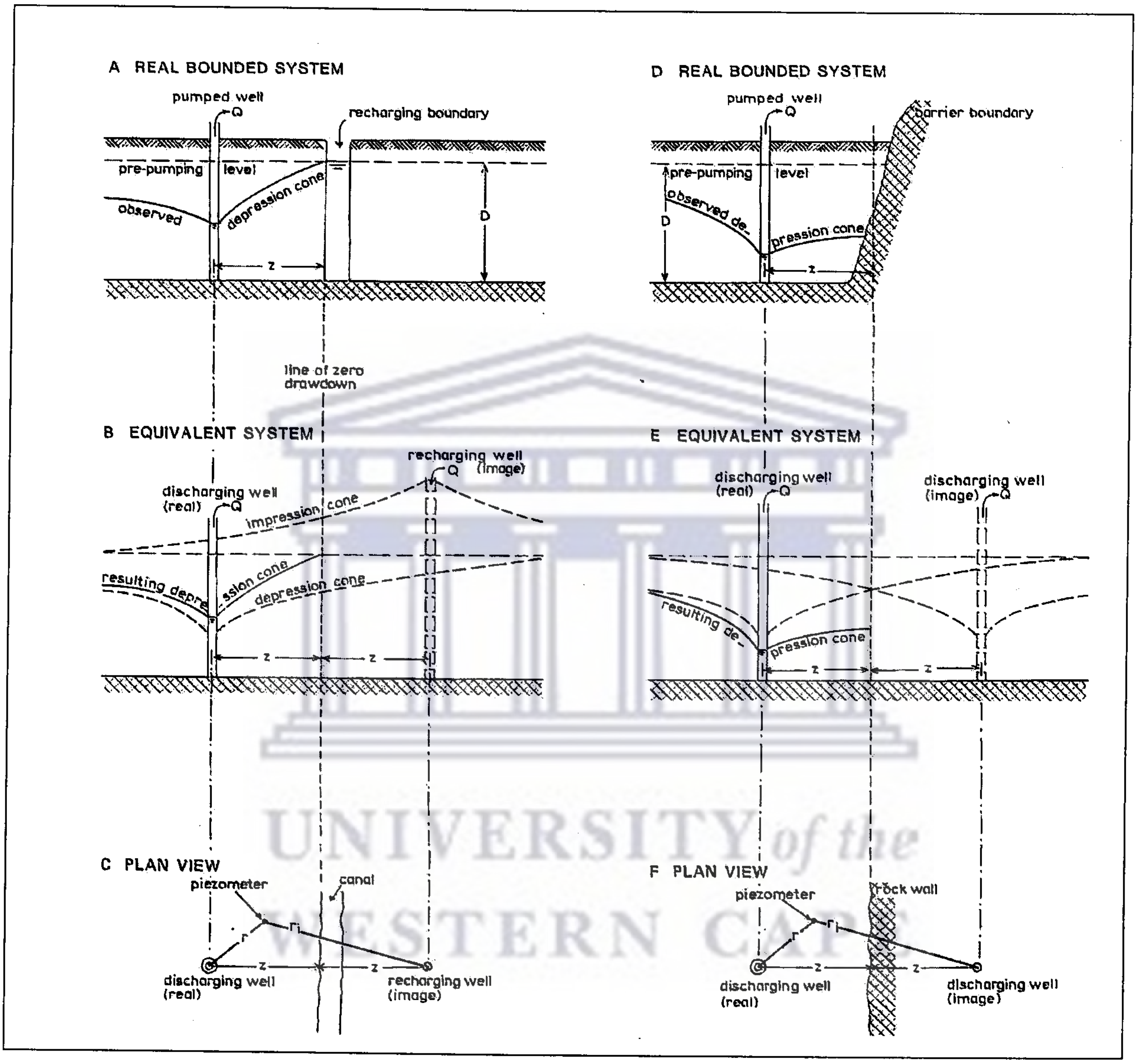


Figure 3: Typical examples of drawdowns in the water table of an aquifer bounded by:

(a) A recharging boundary,

(d) A barrier boundary,

(b) and (e) Equivalent systems of infinite aerial extent,

(c) and (f) Plan views.

(d)

3.1.4.3 Well bore storage

All the theoretical models assume a line source or sink, which means that well bore storage effects, can be neglected. All wells have a certain volume of water stored in it, the equivalent of which must be removed before the aquifer response is obtained. Large diameter wells will store more water and the less the condition for the line source or sink will be satisfied. The effects of well bore storage will appear at early pumping times. In a log-log plot of s versus t, the effect of well bore storage is reflected by a straight line segment of slope unity. The observation data could also be affected by well bore storage and should be kept in mind when interpreting the data (Kruseman & De Ridder, 1991).

Well bore storage occurs due to changes in the water level and compressibility of the water well system. The dimensionless well bore storage coefficient (Wd) is defined as:

$$W_d = \frac{r_e}{2(rw2S)} \qquad (3.15)$$

where, r_e = casing radius where water level change occur

rw = drilled radius

S = specific storage coefficient

This equation is valid if the compressibility of the water-well system is negligible. Immediately after the start of the extraction, all water is pumped from the storage volume of the well, as the gradient within the reservoir is still small, and hence the enormous well bore storage coefficient at the beginning of the test. With time the gradient within the reservoir increases gradually until all extracted water is provided by the reservoir and consequently the well bore storage effects disappear (Van Tonder and Bardenhagen, 2000).

The transmissivity and casing radius influence the effects of well bore storage. In a borehole with a lower T the effects of well bore storage will last longer. In a well with a larger diameter (casing radius) the effects of well bore storage will also last longer (Van Tonder and Bardenhagen, 2000).

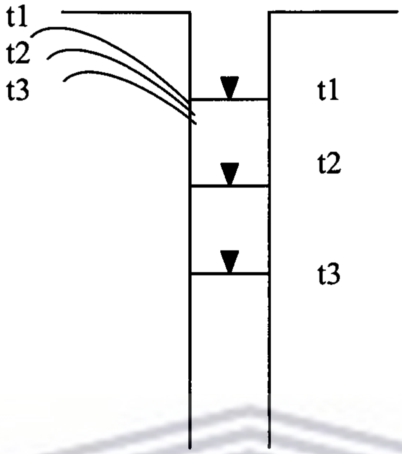


Figure 4: The effects of well bore storage at different time intervals.

3.2. THEORIES OF TEST PUMPING

3.2.1. Analytical Methods

The methods that are currently in use are that of Theis and Cooper-Jacob. These methods are not suitable for the use in fractured rock aquifers because the drawdown due to pumping is affected by several hydrogeological parameters. There are however methods based on the Theis and Cooper-Jacob, which can be used if a constant discharge is carried out in accordance with standard test pump procedures. For the majority of geohydrological problems, the transmissivity, storativity and recharge are the most important parameters to be determined for the prediction of the long-term behaviour of an aquifer (Kirchner and van Tonder, 1995).

Kruseman and de Ridder (1991) states that when a fully penetrating well pumps a confined aquifer the influence of the pumping well extends radially outwards from the well with time and pumped water is withdrawn entirely from storage within the aquifer.

It is important then to understand when an aquifer is in a steady state as well as compared to an unsteady state. In theory, because the pumped water must come from a reduction in storage within the aquifer only unsteady state flow can exist. In practice, the flow to the well is considered to be in a steady state if the change in drawdown has become negligibly small with time.

Methods for evaluating pumping tests in confined aquifers are available for both steady-state flow and unsteady-state flow. The assumptions and conditions underlying the methods used in confined aquifers are:

1) The aquifer is confined.
2) The aquifer has a seemingly infinite areal extent.
3) The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by the test.
4) Prior to pumping, the pieziometric surface is horizontal (or nearly so) over the area that will be influenced by the test.
5) The aquifer is pumped at a constant discharge rate.
6) The well penetrates the entire thickness of the aquifer and thus receives water by horizontal flow.

And in addition, for unsteady-state methods:

7) The water removed from storage is discharged instantaneously with decline of head.
8) The diameter of the well is small, i.e. the storage in the well can be neglected.

3.2.1.1 Thiem's method

Thiem's method was developed for steady-state flow and can be used to determine aquifer parameters such as transmissivity or permeability. The equation is as follows:

$$T = \left[\frac{2.3Q}{2\pi(s_1 - s_2)}\right] * r^2 / r^1 \tag{3.16}$$

, which has been derived from

$$Q = \frac{2\pi KD\left(s^1 - s^2\right)}{2.3\log\left(r^1 / r^2\right)} \qquad (3.17)$$

where, Q = well discharge (m^2/d)

s = steady state drawdown

r = distances of piezometers from borehole

3.2.1.2 Theis method

Theis and Jacob's methods were developed for unsteady-state and can be used to determine transmissivity as well as the storativity of the aquifer. To calculate the transmissivity parameter the following equation can be used:

$$T = Q / 4\pi s * W(u) \qquad (3.18)$$

where, s = drawdown

$W(u)$ = well function; other parameters are as defined earlier

The above equation has been derived from :

$$s = Q / 4\pi KD * W(u) \qquad (3.19)$$

The storativity component can be estimated by using the following equation:

$$S = 4Ttu / r^2, u = r^2 S / 4Tt \qquad (3.20)$$

where, r = distance parameter

t = time

which has been derived from:

$$S = \frac{4KD\left(t / r^2\right)}{1/u} \qquad (3.21)$$

3.2.1.3 Jacob's method

This method is based on the Theis formulae, it does not take in consideration the effect of boundary conditions. Parameters are as defined earlier.

(3.22)

, which has been derived from:

$$s = \frac{Q}{4\pi KD} * W(u) \qquad (3.23)$$

, where $KD = \frac{2.3Q}{4\pi\Delta s}$ (3.24)

The storativity is calculated using:

$$S = \frac{2.25Tt_0}{r^2} \qquad (3.25)$$

These assumptions and conditions cannot always be applied directly to all the different aquifer systems and therefore each aquifer system should be evaluated individually to get a more reliable transmissivity and storativity esimate. This will ensure a better estimate of the sustainable yield of the aquifer system.

For fractured, crystalline aquifers the following assumptions and conditions apply:

1) The aquifer is confined to semi-confined.
2) The aquifer is of infinite areal extent; fractures are not always connected (compromise!).
3) The aquifer is heterogeneous, anisotropic, and not of a uniform thickness over the area influenced by the test.
4) Prior to pumping, the pieziometric surface is not horizontal over the area that will be influenced by the test.
5) The aquifer is pumped at a constant discharge rate.
6) The well penetrates approximately 60 to 100 meters of the saturated aquifer and in so doing seldom penetrates the entire thickness of the aquifer, which can lead

to horizontal as well as vertical flow. Therefore losses should be taken into account here due to energy loss.

And, in addition, for unsteady state methods:

7) The water removed from storage is not always discharged instantaneously with decline of head.

8) The diameter of the well is small, i.e. the storage of the well can be neglected.

And in addition for uniformly fractured aquifers:

9) The aquifer matrix has a lower permeability and a higher storativity than the fracture system and can be divided into three types:

- Fractures are orientated in three main directions, which cut the rock into blocks. In this case the primary porosity of the solid rock may be zero and the rock matrix will be impermeable, this is called a single-porosity system.
- A fractured system, which is accompanied by a dense system of microfissures, increasing the porosity of the rock matrix.
- A double porosity system with two coexisting porosities: the primary or matrix porosity and the secondary or fracture porosity (Kruseman & de Ridder, 1991).

10 (a) Any infinitesimal volume of the aquifer contains sufficient portions of both the aquifer matrix and the fracture system (senario 1).

(b) Any infinitesimal volume of the aquifer does not contain sufficient portions of both the aquifer matrix and the fracture system (senario2).

11) The flow from the aquifer into the fractures is in a pseudo-steady state.

12) The flow to the well occurs entirely through the fractures, and is radial and in an unsteady state. The matrix blocks and the fractures are compressible.

13) Estimated storativity-values depends on distance.

14) The boreholes in badly connected fractures will yield to a high transmissivity (T) and storativity (S) values.

15) Estimated T-values results from conductivity in fracture, horizontal, and vertical conductivity in matrix and aquifer thickness, as a result a range of values is found.

16) If we place observation boreholes in matrix and abstraction borehole in fracture an over-estimation of the T and S-values will occur using the traditional methods.

When comparing these assumptions to that outlined by the methods, it is clear that there significant differences. This proves that extreme care should be taken when applying these methods to areas or aquifer systems that does not conform to the required assumptions and conditions.

3.2.2. Uniformly-fractured aquifers, double porosity concept

The double porosity model assumes that two porous regions of distinctly different porosities and permeabilities within the formation exist (Kruseman and de Ridder, 1991).

For the conventional semi-log analysis, the first straight line represents homogeneous semi-log radial flow in the most permeable medium acting alone; the second straight line corresponds to semi-log radial flow in the total reservoir and; the two straight lines are separated by a transitional period during which pressure tends to stabilize (Gringarten, 1984).

Warren and Root (1963) suggested that the two parallel semi-log straight line behaviour was characteristic of fissured reservoirs; they also noted that it is characteristic of stratified formations.

3.2.2.1 Bourdet-Gringarten's curve-fitting method

The drawdown response to pumping as observed in observation well can be expressed as:

$$s = Q / 4\pi T_f F(u, \lambda, \omega) \qquad (3.26)$$

$$u = T_f / (S_f + \beta S_m) r^2$$

$$\lambda = \alpha r^2 K_m / K_f$$

$$\omega = S_f / S_f + \beta S_m$$

T = effective transmissivity (m2/d)
S = storativity
K = hydraulic conductivity (m/d)

λ = interporosity flow coefficient (dimensionless)

α = shape factor, parameter characteristic of the geometry of the fractures and aquifer matrix of a fractured aquifer of the double- porosity type.

β = factor; for early-time analysis it equals zero and for late-time analysis it equals 1/3 (orthogonal system) or 1 (strata type).

This method can be used if, in addition to the general assumptions and conditions if the following conditions and assumptions are satisfied:

- The aquifer is of double porosity type and consists of homogeneous and isotropic blocks or strata of primary porosity (the aquifer matrix), separated from each other either by an orthogonal system of continuous uniform fractures or by equally spaced horizontal fractures.
- Any infinitesimal volume of the aquifer contains sufficient portions of both the aquifer matrix and the fracture system.
- The aquifer matrix has a lower permeability and a higher storativity than the fracture system.
- The flow from the aquifer matrix into the fractures (i.e. the interporosity flow) is in a pseudo-steady state.
- The flow to the well is entirely through the fractures, and is radial an in an unsteady state.
- The matrix blocks and the fractures are compressible.

  $\lambda < 1.78$ (The double-porosity behaviour of a fractured aquifer only occurs in a restricted area around the pumping borehole. Outside that area, l -values greater than 1.78, the drawdown behaviour is that of an equivalent porous medium (Bourdet and Gringarten, 1980).

This simplified method are recommended as it has been found that this method yields reliable values of T_f, but the S-values still shows the distance dependency as observed by Bredenkamp in 1992 (Kirchner and van Tonder, 1995).

3.2.2.2 Kazemi et.al.'s straight-line method (observation wells)

$$s = Q / 4\pi T_f F(u,\lambda,\omega) \tag{3.27}$$

where: $$F(u,\lambda,\omega) = 2.3\log(2.25u) + Ei - \left(\frac{\lambda u}{\omega(1-\omega)}\right) - Ei\left(\frac{-\lambda u}{(1-\omega)}\right) \tag{3.28}$$

This is valid for u values greater than 100, in analogy with Jacob's approximation of the Theis equation.

- For early pumping times the above equations reduce to:

  $$s = \frac{2.3Q}{4\pi T_f \log 2.25(T_f t / S_f r^2)}$$

  The water flowing to the well during early pumping times is derived solely from the fracture system $\beta = 0$.

- For late pumping times above equations reduce to:

  $$S = \frac{2.3Q}{4\pi T_f \log 2.25 T_f t / (S_f + \beta S_m) r^2}$$

  The drawdown response however, is now equivalent to the response of an unconsolidated homogeneous isotropic aquifer whose $T = T_f$ and $S = S_f + S_m$. Hence, the water flowing to the well, at the late pumping times comes from both the fracture system and the aquifer matrix.

This method is based on the occurrence of two parallel straight lines in the semi-log data plot (u, λ, ω), where $u <= \omega\,(1-\omega)/\,3.6\,\lambda$ describes the early time straight line and $u \geq 1-\omega/\,1.3\lambda \geq 100$, describes the late time straight line. If the two parallel straight lines occur in a semi-log data plot, the value of ω can be derived from the vertical displacement of the two lines, ΔS_V, and the slope of these lines, ΔS:

$$\omega = 10^{-\Delta Sv/\Delta S}$$

Moench, 1984, urged caution in the use of semi-logarithmic straight line method, for example, the Kazemi et al., 1969 for evaluating the product of K and aquifer thickness in double porosity aquifers.

3.2.3. Single vertical fractures

These methods are also based on the general assumptions and conditions:

- The aquifer is confined, homogeneous, and isotropic, and is fully penetrated by a single vertical fracture.
- The fracture is plane (i.e. storage in the fracture can be neglected) and its horizontal extent is finite.
- The well is located on the axis of the fracture.
- With decline in head, water is instantaneously removed from storage in the aquifer.
- Water from the aquifer enters the fracture at the same rate per unit area (i.e. a uniform flux exists along the fracture, or the fracture conductivity is high although not infinite.

3.2.3.1 Gringarten-Witherspoon's - observation wells

According to this method the drawdown data from observation wells placed at specific ocations with respect to the pumped well.

$$s = \frac{Q}{4\pi T} F\left(u_{vf}, r'\right) \qquad (3.29)$$

$$u_{vf} = \frac{Tt}{Sx_f^{\ 2}}$$

r' = square root of $x^2 + y^2 / x_f$

S = storativity of the aquifer

T = transmissivity of the aquifer

x_f = half length of the vertical fracture (m)

x ,y = distance between observation well and pumped well, measured along the x, y axis respectively.

From above equations it can be seen that the drawdown in an observation well does not depend on one parameter, u_{vf} (i.e. on the aquifer characteristics T and S, the vertical fracture half-length, and the pumping time), but also on the geometrical relationship between the location of the observation well and that of the fracture.

3.2.3.2 Huntush-Jacobs method

This method can be used if the following assumptions and conditions are satisfied:

- The assumptions listed at the beginning of this section.
- The flow to the well is in steady state condition.
- $L > 3D$, where L is the leakage factor and D the saturated thickness.
- $r/L <= 0.05$

$$\Delta S_m = \frac{2.3Q}{2\pi KD} \tag{3.30}$$

The slope of the straight portion of the curve; i.e. the drawdown difference ΔS_m per log cycle of r.

To do the calculation substitute the given Q-value and ΔS_m obtained from the graph and determine KD/T. To calculate the hydraulic resistance of the aquitard c, get r_0 when extending the straight line till it intercepts with the x-axis and read off the value, then substitute this value for r_0 and calculated KD into equation:

$$c = \frac{(r_0/1.12)^2}{KD} \tag{3.31}$$

3.2.3.3 Huntush's inflection point method

$$s = \frac{Q}{4\pi KD} W\left(u, \frac{r}{L}\right) \tag{3.32}$$

- The steady state drawdown S_m should be known (from direct observation/ extrapolation).

- The curve of s versus t on semilog paper has an inflection point p where the following relations hold: $S_p = 0.55m = Q/ 4\pi KD\ K_0\ (r/L)$.

The slope of the curve at the inflection point ΔS_p is given by:

$S_p / \Delta S_p = e^{r/L}\ K_0\ (r/L)$, p = at the inflection point.

Either of Huntush's procedures can be used if the following assumptions and conditions are satisfied:

- The assumptions listed at the start of this section.
- The aquitard is incompressible, i.e. changes in the aquitard storage are negligible.
- The flow to the well is in unsteady state.
- It must be possible to extrapolate the steady-state drawdown for each piezometer.

3.2.3.4 FC Method

The FC-Method was developed by the Institute for Groundwater Studies (IGS) for the estimation of the sustainable yield of a borehole and an EXCEL program has been compiled. This method makes use of derivatives, amongst other tools, to give a more detailed analysis. When looking at the derivative-graph you can make certain assumptions:

- Where the derivative strive towards a specific number it can be an indication of a boundary or the end of a fracture zone.
- Double porosity behavior can be seen in the dip in derivatives. Double porosity occurs when water is removed from both the fractures and the matrix of a fractured porous medium and discrete flow in individual fractures. Two co-existing porosities and hydraulic conductivities exist; those of primary porosity and low permeability in the matrix blocks and those of low storage capacity and high permeability in the fractures.
- Radial flow where there is a constant dip in derivative.

- The position of the fractures is seen by a sinus wave: at the fracture position the derivative decreases and after dewatering the fracture the derivative increases again.
- A drastic decrease in the value of the derivative shows a recharge boundary, such as a river or a dam.

The FC method also takes into account the different boundary conditions as well as the influence of other boreholes. After entering all the needed information it calculates the sustainable yield per day or per month for a given borehole.

Included in the FC software program the Step test analysis is contained. That is a single well test in which the well is pumped at a low constant discharge rate until the drawdown in the well approaches stabilization. The pumping rate is then increased to a higher constant discharge rate and the well is pumped until the drawdown stabilizes once more. From this then we can predict the drawdown inside the well for any realistic discharge (Q) at a certain time (t) in relation e.g. a major water strike. The relationship between drawdown and discharge can be used to choose an optimum yield for the well or to obtain information on the efficiency of the well (van Tonder & Xu, 1999).

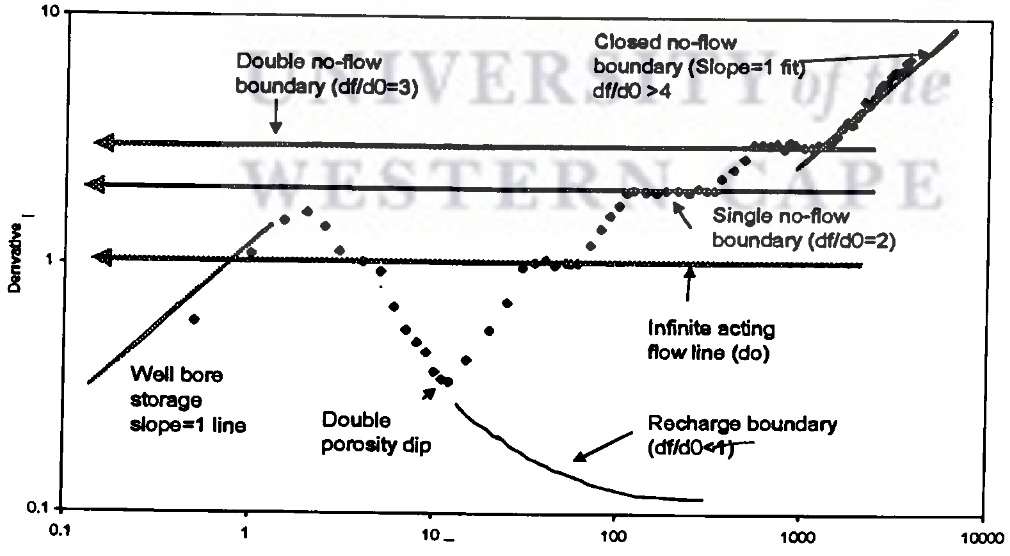


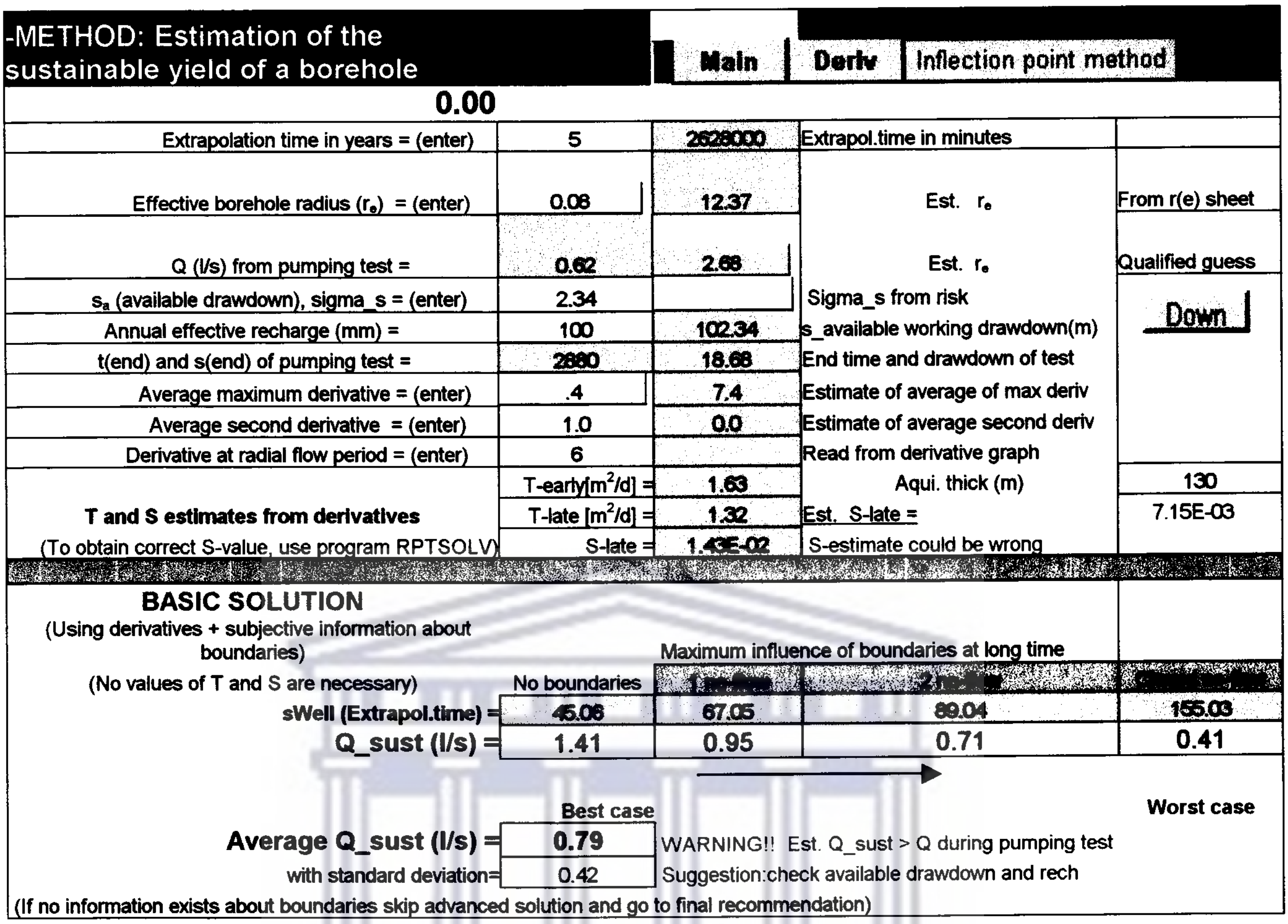
Figure 5: Illustration of well bore storage and boundary conditions

3.2.3.4.1 Implimentation on spreadsheet

This software package makes use of the Constant Discharge Test data to calculate the T and S values. There are several variables that have to be entered into this program before T and S can be calculated. These variables are:

- Extrapolation time in years (depending on the type of climatic environment i.e. arid, semi-arid etc.)
- Effective borehole radius (r_e)
- Available drawdown, sigma_s (calculated from risk)
- Annual effective recharge
- Average maximum derivative (estimated from the drawdown data)
- Average second derivative (estimated from the drawdown data)
- Derivative at radial flow phase

The transmissivity value (T) is estimated by using the derivative curve; T-early is calculated by using the derivative at the radial flow phase and T-late is calculated by using the maximum derivative. The derivative for the radial flow phase is estimated from the derivative curve by the user, thus an amount of error could be induced due to the fact that T-early is very sensitive to this parameter. As indicated in the program, the S estimate could be wrong. The methods used in the program are sensitive to most of the parameters that has to be entered into the spreadsheet.



-METHOD: Estimation of the sustainable yield of a borehole

0.00

Extrapolation time in years = (enter)	5	2628000	Extrapol.time in minutes	
Effective borehole radius (r_e) = (enter)	0.08	12.37	Est. r_e	From r(e) sheet
Q (l/s) from pumping test =	0.62	2.68	Est. r_e	Qualified guess
s_a (available drawdown), sigma_s = (enter)	2.34		Sigma_s from risk	
Annual effective recharge (mm) =	100	102.34	s_available working drawdown(m)	
t(end) and s(end) of pumping test =	2880	18.68	End time and drawdown of test	
Average maximum derivative = (enter)	.4	7.4	Estimate of average of max deriv	
Average second derivative = (enter)	1.0	0.0	Estimate of average second deriv	
Derivative at radial flow period = (enter)	6		Read from derivative graph	
	T-early[m^2/d] =	1.63	Aqui. thick (m)	130
T and S estimates from derivatives	T-late [m^2/d] =	1.32	Est. S-late =	7.15E-03
(To obtain correct S-value, use program RPTSOLV)	S-late =	1.43E-02	S-estimate could be wrong	

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	[illegible]	[illegible]	[illegible]
sWell (Extrapol.time) =	45.06	67.05	89.04	155.03
Q_sust (l/s) =	1.41	0.95	0.71	0.41
	Best case			Worst case

Average Q_sust (l/s) =	**0.79**	WARNING!! Est. Q_sust > Q during pumping test
with standard deviation=	0.42	Suggestion:check available drawdown and rech

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

Figure 6: Sustainable Yield Estimation using the FC-program

3.2.4. Numerical Methods

Numerical methods are tools that can be used in the interpretation of pump test data, which can be used to make predictions on the affects of pumping on the aquifer system. Two of these methods are described below but has not been applied to the data collected.

3.2.4.1 MODFLOW

MODFLOW is a three-dimensional finite-difference groundwater flow model. MODFLOW simulates steady and nonsteady flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined. Flow from external stresses, such as flow to wells, areal recharge, evapotransperation, flow to drains, and flow through riverbeds, can be simulated. Hydraulic conductivities or transmissivities for any layer may differ spatially and be anisotropic and the storage coefficient may be heterogeneous. The model requires input of the ratio of vertical hydraulic conductivity to distance between vertically adjacent block centers. Specified head and specified flux boundaries can be simulated as can head dependent flux across the model's outer boundary that allows water to be supplied to a boundary block in the modelled area at a rate proportional to the current head difference between a source of water outside the modelled area and the boundary block (http://water.usgs.gov/cgi-bin/man_wrdapp?modflow).

The groundwater flow equation is solved using the finite-difference approximation. The flow region is considered to be subdivided into blocks in which the medium properties are assumed to be uniform. The plan view rectangular discretization results from a grid of mutually perpendicular lines that may be variably spaced. The vertical direction zones of varying thickness are transformed into a set of parallel layers. Several solvers are provided for solving the associated matrix problem; the user can choose the best solver for the particular problem. Mass balances are computed for each time step and as a cumulative volume from each source and type of discharge (http://water.usgs.gov/cgi-bin/man_wrdapp?modflow).

3.2.4.2 RADFLOW

Finite difference and finite element codes have been developed for pumping test analysis in one, two and three dimensions. The popular MODFLOW code, discussed above, has been adapted to include a solution in cylindrical coordinates specifically to evaluate drawdown around a borehole. Numerical models can be created that require few of the assumptions that accompany analytical techniques. In most cases the user can alter the list of assumptions to fit any situation (Johnson, 2001).

RADFOW is a two dimensional, finite difference model that simulates axially symmetrical flow to a borehole (i.e., radial and vertical components). The assumption of axially symmetrical flow limits the representation of lateral heterogeneities. Unlike the analytical techniques, RADFLOW imposes no assumptions of vertical flow or storage in aquitards, horizontal flow in aquifers, infinitesimally small well diameter, time limitations on solution validity or other common constraints. This software provides the opportunity for hydrogeologists to make full use of their subjective understanding of the aquifer conceptual model in combination with the quantitative information of pumping tests (Johnson, 2001).

The finite-difference expressions representing flow between grid cylinders are written in terms of radial distance from the centre of the pumping borehole (r) and vertical distance above a reference datum (z). Horizontal and vertical flow components (Q) are computed through the application of Darcy's law in cylindrical coordinates (Johnson, 2001):

$$Q = -(KA/\Delta l)\Delta h \qquad (3.33)$$

K = hydraulic conductivity

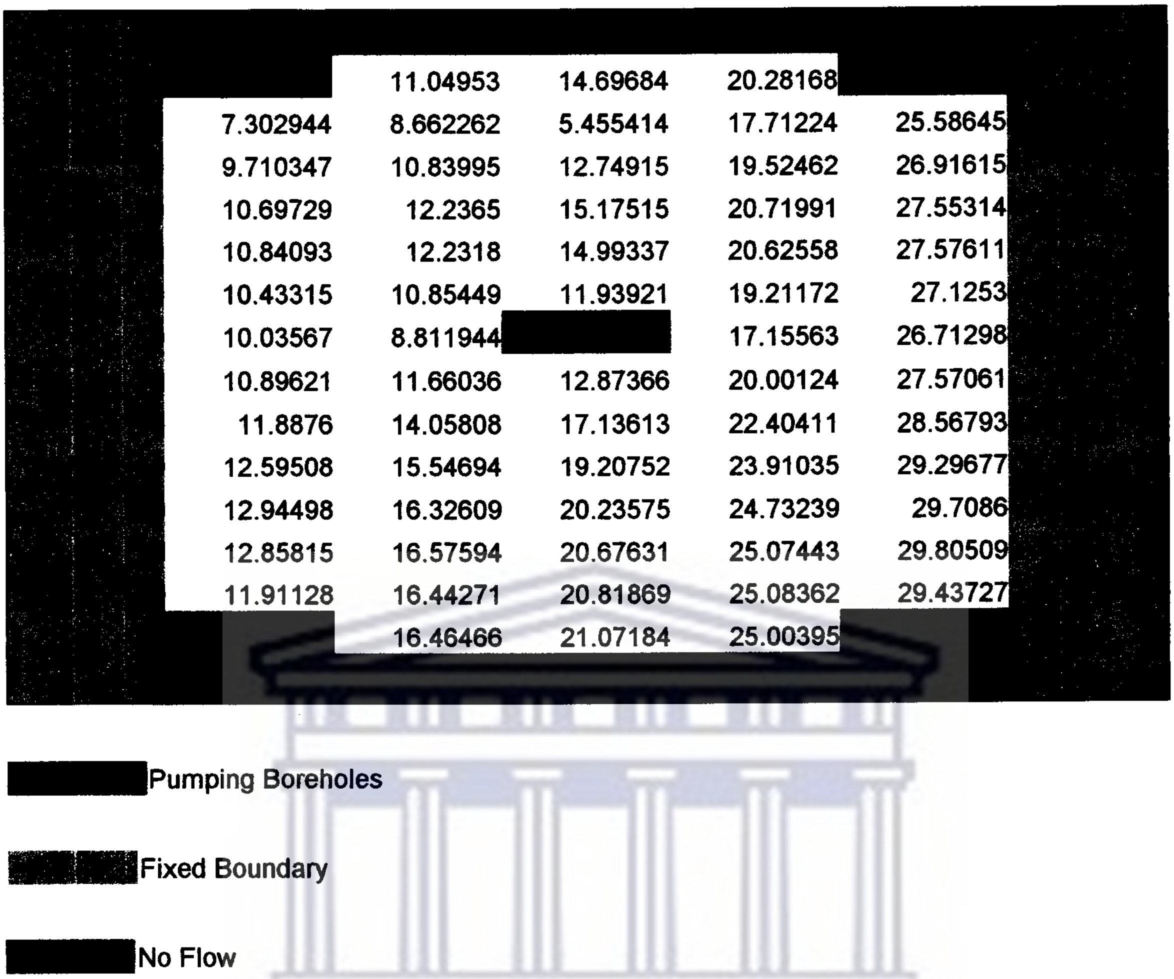
A = cross sectional area

Δl = node separation distance radially and vertically

Δh = the head difference between corresponding node points

3.2.4.3 Simplified Numerical Model

This simplified numerical model has been designed to illustrate the basic principals of numerical modeling. It works on a grid system and when calculating it takes in consideration the surrounding four elements to the point of investigation. The model is bounded on the sides by two no-flow / fixed boundaries. There are five pumping boreholes, which are represented in red. If the values of the pumping boreholes, which represent the pumping rate, are changed the influence will be reflected in the surrounding grid elements.



	11.04953	14.69684	20.28168	
7.302944	8.662262	5.455414	17.71224	25.58645
9.710347	10.83995	12.74915	19.52462	26.91615
10.69729	12.2365	15.17515	20.71991	27.55314
10.84093	12.2318	14.99337	20.62558	27.57611
10.43315	10.85449	11.93921	19.21172	27.1253
10.03567	8.811944	■	17.15563	26.71298
10.89621	11.66036	12.87366	20.00124	27.57061
11.8876	14.05808	17.13613	22.40411	28.56793
12.59508	15.54694	19.20752	23.91035	29.29677
12.94498	16.32609	20.23575	24.73239	29.7086
12.85815	16.57594	20.67631	25.07443	29.80509
11.91128	16.44271	20.81869	25.08362	29.43727
	16.46466	21.07184	25.00395	

■ Pumping Boreholes

▨ Fixed Boundary

■ No Flow

Figure 7: Illustration of simplified numerical model

Numerical modelling should be used in conjunction with pump test methods in areas where few research has been done. This method work on a grid system that does not always show the true effects of what is happening in the field.

3.3. TEST PUMP PROCEDURE

Pumping tests are conducted to determine the performance characteristics of a borehole as well as the hydraulic parameters of the aquifer. The second purpose is to provide data from which the principal factors for aquifer performance, transmissivity and storativity, can be calculated. A pumping test comprises of pumping a well at a certain rate and recording the drawdown in the pumping borehole and in nearby observation boreholes at specific times. There are two primary aquifer tests: step-drawdown tests and constant-discharge tests. Pumping tests will not produce accurate data unless the tests are carried out methodically, carefully recording the time, discharge, and depth measurements (Driscoll, 1986).

Listed below are the procedures that needs to be followed inorder to obtain reliable pump test results:

3.3.1. Pre arrival arrangements

- Pump test contractor must be appointed.
- Date to perform test should be decided upon.
- Notify the owner of the property.
- Pumping activities should stop 72 hours prior to pumping test.

3.3.2. Arrangement after arrival

- Location of boreholes to be tested; can be done using a global positioning system and topographic maps or should be confirmed with the representative for the specific area.
- Removal of existing equipment; great care should be taken during this process because the equipment could be rusted.
- Determine the depth of the borehole and compare with previously recorded depth, which can be supplied by the owner or representative to determine whether the borehole has been closed up.
- Determine depth of observation boreholes.
- Determination of potential yield (slug test); This method can only be use for boreholes with a diameter of 165 mm.
- Installation of pumping equipment; the pump is lowered down into the hole then the other pipes are connected to it. The amount of pipes and the depth of the pump is determined by the depth of the borehole. Normally, the pump is installed at 5 to 6 meters above the bottom of the hole. Lower than this could cause debris and silt to be sucked into the pump.

- Installation of discharge piping; this is installed to remove the discharge water to a point so that it would not affect the results of the pumping test. This pipe should be placed in a downhill direction so that the water does not flow back to the pumping borehole. At the end of the pipe there should not be any disturbance of the water flow because it can influence the yield and water level observations.
- Measuring discharge; using time to fill a container. The time to fill and the size of the container is used to calculate the yield in l/s, e.g. if the size of the container is 25 l and it takes 86 seconds to fill the yield is calculated as 86 / 25 = 3.44 l/s. The yield should be checked frequently.
- Installation of water level measurement equipment; when the pumping equipment was installed, a plastic tube was attached on the outside of the pipes. To measure the water level the water measure tape is lowered down the tube. The more modern way of measuring the water levels or drawdown is by using data loggers.
- Determining static / rest water level; a dipmeter is use to measure the static water level from the distance between the collar of the borehole to when it reaches the water level (Van Bosch, 2000).

3.3.3. Step test

The step-drawdown test is one of the most frequently performed types of pumping test, particularly in the case of single wells. Its aims are to: Determine the behaviour of the well; to evaluate well losses, to determine the aquifer parameters and to calculate the efficiency of the well (Kawecki, 1995).

The step test generally consists of three or more steps. After each step the pumping rate is increased and maintained at that specific rate for an equal length of time, which can be chosen from 60 to 120 minutes. The drawdown for each step is recorded in accordance with the prescribed time schedule. The pumping rate for each step should also be recorded on a data sheet. At the end of the step test the recovery should be measured for the same time period that was used for the steps. During the step and the recovery water levels should also be measured in available observation boreholes.

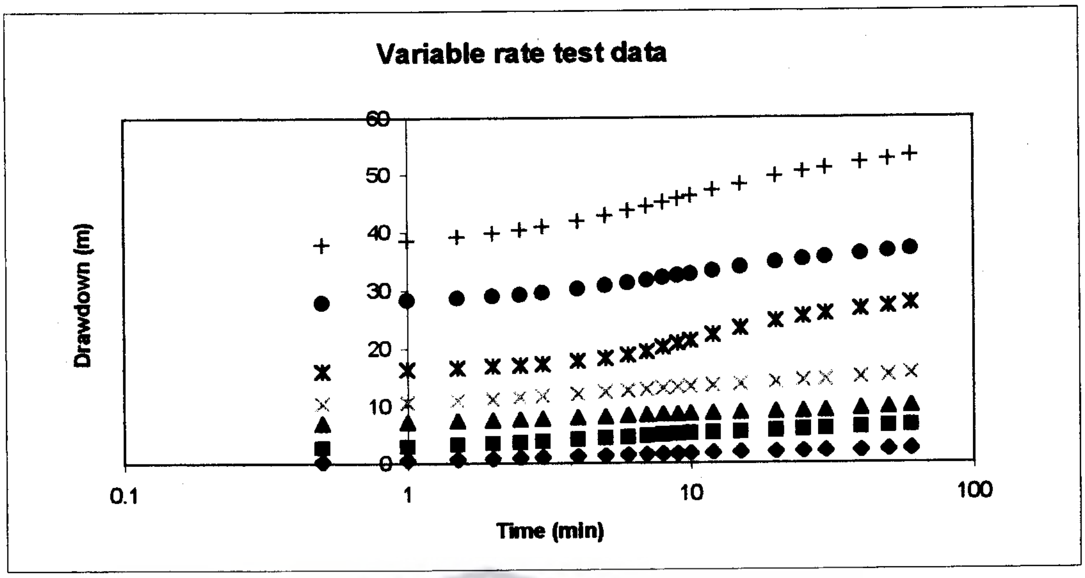


Figure 8: Illustration of a step test

The figure above show a step test drawdowns of a borehole in the Tweerivier region in Namaqualand, taken from the FC-program. The step test consisted of 7 steps, which lasted for 60 minutes each. After 420 minutes the drawdown was down to 53 metres. The performance of the borehole is monitored at different discharge rates to choose a rate for the constant discharge test. This choice should be made carefully so that the rate can be maintained over a time period of 12 to 72 hours, or longer, without the water level reaching the pump.

3.3.4. Multi Rate Test

The multi rate test is similar to the step test with some differences. The main differences between this test and the step test are: In determining the drawdown values no extrapolation is necessary. Secondly, the pumping rates can be increased and decreased during the test and thirdly, additional transmissivity and storativity values can be obtained when doing this test (Van Bosch, 2000).

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. The test is done by pumping the borehole at one third of the expected operational yield of the borehole. After the recommended time period of 60 minutes, pumping is stopped and recovery takes place. After the recovery the pumping rate is increased to two thirds of the expected operational yield and pumped for the same time period as the first one, after which its left to recover again. This procedure is repeated until the pumping rate and the expected operational yield is equal. The drawdown and time is recorded on a sheet (Van Bosch, 2000).

3.3.5. Constant Discharge Test (CD Test)

The CD test is used widely to obtain the specific capacity of a borehole and the transmissivity and storativity values of the aquifer. During the pumping test the well is pumped at a constant rate for either 24 or 72 hours, depending on the type of aquifer that is being dealt with (Domenico and Schwartz, 1990).

It is critical for the pumping rate during the entire pumping test to be kept constant; therefore it should be adjusted when necessary. The aquifer should be allowed to recover to its original water level after the step or multi rate test.

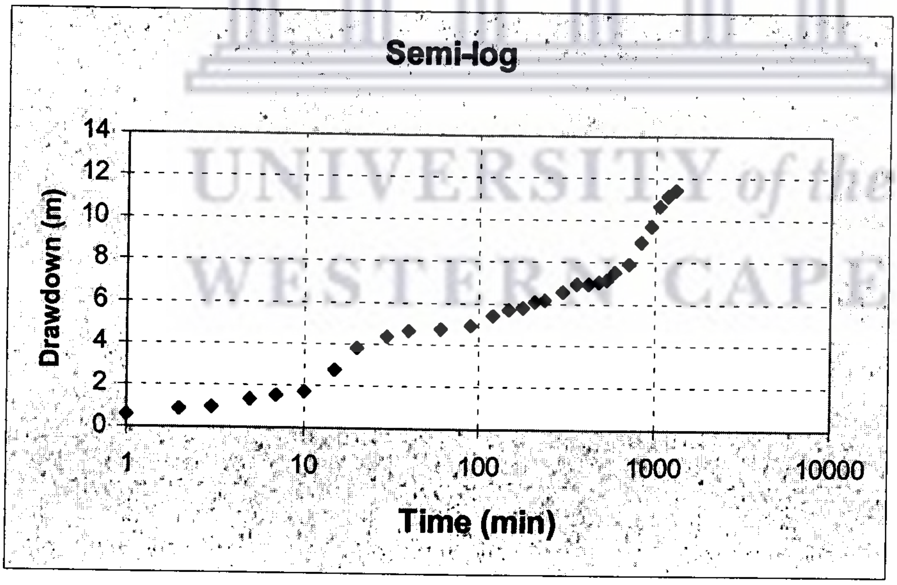


Figure 9: Semi-log plot for Leliefontein

This plot is generated using the CD data that was collected at a borehole in the Leliefontein region in Namaqualand. This plot is used to calculate aquifer parameters using a straight line method. A straight line is fitted through the data plot shown above from which the T and S values are calculated.

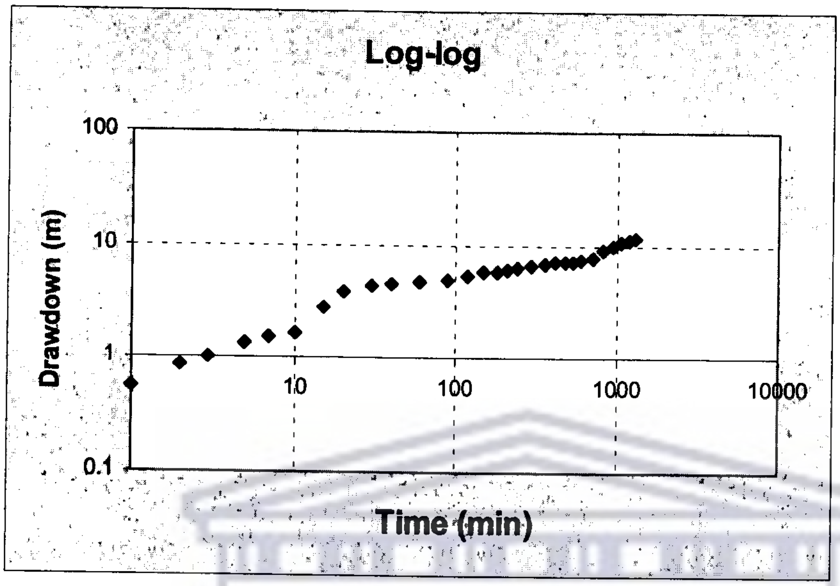


Figure 10: A log-log plot for Leliefontein

Aquifer parameters are calculated using type curves to which the measured data plot are fitted. These two plots reflect well bore storage for the first 10 minutes, thereafter there is a sudden increase in drawdown till about 30 minutes, which could be due to a fracture that is intersected; after 30 minutes the drawdown starts to become smaller but still increases slowly till 850 minutes where it seems another fracture is intersected or a boundary condition occurs.

3.3.6. Recovery Test

When the pump is switched off the water levels will begin to rise, this data is then recorded as the recovery data as known as the residual drawdown (defined as the water level in a borehole after pumping has ceased) and should be recorded at the same intervals as during the pumping test. This data is more reliable than the pumping test data because the recovery occurs at a constant rate, whereas constant discharge during a pumping test is often difficult to achieve in the field. By making use of the recovery data the number of hours that a borehole should be pumped can be estimated by using:

$$h = 24 - (24/x)$$

where, x = the x-axis intercept of the residual drawdown versus recovery plot on semi-log graph paper (Kirchner, 1991).

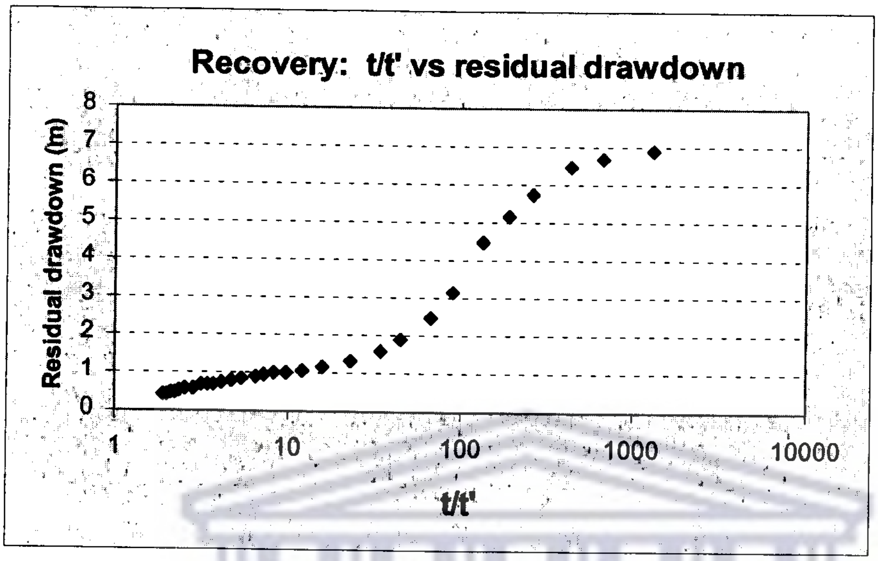


Figure 11: t/t' vs. residual drawdown (Leliefontein)

A constant increase in the residual drawdown for the first 30 minutes is observed after which there is a steep increase till about 700 minutes. After this episode there is again a constant increase in the residual drawdown. In the centre part of the graph, i.e. from 30 to 700 minutes, there is a great inflow of water most probably from a fracture network or individual fractures, as can be compared to the semi-log and log-log plots.

3.3.7. Problems

Many 'problems' can be encountered during pumping tests. The data has to be collected by a reliable observer/contractor. Pumping tests are expensive and involves a greater expense if it has to be repeated. Things that can go wrong on-site are:

- With the removal of the existing equipment the hole can partially collapse if not done properly and this can affect the water level and the depth of the borehole.
- When the pump test equipment is installed it has to be done with caution.
- The machinery has to be in top condition, because if it fails during the test the test has to be redone which could be cost and time consuming.

- If a CD test is conducted the yield has to be checked quite frequently to ensure a constant rate of pumping.
- When collecting the data the drawdown should be measured accurately, therefore its recommended that one person should complete a test.
- Data should not be interpolated but should be measured at all time intervals.

3.4. AQUATEST

3.4.1. Adaptation Theory for AQUATEST

As mentioned previously, the most frequently used methods are that of Theis (1935) and Cooper-Jacob (1946). The latter is frequently used in most software development. For AQUATEST the method by Abramowitz and Stegun (1965) is used to improve the Cooper-Jacob method. The Cooper-Jacob method is illustrated as follows:

$$s = \frac{2.3Q}{4\pi T}\log\frac{2.25Tt}{r^2 S} \qquad (3.34)$$

where, $u = r^2 S / 4Tt$ (3.35)

, $u < 0.01$. This is a very rigid condition, for a five or even ten times higher value of u the error introduced in the result is 2 % and 5% respectively.

An improvement was made on the variability of the u parameter, shown in the previous equation. The Cooper-Jacob method only makes use of the first two terms as illustrated in the formula below, which represents the u parameter:

$$s = \frac{Q}{4\pi T}w(u) = \frac{Q}{4\pi T}\left(-0.5772 - \ln u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \dots\right) \qquad (3.36)$$

As can be seen above the first two terms are – 0.5772 - ln(u), which equals – 0.5772 – ln($\frac{r^2S}{4Tt}$), this can only be used in simplified conditions, where no boundary conditions exist. Abramowitz and Stegun (1965) include the other terms that are disregarded in the Cooper-Jacob and can be expressed as follows:

$0 \leq u \leq 1$

$$w(u) \approx -\ln u + [\{[(a_5 u + a_4)u + a_3]u + a_2\}u + a_1]u + a_0$$

(Max error = 2E −7)

where , $a_0 = -0.57721566$

$a_1 = 0.99999193$

$a_2 = -0.24991055$

$a_3 = -0.57721566$

$a_4 = 0.99999193$

$a_5 = -0.24991055$

$1 \leq u \leq \infty$

$$w(u) = \frac{e^{-u}\{[(u + b_3)u + b_2]u + b_1\}u + b_0}{\{[(u + c_3)u + c_2]u + c_1\}u + c_0}\varepsilon(u)$$

$(|\varepsilon(u)|) < 2E - 8$

where, $b_0 = 0.2677737343$

$b_1 = 0.2677737343$

$b_2 = 0.2677737343$

$b_3 = 0.2677737343$

$c_0 = 3.9584969228$

$c_1 = 3.9584969228$

$c_2 = 3.9584969228$

$c_3 = 3.9584969228$

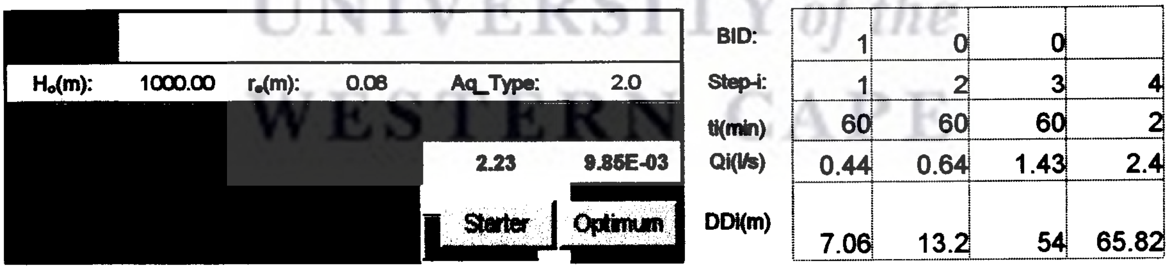
Therefore, this method is more effective when applying it to the collected data. AQUATEST includes this in the program, which makes it very useful in terms of boundary conditions.

3.4.2. Implimentation on spreadsheet

AQUATEST only requires three parameters when calculating T and S values:

- Thickness of the aquifer
- The effective radius
- Option to choose the aquifer type

This program does most of the necessary calculations, which could decrease the amount of human error. More emphasis is placed on the determination of the parameters optimally rather than estimation by human graphic observation. When there is no observation borehole data available the pumping borehole data are used. The S-value is calculated using solver, which allows the T value to be kept constant while curve fitting can be done by changing the S-value, vice versa. Here the sensitive parameter is the effective radius. The aquifer thickness used to convert unconfined aquifers to equivalent of confined conditions, is not such a sensitive parameter due to the confined nature of the aquifer system. The T and S-values determined are average values calculated from the drawdown data collected for the pumping test.



H_o(m): 1000.00 r_e(m): 0.08 Aq_Type: 2.0

2.23 9.85E-03

BID:	1	0	0	
Step-i:	1	2	3	4
ti(min)	60	60	60	2
Qi(l/s)	0.44	0.64	1.43	2.4
DDi(m)	7.06	13.2	54	65.82

Table 4. Input sheet for AQUATEST.

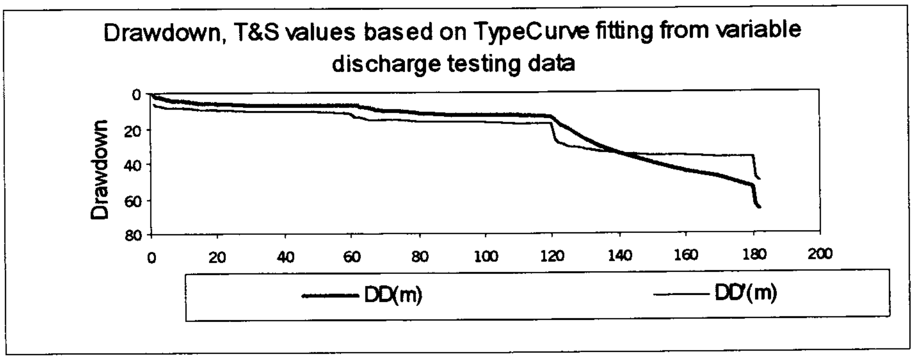


Figure 12: T & S calculation using AQUATEST

Borehole ID allows for the input of the specific site name, H (m) is the aquifer thickness and r_e (m) refers to the effective radius. It also requires the input of the aquifer type, three options in table to choose from, in this case the Theis method was chosen. For this specific borehole there were 38 points entered in the column, which represents the time at which the drawdown data were collected. The next column Q_{step} (l/s) gives the different pumping rates selected during the test, where the 0.95 represents the average of all the data entered in this column. DD (m) represents the drawdown data that is entered into the cells below it, where 65.82 is the maximum drawdown calculated for the test. After entering these values AQUATEST calculates the following parameters: C (d^2/m^5), T and S-values. The starter button is used after entering a new set of data to allow for a new calculation by choosing the correct method or boundary condition. Optimum allows the program to do the necessary calculations and optimize parameters. After all the calculations the number of steps, time to complete each step, the rate of pumping for each step and the drawdown at the end of each step are displayed. The curve shows the measured drawdown data (DD) fitted to the theoretical drawdown data (DD') over the time period entered by the user.

The advantages using AQUATEST includes the use of step test data, effective radius estimation as well as drawdowns for longer periods at different pumping rates can be used as input data.

4. CASE STUDY

4.1. STUDY AREA

The study, involving the nterpretation of pump test data, was conducted in the Northern Cape Province of Southern Africa. It is approximately 500 km's north of Cape Town. Borehole data were collected in terms of its availability and covers different towns between Garies and Springbok. The borehole data includes raw data of pumping tests as well as the borehole logs of pumping and observation boreholes.

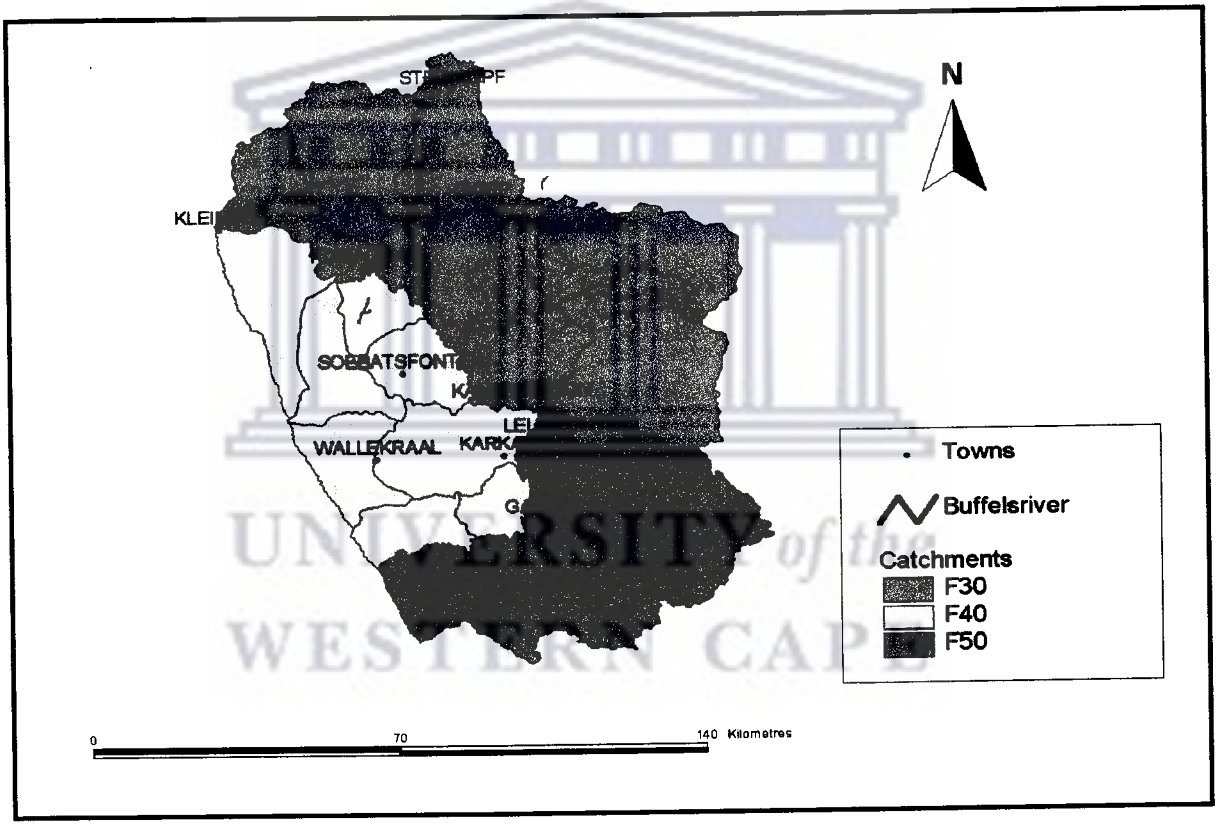


Figure 13: An illustration of the study area

Raw data of 38 boreholes were gathered from all three catchments outlined above, 26 pumping and 12 observation boreholes. The data was collected from DWAF (Department of Water and Forestry, Toens and Partners and Hippo (contractors that collected some of the pump test data). Futhermore, 6 data sets were collected with A & B Pumps on pumping boreholes, contracted by DWAF. All the data used for this section is included in the Appendix.

4.1.1. Climate

The Northwestern part of South Africa, particularly, the Namaqualand area is one of the driest regions of the country. Highly variable sporadic rainfall and flunctuating temperatures daily as well as seasonally characterize the area. Most of the area receives winter rainfall although the eastern low lying parts have summer rainfall. The average rainfall varies from about 100mm on the low lying areas to 300mm on the higher lying areas. This has important implications for the water resources, both in terms of quality and quantity.

4.1.2. Geomorphology

The Namaqualand region is characterized by an undulating topography, consisting of valleys and granitic domes. There are three types of inselbergs that desribes these hills that rise sharply from the surrounding flat plains, which is bornhardts, nubbins and catle koppies. Bare domical masses are reffered to as bornharts, nubbins are block or boulder strewn inselbergs and castle koppies are angular castellated forms. Each dome or nubbin are developed on a fracture defined block. The bornharts are the basic form from which the other two developes. Though each most characteristally occurs in isolation bornharts and nubbins are also found in groups, as for instance in the Kamiesberge Massif of Namaqualand, where in the west the ranges of rounded hills form the uplands and in the east the hill country consists innumerable nubbins (Moon and Dardis, 1992).

4.1.3. Geology

The Northern Cape region (Namaqualand & Bushmanland) can be subdivided into three major geological groups, namely the basement rocks of the Namaqua Province, the volcano sedimentary rocks of the Gariep Province in the northwest, and a younger cratonic cover. The Namaqua Province forms most of the crystalline basement in Southwestern Africa. It covers the Northern Cape and Southern Namibia as is exposed in a triangular area. Most of the Namaqua Province is represented by the Central Zone, a complexly deformed heterogeneous group of gneisses and intrusions metamorphosed to medium and high grade, collectively known as the Namaqua Metamorphic Province (Tankard, 1982).

In the western centre of the Central Zone is a small wedge-shaped area of low-grade supracrustal rocks and high-level intrusions referred to here as the Western Zone. In the extreme west, crustal reworking during the Late Precambrian truncated the Namaqua Province; the zone of reworking delineates much of the western margin, the remainder being represented by the Atlantic Ocean (Tankard, 1982).

GEOLOGICAL PROVINCE	UNIT	GROUP	LOCALITY
Namaqua Province	Central Zone	Namaqua Metamorphic Province	Most of Namaqualand and Bushmanland
	Western Zone	Vioolsdrif Intrusive Suite	Northeastern part of Richtersveld
		Orange River Group	Vioolsdrif
	Eastern Marginal Zone		Upington

Table 5: Summary of the geological units in the Namaqua Province.

The Namaqua Metamorphic Province is an assemblage of metasedimentary, metavolcanic and intrusive rocks. These rocks underwent several phases of intensive folding as well as faulting and were intruded on a large scale by syntectonic granites. The high grade and multiphase deformation undergone by these rocks destroyed the normal stratigraphic criteria and produced generations of tight and isoclinal folding. The base of the sequence, which is truncated by intrusion of younger granatoid gneisses, is a thick westward tapering wedge of pink-weathering biotite gneiss with a highly quartzfeldspatic nature which suggests formation in a continental environment. Above the pink gneisses are metasediments such as metapelite, gneiss, metaquartzite, and minor metaconglomerate, calc-silicate rocks and marble (Tankard, 1982).

are metasediments such as metapelite, gneiss, metaquartzite, and minor metaconglomerate, calc-silicate rocks and marble (Tankard, 1982).

Early Proterozoic tectonism gave rise to the Orange River Group (2000 Ma) and the slightly younger Vioolsdrif intrusive suite. The Namaqua Metamorphic Province originated in the Middle Proterozoic times, chronologically built of the Nababeep augen gneisses, the Bushmanland Metamorphic suite, and the Rietberg-, Concordia-, and Okiep basic rocks. All Proterozoic stages of orogeny were characterized by abundant syntectonic partial melting in the lower crust and large scale intrusion of granites, probably induced by continental convergence. Basement reworking along the coast set the stage for Pan African basement development. Rifting and continental crust was followed by the opening of the proto-South Atlantic Ocean during the late Proterozoic at about 900 Ma. Thick syn-tectonic clastic deposits accumulated in the basin fed by detritus from the rising Namaqua massif and supracrystal successions were preserved by their crystalline basement. Subsequent plate convergence, starting 700 Ma ago, is most frequently suggested as the cause of metamorphism and deformation in these basins. An early Paleozoic rifting phase might have initiated a reactivation of a older structural trend in Namaqualand. The diversity of structures is difficult to distinguish due to the multiple deformation phases.

4.1.4. General Hydrogeology

Granite gneisses covers most of the area and are characterized by the large granitic domes. This rock type is basically granite, which has been subjected to metamorphism and has therefore taken on a gneissoid structure. The rock is composed mainly of quartz, feldspar and mica's. In crystalline rocks like these, there is little pore space between the grains, which have crystallized into their present positions, which causes it to be closely interlocked with one another. Therefore the only rapid circulation of water must be through joints and fractures that developed at the time of crystallization (Wright, 1987). We need to understand how water moves in a particular flow system to be able to study and interpret it. Figure 14 (Herbert, 1987) shows the major elements of groundwater flow in hard rock aquifers.

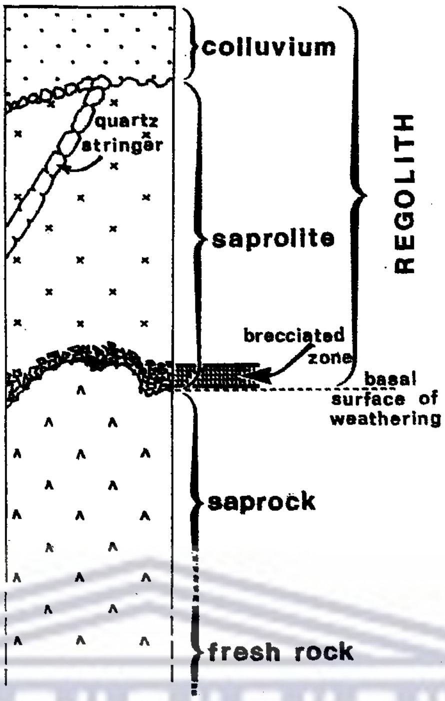


Figure 14: Major elements of groundwater flow in hard rock aquifers.

In trying to identify the flow in a particular system we have to take in account factors such as recharge and evaporation. These factors will control the amount of water, which influences the flow in a system. The circulation below the water level in any fractured rock is both lateral and vertical. A connected series of joints will therefore have a very complex circulation. The main circulation will in most cases be towards and along the fractures having the largest openings and the nearest outlets. The general movement of the groundwater will be in the direction that the land slopes (Herbert, 1987).

Perched aquifers/ upper zones of high permeability promoting lateral flow may occur above aquitards. The bedrock type and structural features can affect the lithology and thickness of regolith, and some important correlations are listed below:

- Coarse grained granite rocks produce more permeable regolith than finer grained granite rocks. Fracturing in the former is more spaced but the fractures are more extensive which results in both thicker and more permeable regolith.
- Fine grained feldspatic gneisses have thinner regolith (Wright, 1987).

In hard rock aquifers a lot of emphasis is placed on the occurrence of fractures for water supply. Although the fracture is the initial feature of interest, it is the hydraulic character of the fracture that is the most important aspect. Fractures exhibit random, variable aperture size and distribution due to irregular mechanical dislocation, fault-rock material as well as veining material. The manner in which groundwater flow occurs is controlled by the interconnections of the fractures (Lloyd, 1999).

The drop in water level of the pumping and observation boreholes measures the response of an aquifer to pumping. Quantitative information on aquifer and well conditions is needed to determine the relationship between the yield and drawdown over longer periods than that of the pumping tests. The scale of heterogeneity in a fractured hard rock aquifer may be large relative to the scale of the test. Therefore, the conventional methods that have been developed for homogeneous porous aquifers will not effectively describe the drawdown response in fractured hard rock aquifers. Different types of aquifer and well conditions exist at different times during a pumping test, which will affect the response of the drawdown in a specific way (Lloyd, 1999).

4.1.5. Adaptation in Crystalline Aquifer

Most of the methods outlined before can only be applied to homogeneous, isotropic type of aquifer systems. The crystalline aquifers in the Namaqualand area are very complex systems because of the intense deformation that occurred in the area. There are the above mentioned assumptions and conditions that have to be met before any of the methods can be applied. There are some assumptions and conditions that seemed to be problematic when the methods was applied in the first few situations:

- **The aquifer is confined?**

  Most of the aquifer systems in the study region ranges from unconfined, semi-confined to confined conditions. Most of the methods outlined should only be used in confined conditions. For the data to be usable we need to convert from unconfined to confined conditions by using the formula:

$$s' = s - (s^2/2D) \qquad (4.1)$$

where, s' = the calculated drawdown

s = measured drawdown

D = saturated thickness

- **Infinite areal extent – boundaries?**

  Another condition is that the aquifer should be of infinite areal extent; once a boundary is encountered this condition does not hold. There are different methods that can be used to overcome this problem.

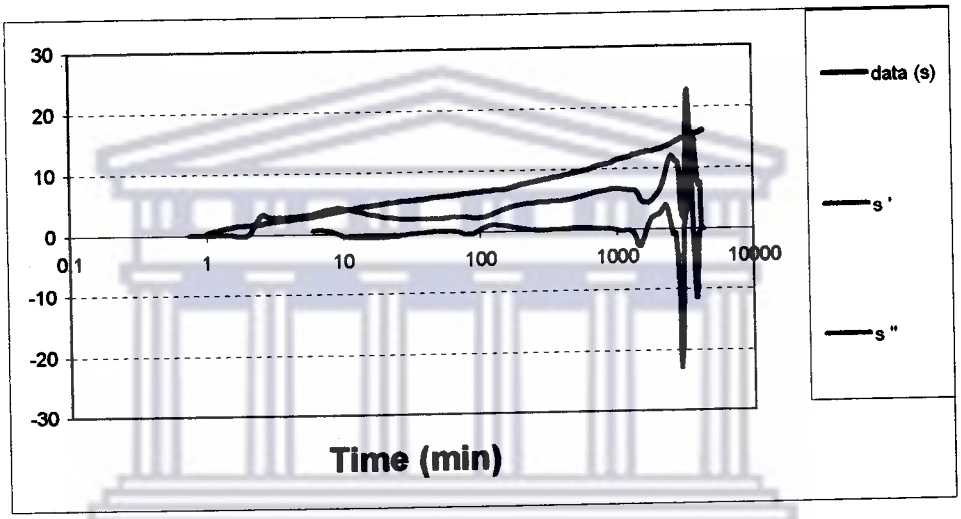


Figure 15: Derivative curve for the Tweerivier region.

The FC-program uses derivatives to identify certain characteristics for drawdown versus time curves. To make use of derivatives is a good tool because of it's sensitivity to small changes in drawdown. When the first derivative curve has a slope of 1 it indicates a closed boundary; where there's a downward trend in the derivative it is an indication of a recharge boundary; where the slope equals 2 it shows a no-flow boundary; and where the second derivative equals 1 closed boundary is represented. Also, the use of imaginary boreholes is a good tool when dealing with an assumption of infinite areal extent.

- **The aquifer should be homogeneous and isotropic & the well penetrates the entire thickness of well and therefore receives horizontal flow.**

  The Namaqualand area is characterized by a heterogeneous, anisotropic system due to intense deformation of the area. In most cases the well does not penetrate the entire thickness of the aquifer because of the nature of the aquifer system. To be able to apply the methods in this situation we need to determine the REV (Relevant Elementary Volume). The REV is known as the distance away from the pumping borehole at which radial flow occurs. If this data is used for interpretation it will reflect an aquifer that is homogeneous, isotropic with horizontal flow to the borehole and therefore the calculation will be more accurate.

4.2. CONCEPTUAL MODELS

As mentioned before 38 data sets were collected from, 28 pumping and 12 observation boreholes. The data was collected from DWAF (Department of Water and Forestry), Toens and Partners and Hippo and A& B Pumps (contractors that collected some of the pump test data). Data were collected from reports that had calculated transmissivity (T) and storativity (S) values for different areas in Namaqualand. These values have been calculated using the well known analytical methods, mostly Theis and Cooper-Jacob. The FC-Method, discussed above, is also popular when interpreting pump test data, but can only be used by people with experience in this field.

Town	**Borehole number**	**Transmissivity (m^2/d)**	**Storativity**
Tweerivier	LF 90/201	9.5	5.05 E-4
Steinkopf	Steinkopf aquifer	unknown	2.1 E-7
	SK 103 (confined)	1505; 260	1.95 E-5
	SK 102 (semi-confined)	*Various T values	7.9 E-2
	SK 93/106 (unconfined)	2	
	93/107 (unconfined)	29.5	
	93/108 (unconfined)	38.8	
	SK 91/102 (con. To semi-con.)	4720*	
	91/103 (con. to semi-con.)	1254*	

Cont.	91/104 (con. to semi-con.)	922*	
	91/105 (con. to semi-con.)	27.15	
Komaggas	KG 91/100 (con. To semi-con.)	52	
	KG 91/101 (con. To semi-con.)	2.1	
	KG 91/102 (con to semi-con)	15.04; 0.95	
Leliefontein	LF 90/201 (confined)	40	
Garies	GA 91/1 (uncon. To semi-con.)	10.3	2 E-4 to 7.2 E-4
Karkams (estimated values)	G37133 (semi-con.)	1193	
	G37152	1170*	
	G37159	816*	
	G37166	6426*	
	G37174	12040*	

* Unrealistic high values.

Table 6: Data collected from DWAF and TOENS reports

It can be seen from table 5 that for some areas the T-values are unrealistically high for this type of aquifer formation, reason probably the use of wrong methods. Another Software package, AQUATEST, was used for the interpretation of recently collected pump test data. This program makes use of step test data when calculating transmissivity and storativity values. It also converts the drawdown data by using equation 4.1 as mentioned above.

This formula allows transition from unconfined to confined conditions, which gives the corrected drawdown value. This corrected value is then used to plot the drawdown versus time curve used to calculate the aquifer parameters. The saturated thickness in this program is assumed to be 1000 meters; as the aquifers are assumed to be confined and fully saturated any large thickness can be assigned to this parameter.

The transmissivity and storativity values, without considering boundary conditions, calculated using AQUATEST are presented in the tables below.

Location of boreholes	Transmissivity (m^2/d)	Storativity
KG 93/114	0.28	2.66 E-3
KG 93/113	14.61	6.07 E-4
KG 93/111	0.10	1.27 E-3
KG 93/106	0.31	4.71 E-3
KG 93/107	0.68	1.00 E-2
KG 93/217	0.11	1.00 E-2
KG 93/216	0.08	1.00 E-2
KG 93/218	0.11	1.00 E-2
KG 91/100	Negative drawdown	
KG 93/108	1.62	8.48 E-4
KG 93/115	3.57	2.62 E-3

Table 7: T and S values for Kommagas

LF 98/312	0.08	9.54 E-4
LF 98/311	0.24	1.00 E-2

Table 8: T & S values for Klipfontein

G 45805	0.38	1.42 E-4

Table 9: T & S values for Spoegrivier

G 45779	0.38	1.42 E-4
G 45781	1.43	1.67 E-4

Table 10: T & S values for Garies

When comparing the data of Garies and Kommagas and the parameters calculated using AQUATEST and the parameters stipulated in the reports, it's clear that when using AQUATEST the T-values are much lower and realistic for this type of environment than the T-values stipulated in the old reports. Although a direct comparison between specific boreholes cannot be drawn, it can be assumed that there cannot be as a big difference in the T-values as indicated by the present interpretations and thosa done previously. It can be seen from these tables that the T-value for the different areas are low with exceptional higher values.

4.2.1. Porosity systems

Kruseman & de Ridder (1991) identified three porosity systems as can be seen in Figure 16.

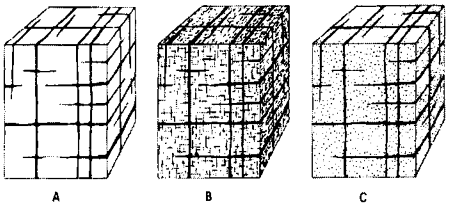


Figure 16: Porosity Systems

(a) Single porosity systems occurs where fractures can be orientated in three main directions that cut the rock into blocks. Theoretically, the primary porosity of a dense solid rock may be zero and the matrix of the rock will be impermeable.

(b) Micro-fissured system which in some rocks notably crystalline rocks the main fractures are accompanied by a dense system of micro-fissures, which increases the porosity of the rock matrix.

(c) Double porosity systems occur where two types of porosities co-exist; that is the primary porosity (matrix porosity) and the secondary porosity (fracture porosity).

The micro-fissured system has been adopted for this region because the data plots (i.e. log-log and semi-log plots) shows that a fracture network as well as a matrix exists. The matrix comprises micro-fissures and stores most of the water, which get transmitted by the large fractures. Table 10 gives an indication of the different porosities for various crystalline rocks.

Crystalline Rocks	**Porosity (%)**
Fractured Crystalline rocks	0 - 10
Dense Crystalline rocks	0 – 5
Basalt Crystalline rocks	3 - 35
Weathered Granite	34 - 57
Weathered Gabbro	42 - 45

Table 11: The porosities of Crystalline rocks (Kruseman and de Ridder, 1991).

After identifying the type of system, the intrinsic properties of the aquifer should be determined; that is, the ability of the aquifer to transmit and store water. The larger fractures have a high transmissivity and a low storativity, whereas the microfissures or matrix have a low transmissivity and a high storativity. Water moves from one point to another under the influence of hydraulic gradient. Therefore, water will flow from the microfissures into the fractures if there is pressure difference.

4.2.2. Concept of Hydraulic Connectivity

Hydraulic connectivity gradients exist due to hydraulic and physical boundaries. As can be seen in the interpretation of pump testing data of the pumping and observation holes. When the data shows a drop in drawdown of both holes a hydraulic connectivity gradient exist between the two holes. If drawdown only increases or drops in the pumping hole and no effects are seen in the observation hole a hydraulic connectivity contrast is likely to exist. This contrast indicates two different hydraulic systems or aquifers, which can occur only a few meters apart when dealing with a fractured aquifer.

Data that were collected at eight boreholes (four pumping and four observation boreholes) in the Buffelsrivier, Garies and Spoegrivier regions allowed an understanding of the aquifer systems in terms of its hydraulic connectivity. This gives an idea of the groundwater flow pattern as well as aquifer parameters such as transmissivity and storativity.

The data at Garies and Spoegrivier were collected recently, whilst the data collected at Buffelsrivier are old data collected by Toens and Partners.

4.2.2.1 Garies (G45779)

The rates selected for the step test was too high and had to be reduced. The constant discharge test only lasted for 18 hours at a lowered pumping rate of 1.2 l/s, which gave 40 litres in 33 seconds. After 18 hours the water level dropped to 79.74 mbgl almost reaching the pump that has been installed at 82 meters.

There seemed to be very little hydraulic connectivity between the pumping borehole and the observation borehole because there is a constant drop in the water level of the pumping borehole, while the observation borehole show a constant water level of 0.44 meters for the first 2 hours after which it dropped only 0.1 meters in the next 16 hours. This indicates that the system comprises a complex, heterogeneous fracture network that has a very low hydraulic connection to other transmissive material. In this case, use of observation borehole data would result in unrealistic high T values.

In 18 hours the borehole had recovered to 32.94 mbgl, which indicates a very slow recovery of the aquifer, again showing very low interconnectivity with other fractures or low transmissivity of the matrix.

4.2.2.1.1 Problems

For this spicific borehole the following difficulties were experienced:

- The placing of the observation borehole should be closer to the pumping borehole.
- To get a good estimation on aquifer parameters the observation borehole should be placed in the same aquifer system as the pumping borehole.
- Some methods only uses the data of the observation hole and therefore it should be hydraulically connected to the pumping hole to make valid conclusions and calculations.

- The rates for the pumping tests were too high, probably starting off with lower rates such as 0.5, 1, 1.5, would have been preferable.

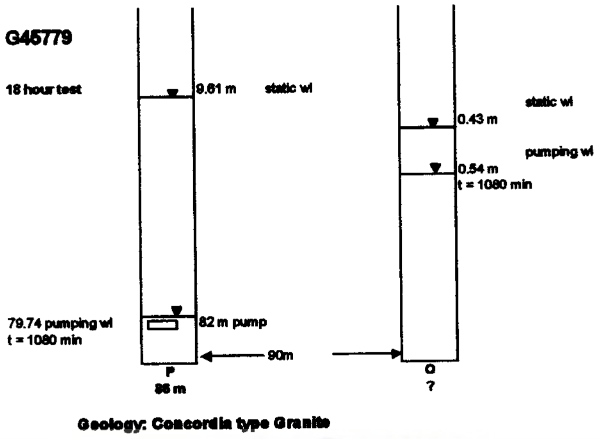


Figure 17: Logs of the pumping and observation boreholes at Garies (G45779)

4.2.2.2 Garies (G45781)

The rates selected for the step test was too high and they had to reduced to 1 l/s. A 72-hour constant discharge test was conducted, which proved to be an efficient rate. After 72 hours the water level dropped to 31.19 mbgl.

There is a hydraulic connection between the pumping and the observation borehole. The water levels between the two boreholes have a constant difference of about 10 meters. This is an indication of the complex and intense fracturing that occurs in the area. This borehole could possibly be drilled on a fracture that is interconnected with a matrix that feeds the fracture so that the system is in equilibrium (that is the outflow equals the inflow).

The borehole recovered to 5.28 meters in 72 hours, which indicates that it did not recover fully and therefore the aquifer is being dewatered. Figure 18 is an illustration of the logs for pumping and observation boreholes for Garies (G45781).

4.2.2.2.1 Problem

The correct selection of the different pumping rates during the step test is crucial. When starting off with a high pumping rate it might have to be repeated to get an efficient rate by decreasing the pump test rates.

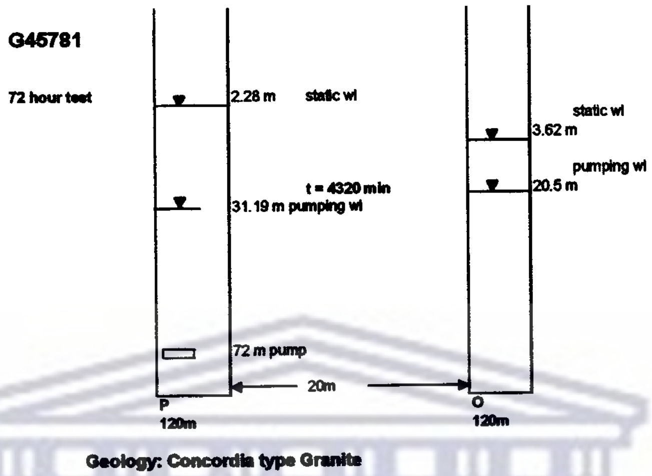


Figure 18: Logs of pumping and observation boreholes for Garies (G45781)

4.2.2.3 Spoegrivier (G 45807)

Step test started at a rate of 1l/s; if this rate was decreased it could possibly have produced better results. Looking at the performance of the borehole during pumping it seemed like it would not have been a very productive borehole.

The rest water level for the observation borehole was 3.62 meters below surface. The observation borehole has not been affected by the pumping, i.e. (at 840 minutes water level for the pumping borehole was at 96.89 meters while for the observation borehole it was at 4.11 meters. The water level in the pumping borehole dropped during pumping, while the observation borehole showed a small in water level, illustrated in figure 19.

It is possible that the boreholes (i.e. pumping and observation) are not hydraulically connected therefore the hydrogeologic environment can be considered to be a complex system of two/more environments with different prevailing transmissivities.

If we consider the inhomogeneity of the rocks in Namaqualand (dominated by fractures and fissures), the water pumped from the pumping borehole is probably supplied via fractures, from a less transmissive matrix, causing the system to be less hydraulically connected. The two boreholes may be declared as occurring at different hydraulic system although they are sited few meters from each other and the fractures are not connected in this case to make the entire system to be uniform in terms of its hydraulic conductivity.

On recovery, the pumping borehole had not recovered well. After 960 minutes of recovery, the water level was at 34.61m and was still 22.19m from the rest water level. The observation borehole showed to recover well after 1080 minutes.

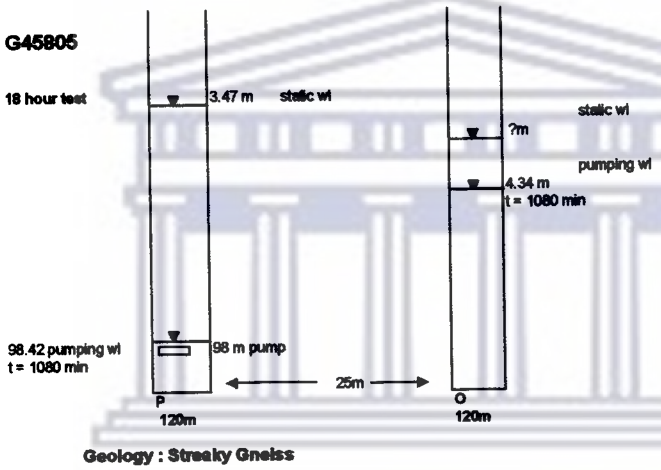


Figure 19: Logs of pumping and observation boreholes for Spoegrivier (G45805)

4.2.2.4 Buffelsrivier (KG 91-30)

The constant discharge test was carried out over 72 hours after which the drawdown was at 1.962 meters. The drawdown in the observation borehole showed a slow response of 0.426 meters after the pumping test was completed.

The observation borehole is approximately 11.5 meters from the pumping borehole but does not respond well to the pumping, which indicates a low hydraulic connectivity. This could be due to very low transmissive zones as opposed to high transmissive zones.

As for the recovery, both the boreholes had a quick recovery. The pumping borehole recovered fully after 17 hours and so did the observation borehole. This indicates that the observation hole has a much lower transmissivity than the pumping borehole; the observation borehole was at 0.426 and took 17 hours to recover while the pumping borehole was at 9 meters and took the same time to recover.

The test pumping data could not be interpreted. The borehole yield appears to be somewhat higher than 5 l/s, the early small increment, low yield steps are therefore not well differentiated. If higher rates e.g. 3.5, 4.5, 5 l/s, have been used the step test could have been more efficient. Even for high yielding boreholes, low rates could be used for purpose of pumping tests. Figure 20 is an illustration of the logs for pumping and observation boreholes for Buffelsrivier (KG 91-30).

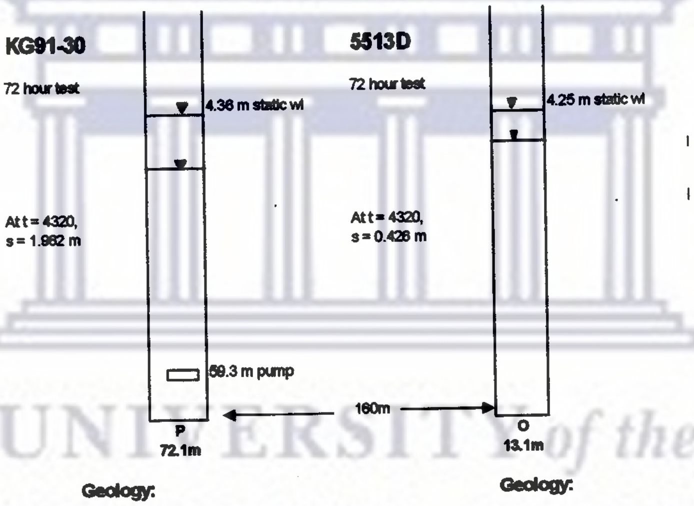


Figure 20: Logs of pumping and observation boreholes for Buffelsrivier (KG 91-30)

To determine reliable transmissivity and more importantly storativity values are problematic when the observation boreholes are not placed in the same aquifer system. To apply the methods mentioned above observation data should be used. When this is not present or useful the pumping borehole's data can be used but there are some constraints such as the correct determination of aquifer storativities.

4.2.3. Estimation of aquifer storativities

The storativity (S-value) has been determined using analytical methods such as Theis and Jacob. Most of the times only one observation borehole is used that disregards the fact that the S-value determined by the interpretation from the pumping tests become smaller as the distance of the observation borehole from the pumping borehole increase. New evidence has indicated that for large values of r, the inferred S values become unrealistically small (Bredenkamp, 1995).

When using AQUATEST for the calculation of T and S values it shows that the apparent storativity values decreasing with increasing distance from the pumping borehole, does not hold for all situations. The effective radius is the critical parameter used when determining the storativity of a borehole. It is impossible to obtain the correct S-value using data from a pumping borehole alone, unless the actual effective borehole radius is known (Kirchner and van Tonder, 1995).

When the effective radius are changed as can be seen from Figure 21 it influences the storativity values, this can be explained by the following two situations: If a borehole is drilled and pumped in an ideal situation where the aquifer is homogeneous, isotropic and fully penetrated it will be represented by a theoretical type curve. In practice these ideal conditions seldom exist and therefore corrections have to be made for the analytical equations to be used.

4.2.3.1 Positive skin effect

The skin effect is a fracture surface which is altered by mineral deposition or coating. In most cases the permeability of the skin is an order of magnitude less than that of the matrix blocks (Kirchner and van Tonder, 1995).

If the measured drawdown is more than the theoretical drawdown it can be due to positive skin effect. The skin effect causes an increase in the drawdown and has to be corrected for. Therefore, using the effective radius equal to the borehole radius the curve that would be interpreted would be the curve affected by skin.

This effect can be overcome in two ways:

- Drilling of observation boreholes so that it can give an indication of the correct drawdown by using an effective radius equal to the distance between the pumping and observation boreholes.
- If no observation boreholes are present, the effective radius can be determined by extending the theoretical drawdown curve to where it intersects with the measured drawdown. The distance from the centre of the borehole to the point of intersection will be the effective radius for the pumping borehole.

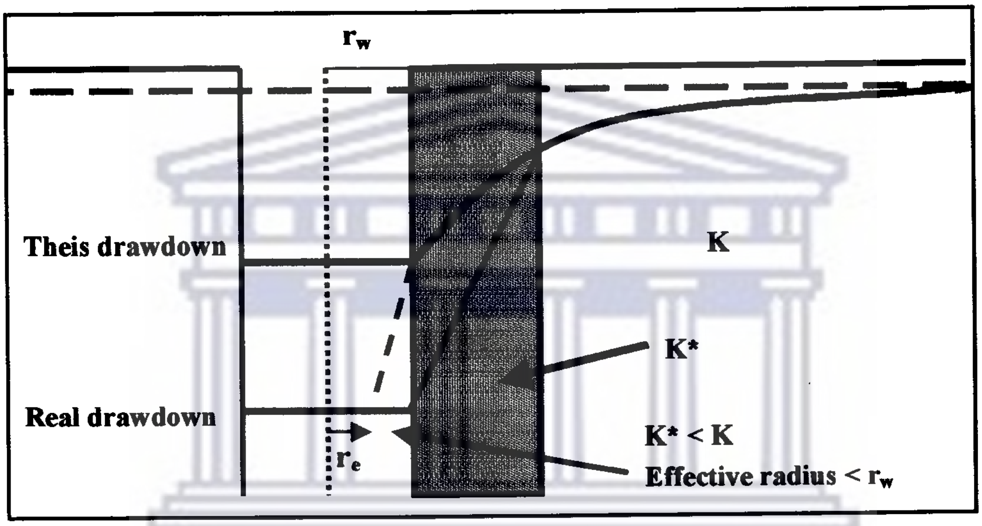


Figure 21: Positive skin effect

4.2.3.2 Negative Skin effect

If the theoretical drawdown is more than the measured drawdown it can be due to a negative skin effect caused by the presence of a fracture, figure 22. In this case the effective radius that should be used to calculate certain parameters related to the theoretical graph must be taken between the center of the borehole and any point on the measured graph so that it can give an indication of the true drawdown and not the observed drawdown.

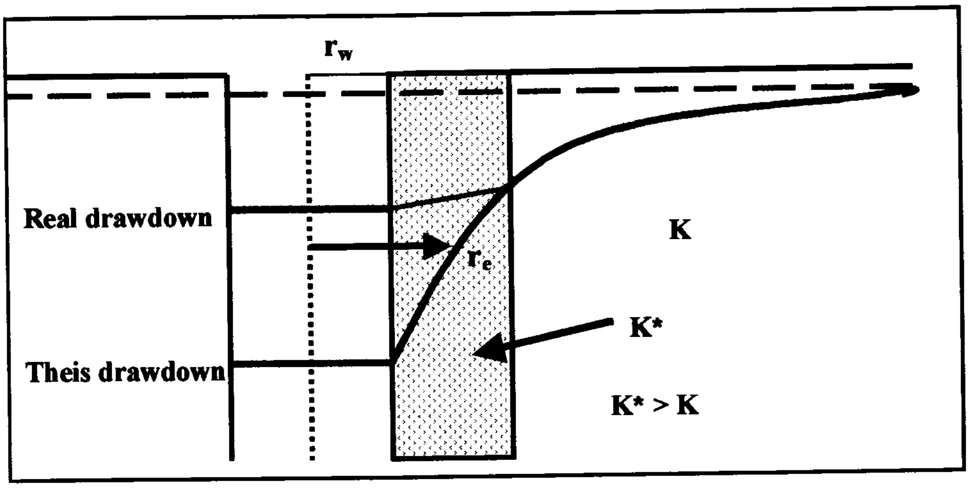


Figure 22: Negative skin effect

4.2.4. Discussion

The analytical methods used to interpret pumping tests were developed for less complicated aquifer systems. It has been proved that these methods can be applied in the study area, although we are dealing with a heterogeneous type of aquifer system.

Also, the conceptual understanding of the aquifer system is of utmost importance when determining the aquifer parameters (transmissivity and storativity). The pumping test rates to be used during step tests should be kept as low as possible when dealing with a fractured system so that the flow is horizontal.

The general assumption that storativity values decrease as the distance of an observation borehole is increased away from the pumping borehole, does not apply to all situations. Every borehole should be treated individually taking in consideration all the aspects listed above.

4.3. APPLICATIONS OF AQUATEST

4.3.1. Comparison of results between AQUATEST and FC

For the illustration of the differences in T and S values, between these two methods, pump test data collected at Paulshoek was chosen.

PROGRAM	**TOWN**	**T-VALUE (m^2/d)**	**S-VALUE**
FC	Paulshoek (G 45816)	Early – 3.27 Late – 1.32	1.43 E-02
AQUATEST		2.23	9.85 E-03

Table 12: FC and AQUATEST displays different T & S values for Paulshoek.

The average T-value for FC is 2.51 and for AQUATEST 2.23. The difference between the two is small and both values can be accepted as a relatively good estimate of the transmissivity of this aquifer. In terms of the S-value, low values could be expected due to the fractured nature of the aquifer. For fractured aquifers S-values ranges from E-4 to E-07 (Kruseman & de Ridder,1991). Therefore, the S-value calculated using AQUATEST could be seen as a better estimate for storativity of this aquifer system. A lot of emphasis should be placed on the effective radius (r_e), as mentioned previously, when calculating the S-value. For this illustration 0.08m were used as r_e , because the calculations were done using the water levels of the pumping borehole as no observation borehole was present.

The table below summarizes the transmissivity and storativity values for the two programs:

Program	**Town**	**T-Value (m^2/s)**	**S-Value**
FC	**Paulshoek (G45815)**	T (Early) = 36.72 T (Late) = 6.58	S = 6.6 E-03
AQUATEST		T = 17.03	S = 1 E-04 (r_e = 0.9m)
FC	**Paulshoek (G45820)**	T (Early) = 10.00 T (Late) = 2.06	S = 4.4 E-04
AQUATEST		T = 6.79	S = 9.8 E-04 (r_e = 0.3m)
FC	**Kamassies (91/1)**	T (Early) = 3.79 T (Late) = 1.33	S = 5.5 E-03

Cont. AQUATEST		T = 2.23	S = 9.85 E-03 (r_e= 0.08m)
FC	**Nourivier (G45839)**	T (Early) = 0.40 T (Late) = 0.35	S = 4.4 E-03
AQUATEST		T = 0.23	S = 1 E-03 (r_e = 0.19 m)
FC	**Leliefontein (?)**	T (Early) = 1.13 T (Late) = 0.57	S = 2.2 E-03
AQUATEST		T = 1.45	S = 1.5 E-03 (r_e = 0.4m)

Table 13: Summary of transmissivity and storativity values.

The transmissivity valuesdetermined for both programs do not vary a lot, whereas there are differences in the storativity values. With AQUATEST more emphasis is placed on the use of the effective radius to calculate the S-value. The different r_e -values listed in the table are determined by changing the r_e value until a close fit is established between the two curves i.e. the measured drawdown plotted against time (DD) and the calculated drawdown plotted against time (DD') in the table above. The FC program depends more on the use of the aquifer thickness for the calculation of the S-value. For hard rock aquifers a value of < 40m is recommended by this program.

4.3.2. Dealing with boundary conditions

To analyse the flow in bounded aquifers, the principle of superposition is applied. According to this principle, the drawdown caused by two or more boreholes is the sum of the drawdown caused by each separate borehole. By introducing imaginary boreholes, or image boreholes, an aquifer of finite extent can be transformed into one of seemingly infinite extent, which then allows one to use the analytical methods for interpretation of borehole data.

One of the DWAF data sets were used for a comparison between the results found by DWAF and AQUATEST in terms of T and S values. DWAF made use of the Cooper-Jacob method and Aquatest as previously mentioned makes use of the improved Cooper-Jacob method that takes in consideration boundary conditions. The T-value calculated by DWAF was 9.5 m^2/d and the S-value was 5.05 E-04. AQUATEST includes various boundary conditions or methods as can be seen in table 13 below. The middle three in table 13 is also known as the Stallman method and the last one was developed by Stretsolva in 1988.

Types of Boundaries	**T-value (m^2/d)**	**S-value**
Infinite Aquifer	8.42	3.73 E-03
Single line	8.04	5.78 E-03
Two lines at 90 D	7.64	1 E-02
Two parallel lines	7.91	6.75 E-03
Squared Barry	443970272.4	1 E-02

Table 14: Types of boundaries

There are various T and S values depending on the boundary conditions that exist. The T-value is not as sensitive to change in boundary conditions as the S-value. The closer the boundaries are to the borehole the greater the S-value, which can be ascribed to the amount of pore space that exists in the formation. Depending on what type of boundary condition is present in a particular aquifer system, the appropriate boundary condition can be chosen. If this information is not known, the parameters can always be calculated using the worse case scenario or if the interpreter has a good conceptual understanding of the aquifer system the correct boundary condition can be estimated and then used to calculate the parameters.

4.4. TOTAL WELL LOSS APPLICATION

4.4.1. Theory

(1) Determine the aquifer transmissivity from recovery data. If the recovery analysis does not produce an approximately straight line, then the conditions for the validity of equations 3.11 and 3.12 (described in chapter 3) are not satisfied and the total well loss method cannot be applied.

(2) Select a reasonable range for the well radius, $r_{w1} \leq r_w \leq r_{w2}$, and , if not known precisely, the aquifer storage coefficient, $S_1 \leq S \leq S_2$. Determine $r_w = (r_{w1} * r_{w2})^{\frac{1}{2}}$ and $S = (S_1 * S_2)^{\frac{1}{2}}$

(3) For each time during the pumping part of the test at which the drawdown was measured, calculate the well loss, L_w, using equations 3.11 and 3.12 with r_w and S determined in step 2 above.

(4) Plot L_w / Qn against Qn and fit a straight line. Determine B_2 from the intercept with the vertical axis and C from the slope.

(5) Substitute B_2 and C in the equation: $L_w = B_2 Qn + CQn^2$ to estimate the total well loss at any discharge rate.

(6) The range of the total well loss is given by the above equation with $B_2 \pm \Delta B_2 / 2$ in which ΔB_2 is defined by equation 3.14 outlined in chapter 3. Alternatively, it can be calculated for any discharge.

The graphical analysis is similar to the usual analysis of step-drawdown tests. The difference is that total well loss is considered instead of drawdown. This method is valid only for:

- confined aquifers
- Can be used with steps of any length
- Crucial to maintain steady discharge within steps.
- Total well loss should theoretically be the same in each step. Very early points may slightly be affected by well bore storage.
- Any scatter of points represents errors in measurements made during the test (Kawecki, 1995).

4.4.2. Application using AQUATEST

The total well loss can also be calculated using the AQUATEST software, which is based on the same formulae that are described above. AQUATEST calculates the $s(r_w,t)$ component which is then subtracted from the observed drawdown to calculate the total well loss. To test AQUATEST a case study was taken, which was done by Kawecki (1995). The T-value was calculated using the recovery data and equal to 424 m^2/day. A well radius was assumed to be 0.14 m, assumed the radius of the borehole multiply with twice the open hole radius to the power ½. S was taken as 1.6 E-04. With the above information and the observed drawdown data collected at this specific borehole the total well loss can be calculated.

The following table represents the calculated total well loss which was done by Kawecki (1995). A comparison was made between the case study of Kawecki (1995) and AQUATEST. It was found that it makes use of almost exactly the same principles, except that the Kawecki is making use of the Cooper-Jacob method and AQUATEST makes use of the improved Cooper-Jacob method as outlined earlier in this thesis. After the comparison, the method is applied to 3 sites for the calculation of the total well loss component.

Time (min)	s_w (m)	L_w (m)	Time (min)	s_w (m)	L_w (m)
2	43.26	33.86	67	18.39	13.59
4	49.80	39.89	68	18.02	13.27
6	51.74	41.76	70	17.36	12.70
8	52.68	42.52	75	17.05	12.54
10	53.40	43.09	80	17.31	12.89
12	54.40	43.96	85	16.70	12.34
15	55.24	44.64	90	16.60	12.29
20	57.10	46.30	95	16.65	12.38
25	58.32	47.37	100	16.65	12.41
30	59.17	48.09	105	16.64	12.42
35	60.10	48.91	110	16.65	12.45
40	60.95	49.66	115	16.74	12.55
45	61.50	50.13	120	17.09	12.91
51	62.14	50.69	122	28.66	12.48
55	62.68	51.18	123	31.08	24.29
60	63.18	51.61	124	31.75	24.92
62	21.78	16.43	125	31.97	25.11
64	18.71	13.67	126	32.13	25.24

Table 15: Summary of the total well loss as calculated by Kawecki, 1995.

The above data taken from Kawecki (1995) is used to test AQUATEST software for total well loss application. When applying the same T, S, effective radius and observed drawdown data to AQUATEST the following results were obtained. As can be seen below the L_w component in the two tables compare well. When comparing the first two terms the difference between the two is 0.06 meters.Therefore, AQUATEST can be used to calculate the total well loss in a borehole as will be illustrated using three sites: Garies, Komaggas and Buffelsrivier.

Time (min)	s_w (m)	L_w (m)	Time (min)	s_w (m)	L_w (m)
2.00	43.26	33.92271	68.00	18.02	13.53736
4.00	49.80	39.9655	70.00	17.36	12.92558
6.00	51.74	41.85734	75.00	17.05	12.70501
8.00	52.68	42.60404	80.00	17.31	13.02664
10.00	53.40	43.17166	85.00	16.70	12.46146
12.00	54.40	44.04635	90.00	16.60	12.39522
15.00	55.24	44.73238	95.00	16.65	12.47126
20.00	57.10	46.39325	100.00	16.65	12.4917
25.00	58.32	47.45847	105.00	16.64	12.49795
30.00	59.17	48.18186	110.00	16.65	12.52097
35.00	60.10	49.00473	115.00	16.74	12.62146
40.00	60.95	49.7619	120.00	17.09	9.773545
45.00	61.50	50.22998	122.00	28.66	21.79011
51.00	62.14	50.78291	123.00	31.08	24.19696
55.00	62.68	51.27038	124.00	31.75	24.85265
62.00	21.78	17.06565	125.00	31.97	25.05856
64.00	18.71	14.09375	126.00	32.13	25.20509
67.00	18.39	13.87941			

Table 16: L_w calculated using AQUATEST

The L_w component for the two methods compare well and therefore we can apply this method using AQUATEST to calculate the total well loss for the Namaqualand data. The total well loss is an important parameter to calculate when determining the correct drawdown of a borehole.

4.4.3. Application to Namaqualand data

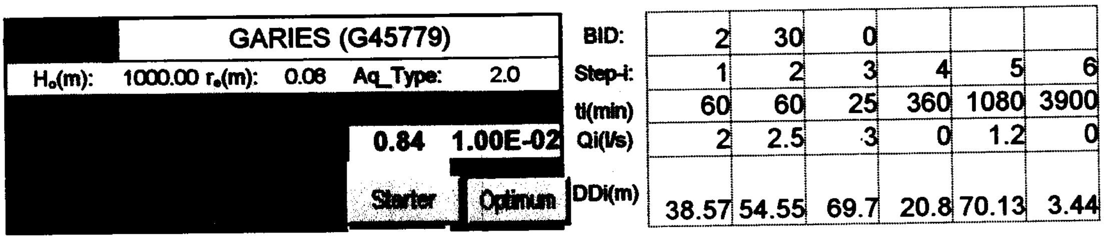
Three sites were chosen to apply the above mentioned method to, namely Garies, Komaggas and Buffelsrivier. Steps to follow using AQUATEST are as follows:

1. Calculate the T-value using the recovery method.
2. By keeping the T-value constant, calculate the S-value over the whole pumping activity .
3. If boundary conditions are known choose the appropriate method.
4. For these specific T and S values calculate, using AQUATEST, the total well loss by subtracting the measured drawdown from the theoretical drawdown..

4.4.3.1 Garies

The T-value was calculated using AQUATEST, this is done by specifying the part of the data that is of interest. Both the step test recovery and the constant test recovery data was used for the calculation and the average of the two values was taken as the T-value (0.84 m^2/d). The S-value (1E-02) is calculated over the whole pumping activity, that is the step test, recovery after step, constant test and recovery after constant. At this specific site the pumping borehole (G45779) data had to be used because observation borehole (G45778) was not hydraulically connected to the pumping borehole. The distance between these two boreholes was 90 m, and because of the heterogeneity of the aquifer system the boundary condition could be at any point between the boreholes. Therefore, the aquifer is not of infinite areal extent and the Theis method cannot be applied. Instead the single line method of Stallman was applied using AQUATEST. For this specific borehole the S-value calculated using Theis and the one calculated using Stallman was exactly the same.

The measured drawdown and the theoretical drawdown is then used to calculate the total well loss as illustrated in equation 3.11 and 3.12. As can be seen from table 16 below, the total well loss calculated for Garies are negative. This is in actual fact a negative skin effect, where the theoretical drawdown is more than the observed drawdown due to the fractured nature of these rocks.



GARIES (G45779)		
H_o(m): 1000.00	r_e(m): 0.08	Aq_Type: 2.0
0.84	1.00E-02	

BID:	2	30	0			
Step-i:	1	2	3	4	5	6
ti(min)	60	60	25	360	1080	3900
Qi(l/s)	2	2.5	3	0	1.2	0
DDi(m)	38.57	54.55	69.7	20.8	70.13	3.44

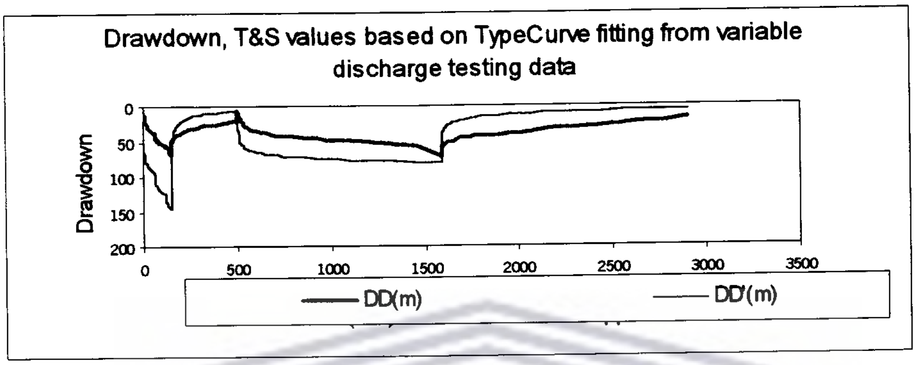


Figure 23:T, S & L_w calculations using step test, constant test and recovery data for Garies.

As can be seen from the diagram above there were six steps involved which includes the recovery. The effetive radius was taken as the radius of the pumping borehole which was 0.08 m.

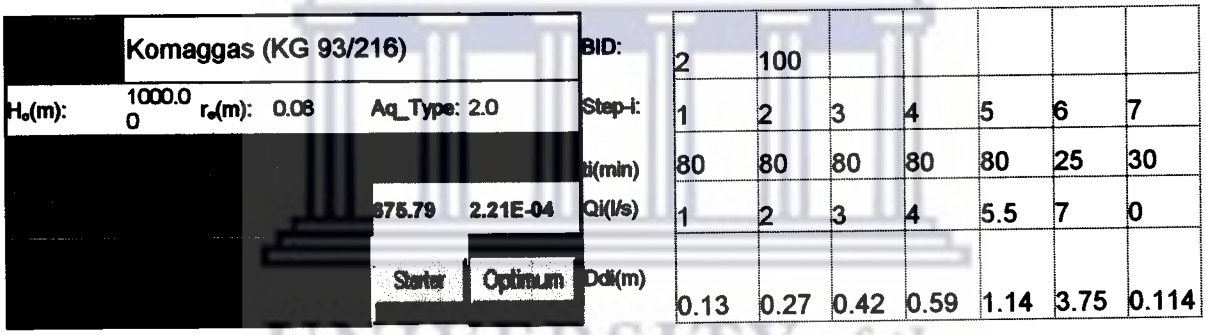
Total well loss **cont. (1)** **cont. (2)**

Total well loss
-44.88
-53.46
-58.03
-62.79
-65.52
-66.60
-67.77
-68.05
-67.72
-67.97
-68.20
-68.80
-69.98
-71.10
-81.01
-82.95
-83.67
-84.56
-85.27
-85.95
-86.87
-87.14
-87.25
-87.53
-87.86
-87.87
-88.89
-90.05
-99.09
-101.06
-102.07
-103.47
-104.74
-105.68
-106.78
-107.75
-103.37
-99.79
-48.53
-35.37
-27.90
-20.85
-15.15
-10.81
-6.03
-2.53
1.90
4.82
7.20
10.04
11.96
12.53
13.68
14.50
14.57
14.75

Table 17: Total well loss for Garies (45779)

4.4.3.2 Komaggas

Only step test and step recovery data were available for the pumping borehole (KG 93/216) and the obseravtion borehole (KG 93/217). The T-value was calculated the same way as mentioned above with a value of 675.79 m^2/d. The S-value was also calculated in the same way as mentioned above. The S-value using Theis differed from the S-value using the Stallman method (100 m), which illustrates the importance of boundary conditions and its effects on the storativity parameter. For Theis a S-value of 1E-04 was calculated and for the Stallman method a S-value of 2.21E-04 was calculated. There is not a vast difference between the two answers but the closer the estimate the less error in the final calculation of the sustainable yield of an aquifer system. These two parameters are then kept constant while determining the well loss of the borehole, as illustrated in table 17 below.



Komaggas (KG 93/216)

H_o(m): 1000.00 r_e(m): 0.08 Aq_Type: 2.0

675.79 2.21E-04

BID:	2	100					
Step-i:	1	2	3	4	5	6	7
ti(min)	80	80	80	80	80	25	30
Qi(l/s)	1	2	3	4	5.5	7	0
Ddi(m)	0.13	0.27	0.42	0.59	1.14	3.75	0.114

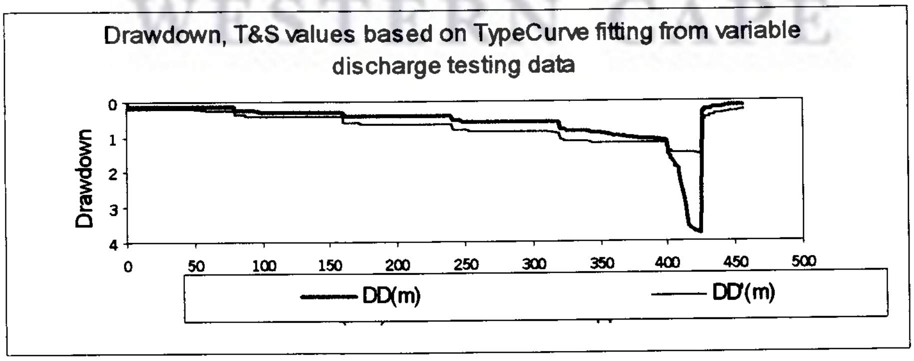


Figure 24: T, S & L_w calculations using step test, constant test and recovery data for Komaggas

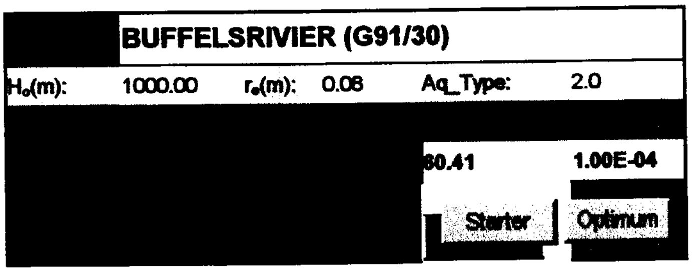
The T-recovery is kept constant, while using the Stallman method that includes a single boundary condition solves S. The pumping activity included 7 steps with the recovery data. Again a negative well loss was encountered due to the fractured nature of the rocks.

Total well loss	**cont. (1)**	**cont. (2)**
-0.06	-0.08	-0.13
-0.06	-0.07	-0.12
-0.05	-0.07	-0.13
-0.05	-0.08	-0.14
-0.06	-0.14	-0.14
-0.06	-0.13	-0.15
-0.06	-0.14	-0.15
-0.07	-0.14	-0.16
-0.07	-0.13	-0.19
-0.06	-0.14	-0.19
-0.06	-0.11	-0.19
-0.07	-0.11	-0.19
-0.07	-0.12	-0.19
-0.06	-0.12	-0.20
-0.06	-0.12	-0.20
-0.06	-0.12	-0.20
-0.06	-0.13	-0.21
-0.07	-0.13	-0.21
-0.07	-0.13	

Table 18: Total well loss for Komaggas (KG 93/216)

4.4.3.3 Buffelsrivier

All step, constant and recovery data were available for the interpretation. The pumping borehole (KG 91/30) and observation borehole (5513D) were used for the data collection. The T-value calculated was 60,41 m^2/d and the S-value was 1E-04. The distance between these two boreholes is 160 m. As mentioned previously, the area is characterised by heterogeneity, therefore the exact distance to boundary is dubious. The results are illustrated below in Figure 25 and table 18.



BUFFELSRIVIER (G91/30)

H_o(m): 1000.00 r_e(m): 0.08 Aq_Type: 2.0

80.41 1.00E-04

BID:	1	0	0						
Step-i:	1	2	3	4	5	6	7	8	9
ti(min)	60	60	60	60	60	60	120	4320	900
Qi(l/s)	0.714	1.09	1.47	1.98	2.68	5.2	0	0.4	0
Ddi(m)	0.24	0.47	0.69	0.78	1.1	1.68	0.1	1.962	0.03

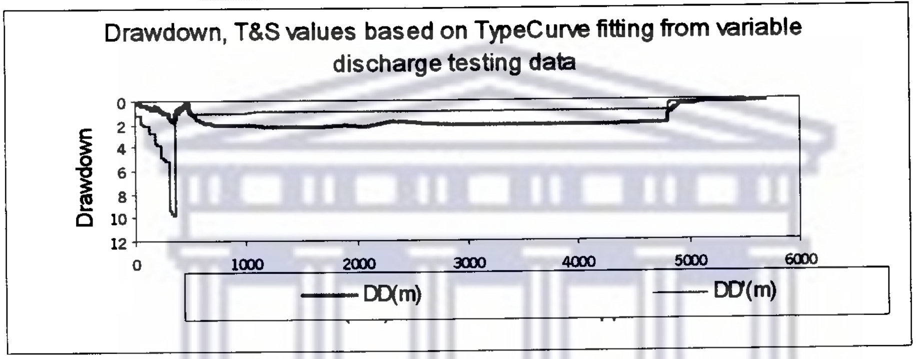


Figure 25: T, S & L_w calculations using step test, constant test and recovery data for Buffelsrivier

Total well loss
-0.84
-0.89
-0.92
-0.94
-0.96
-0.98
-1.00
-1.02
-1.03
-1.04
-1.05
-1.04
-1.05
-1.07
-1.07
-1.08
-1.09
-1.09
-1.09
cont. (1)
-1.08
-1.06
-1.54
-1.55
-1.56
-1.56
-1.57
-1.58
-1.58
-1.58
-1.59
-1.59
-1.60
-1.59
-1.60
-1.60
-1.60
-1.61
-1.58
cont. (2)
-1.60
-1.59
-1.57
-1.57
-2.03
-2.05
-2.06
-2.06
-2.07
-2.08
-2.09
-2.10
-2.11
-2.11
-2.11
-2.11
-2.10
-2.10

Table 19: Total well loss for Buffelsrivier (KG91/30)

4.4.3.4 Discussion

The total well loss is, as proven above, a meaningful indicator of well performance. When using this method the advantage is that any stepped pumping pattern can be used and any observed flunctutions in discharge during the steps can be treated as additional steps. This method is successful because the calculations are insensitive to the true well radius and aquifer storage coeficient.

All three sites, that is Garies, Komaggas and Buffelsrivier revealed a negative total well loss. For this type of formation it is expected, due to the fractured nature of the rocks. In this case the theoretical drawdown is more than the observed drawdown which is due to a negative skin effect. This skin effect is caused by the presence of fractures which increases the theoretical drawdown. Ultimately, this tool is crucial to the calculation of the correct drawdown in a borehole. The drawdown is one of the most essential parameters used in all of the above calculations.

5. RECOMMENDATIONS AND CONCLUSIONS

5.1. CONCLUSIONS

Various factors, as can be seen above, influences the end result of a pumping test. It can be influenced right from the start, which is the construction of a borehole. One of the main influences on the pumping tests is whether the borehole is fully penetrating or not. This controls the flow to a well, which can either be both vertical and horizontal flow, or as required from the methods only horizontal flow for a fully penetrating well.

Also, the placing of the pump can play an important role in the amount of water that can be extracted from the aquifer. In the study area the pump is usually placed at the maximum distance the lenght of pipes that can fit into the borehole. Also to be kept in mind is that it cannot be placed right at the bottom of the borehole due to the uptake of silt and sand particles that can damage the pump.

The drilling of observation boreholes is an important factor because the existing methods can only be applied to data collected from these boreholes. The position where the observation borehole is placed is also critical. If the two boreholes, i.e. the pumping borehole and the observation borehole do not show interaction, the data cannot be applied to the methods. It could be a solution to a lot of 'problems' if a pumping test is conducted with a pumping as well as an observation borehole. If the observation borehole is placed in the same aquifer system, which should be relatively close to the pumping borehole due to extremely heterogeneous aquifer type, the data collected for the observation borehole can be used and better T & S estimates can be calculated. Therefore, it will result in more effective sustainable yield calculations. Because in some instances merely the pumping borehole data are used it could contribute to the fact that boreholes in the study region does not generate water for a long enough period.

The other difficulty encountered in the Namaqualand area is the fact that most of these boreholes have low yields and when recommending a low abstraction rate the towns may not receive enough water. This can lead to another situation, i.e. the people vs. the aquifer system, where one has to make a choice between: 1) whether the aquifer has to be mined to see to the needs of the people or, 2) if the water in the aquifer is going to be used sustainably. With all these difficulties that exist, it is better to make your calculations on the data collected from the observation boreholes so that if choices like the above-mentioned have to be made the current situation is known in terms of water supply and therefore the life-span can be estimated.

Most of the methods can be applied to the study area provided one has a good conceptual understanding of the aquifer system and its hydraulic characteristics; as well as an understanding of the methods. The interpreters of the data should be present on site to improve the conceptual understanding of the aquifer system. Arial photographs, satellite images, topographic maps etc. should be of secondary importance and not primary especially in areas that are unknown with respect to this field.

Consultants should ensure that the pump testing are carried out reliably. If the data is unreliable the results will also be unreliable.

5.2. RECOMMENDATIONS

The methods outlined in this thesis can be applied to fractured rock environment if used with utmost caution. As summarized, these methods cannot be used directly, as conceptual models have to be established before attempting any interpretation phase. In terms of hydraulic connectivity gradients and contrasts, it has been proven that the nature of the fractured crystalline aquifer system is very complex due to heterogeneity. One important condition for the application of these methods is the use of observation borehole data. Once a hydraulic connectivity contrast exist between a pumping and observation borehole other options have to be investigated.

Such contrasts exist due to skin effects, which has a direct effect on the drawdown within a borehole. This plays an important role when calculating the aquifer parameters. When calculating the storativity component, which may be distance dependent, the effective radius has to be determined. The manner in which this should be done is outlined in the thesis. Also, the skin effect can be eliminated by determining the total well losses. This is crucial for the correct determination of the T and S-values. Boundary conditions found in this type of environment is included when doing all the necessary calculations. AQUATEST is suggested as an excellent software package, which can address and solve most of the above-mentioned problems.

In short the following are important considerations:

- Identify the type of aquifer system.
- Develop a good conceptual understanding of the aquifer system.
- Choose applicable method for interpretation.
- Data should be collected form both the pumping and observation boreholes.
- Where possible the observation boreholes should be placed in the same aquifer system as the pumping borehole.
- The pump test data should be collected by a reliable source.
- Apply the chosen method to the collected data.

5.3. FLOW CHART: DETERMINING CORRECT SUSTAINABLE YIELD

Pumping tests have two purposes: 1) To obtain aquifer parameters T and S and,

2) To derive sustainable yield. To facilitate the derivation of sustainable yield the following functional chart is proposed, figure .

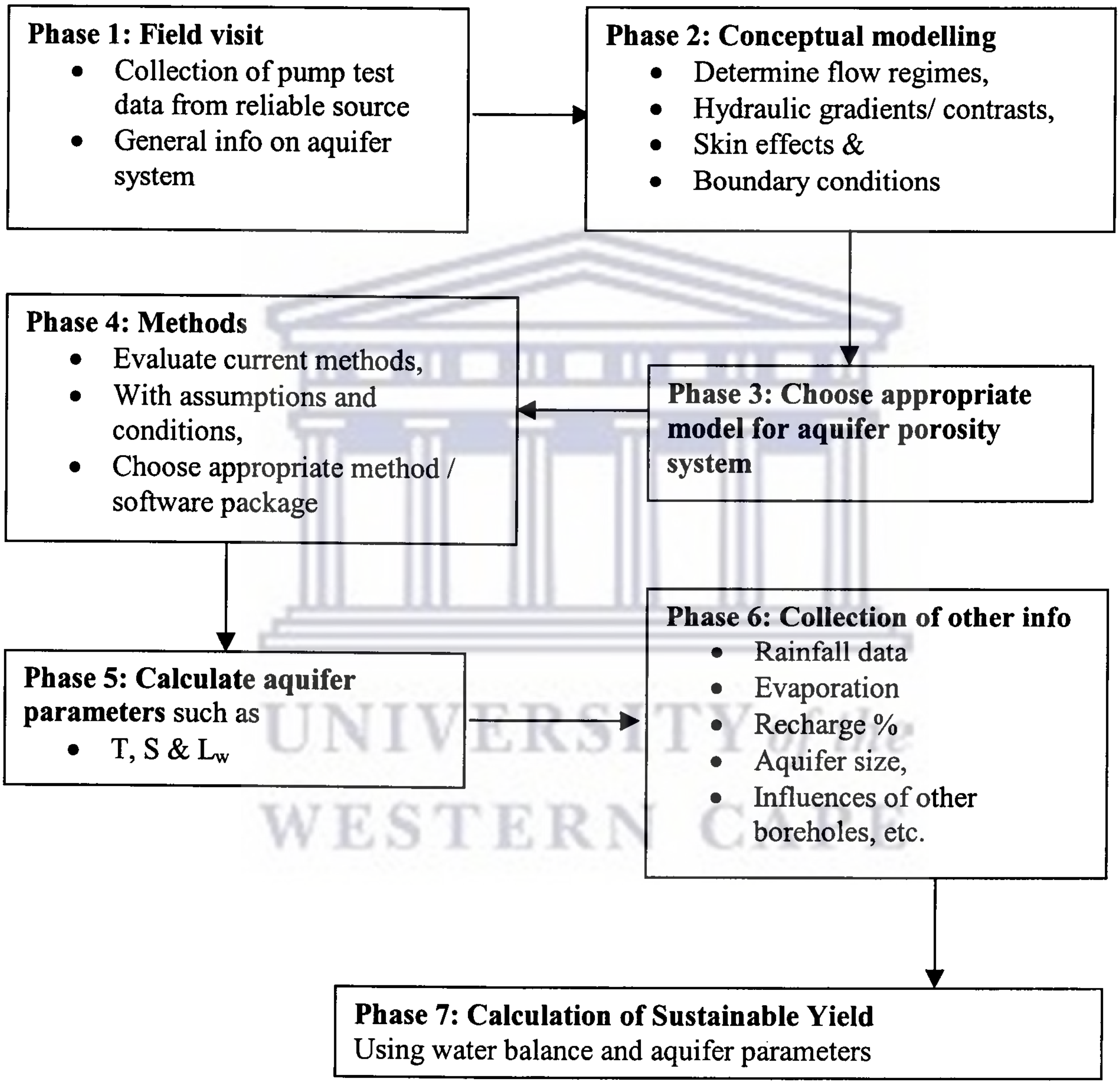


Figure 26: Proposed steps for the determination of sustainable yield.

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APPENDIX

(Pumping Test Data)

KG 93/114 **30/01/94**

Borehole depth	87m
Supervisor	Rory
Datum	0.48m
Water level	23.95m
Pump depth	80m

	STEP 1(0.52 L/S)	STEP 2 (1.15 L/S)	STEP 3 (2.2 L/S)
	150 RPM	290 RPM	580 RPM
Time	Drawdown	Drawdown	Drawdown
0.5	0.78	2.71	6.86
1	1.01	3.04	7.77
1.5	1.19	3.3	8.45
2	1.34	3.51	8.96
2.5	1.44	3.69	9.37
3	1.53	3.86	9.69
4	1.65	4.09	10.24
5	1.74	4.28	10.63
6	1.8	4.4	10.89
7	1.85	4.51	11.09
8	1.89	4.67	11.22
9	1.92	4.7	11.29
10	1.95	4.93	11.34
12	1.99	5.18	11.5
15	2.05	5.41	11.65
20	2.1	5.57	11.8
25	2.18	5.65	11.9
30	2.22	5.71	11.97
40	2.32	5.8	12.18
50	2.38	5.9	12.39
60	2.43	5.99	12.43

STEP 4 (3 L/S)	STEP 5 (4.5L/S)	**Recovery**		
800 RPM	1040 RPM			
Drawdown	Drawdown	Time		Residual Drawdown
13.12	18.32	0.5	15.3	46.44
13.82	19.55	1		39.32
14.41	20.32	1.5		32.76
14.86	21.58	2		26.46
15.2	23.77	2.5		20.77
15.48	26.07	3		17.06
15.9	27.7	4		11
16.18	33.56	5		7.45
16.35	36.77	6		5.4
16.45	39.74	7		4.22
16.66	42.54	8		3.52
16.79	45.12	9		3.06
16.85	47.53	10		2.79
16.94	52.4	12		2.45
17.08	53.15 pump	15		2.15
17.08		20		1.81

17.08
17.08
17.54
17.54
17.54

25		1.67
30		1.52
40		1.37
50		1.25
60		1.17
70		1.09
80		1.05
90		1.01
100		0.99
120		0.95
150		0.87
200		0.8
250		0.76
300	5.15	0.72
840		

Constant Discharge
1.5l/s

01/02/94

Time	Drawdown
0.5	2.55
1	3.35
1.5	4.02
2	4.55
2.5	5.01
3	5.38
4	5.88
5	6.38
6	6.77
7	7
8	7.23
9	57.54
10	7.72
12	8.01
15	8.46
20	8.79
25	8.9
30	8.9
40	8.9
50	9.14
60	9.27
70	9.35
80	9.47
90	9.52
100	9.58
120	10.03
150	10.3
200	10.5
250	10.65
300	10.89
400	11
500	11.39

Recovery after CDT

04/02/94	3.77m
05/02/94	2.71m
06/02/94	1.85m
07/02/94	1.39m
08/02/94	1.16m

Monitoring borehole **KG 93/113**
1400m from pmping hole
Datum top of casing

Date	**Drawdown**
29/01/94	0
01/02/94	0
02/02/94	0
03/02/94	0

600	11.5
700	11.54
800	11.58
900	11.67
1000	11.88
1100	12.04
1200	12.29
1300	12.41
1400	12.54
1440	12.73
1500	12.91
1600	13.13
1700	13.26
1800	13.48
1900	13.69
2000	13.91
2100	14.13
2200	14.4
2300	14.7
2400	14.99
2500	15.19
2600	15.4
2700	15.61
2800	15.7
2880	15.85

KG 93/113 **04/02/94**

Borehole depth	89m
Supervisor	Rory
Datum	0.46m
Water level	25.84m
Pump depth	51m

	STEP 1(1.1 L/S) 160 RPM	STEP 2 (2.1 L/S) 320 RPM	STEP 3 (4.2 L/S) 600 RPM	STEP 4 (7.7 L/S) 1080 RPM
Time	Drawdown	Drawdown	Drawdown	Drawdown
0.5	0.76	2.31	5.35	10.35
1	0.79	2.45	5.83	11.51
1.5	0.82	2.53	5.99	12
2	0.84	2.58	6.21	12.32
2.5	0.86	2.63	6.34	12.59
3	0.88	2.69	6.46	12.79
4	0.95	2.83	6.68	13.13
5	1	2.93	6.86	13.44
6	1.05	3	7.02	13.89
7	1.08	3.06	7.12	13.93
8	1.12	3.1	7.18	14.07
9	1.16	3.15	7.25	14.28
10	1.18	3.21	7.35	14.51
12	1.2	3.3	7.52	14.93
15	1.26	3.41	7.74	15.29
20	1.35	3.53	8.03	15.85
25	1.41	3.67	8.27	16.31
30	1.48	3.78	8.48	16.64
40	1.69	3.96	8.84	17.15
50	1.83	4.14	9.1	17.97
60	1.95	4.3	9.37	18.6

Recovery

Time	Residual Drawdown
0.5	15.25
1	13.98
1.5	13.41
2	13
2.5	12.57
3	12.32
4	11.9
5	11.5
6	11.13
7	10.74
8	10.39
9	10
10	9.71
12	9.21
15	8.72
20	7.65
25	7.09
30	6.41

40		5.81
50		5.21
60		4.93
70		4.68
80		4.47
90		4.32
100		4.21
120		3.95
150		3.63
200		3.24
250		2.96
300		2.69
840	next morn 7h45	1.29

Constant Discharge **05/02/94**

1.5l/s **Recovery after CDT**

Time	Drawdown	Time	Residual Drawdown
0.5	1.79	0.5	6.25
1	1.86	1	6.12
1.5	1.94	1.5	6.03
2	1.99	2	5.97
2.5	2.05	2.5	5.92
3	2.09	3	5.88
4	2.14	4	5.84
5	2.19	5	5.8
6	2.23	6	5.76
7	2.28	7	5.73
8	2.32	8	5.71
9	2.35	9	5.69
10	2.38	10	5.67
12	2.42	12	5.63
15	2.5	15	5.58
20	2.57	20	5.5
25	2.65	25	5.44
30	2.72	30	5.39
40	2.82	40	5.31
50	2.93	50	5.23
60	3.01	60	5.16
70	3.09	70	5.1
80	3.14	80	5.05
90	3.2	90	5.01
100	3.26	100	4.94
120	3.39	120	4.82
150	3.52	150	4.92
200	3.71	200	4.51
250	3.87	250	4.35
300	4.05	300	4.14
400	4.27	400	3.93
500	4.48	500	3.75
600	4.68	600	3.57

700	4.88	700	3.42
800	5.05	800	3.23
900	5.17	900	3.06
1000	5.25	1000	
1100	5.42		
1200	5.55		
1300	5.64		
1400	5.66		
1440	5.69		
1500	5.75		
1600	5.83		
1700	5.94		
1800	5.98		
1900	6.04		
2000	6.11		
2100	6.18		
2200	6.23		
2300	6.33		
2400	6.42		
2500	6.49		
2600	6.53		
2700	6.6		
2800	6.65		
2880	6.7		

KG 93/111 **27/01/94**

Borehole depth	138.74m
Supervisor	Rory
Datum	0.46m
Water level	3.42m
Pump depth	87m

	STEP 1(0.22 L/S) 60 RPM	STEP 2 (0.46 L/S) 120 RPM	STEP 3 (0.92 L/S) 210 RPM
Time	Drawdown	Drawdown	Drawdown
0.5	0.1	2.07	5.14
1	0.13	2.26	5.44
1.5	0.28	2.41	5.52
2	0.41	2.52	5.6
2.5	0.51	2.63	5.66
3	0.65	2.74	5.9
4	0.8	2.91	6.12
5	0.92	3.07	6.39
6	1.02	3.24	6.71
7	1.09	3.33	7.05
8	1.15	3.44	7.29
9	1.22	3.54	7.55
10	1.29	3.64	7.76
12	1.38	3.78	8.16
15	1.48	3.96	8.52
20	1.63	4.18	9.07
25	1.71	4.34	9.42
30	1.76	4.46	9.76
40	1.86	4.67	10.39
50	1.95	4.85	10.91
60	1.96	4.97	11.24

STEP 4 (1.2 L/S) 300 RPM	STEP 5 (1.7L/S) 480 RPM	**Recovery**	
Drawdown	Drawdown	Time	Residual Drawdown
11.37	21.6	0.5 14h00	47.55
11.4	21.9	1	45.65
11.42	22.21	1.5	43.67
11.45	22.49	2	41.94
11.47	22.8	2.5	40.02
11.5	23.02	3	38.76
11.53	23.6	4	36.39
11.53	24.3	5	33.11
11.54	25.09	6	31.57
11.55	25.82	7	29.2
11.56	26.4	8	27.15
11.57	27.1	9	25.28
11.65	27.64	10	23.31
12.48	28.61	12	19.9
13.59	29.78	15	15.55
15.56	31.18	20	11.6
16.98	32	25	10.26
18.07	32.31	30	9.12

19.61	32.32	40		7.09	
20.82	39.11	50		5.85	
21.46	49.64	60		5.24	
		70		4.68	
		80		4.27	
		90		4.03	
		100		3.78	
		120		3.44	
		150		3.05	
		200		2.57	
		250		2.22	
		300	05h00	1.96	
			next morn	0.82	06H00
				0.77	10H00

Constant Discharge **28/01/94**

0.62l/s **Recovery after CDT**

Time	Drawdown	Time	Residual Drawdown
0.5	1.12	0.5	12.58
1	1.46	1	12.16
1.5	1.74	1.5	11.77
2	1.96	2	11.6
2.5	2.15	2.5	11.58
3	2.35	3	11.58
4	2.67	4	11.43
5	2.95	5	11.09
6	3.23	6	10.81
7	3.46	7	10.57
8	3.66	8	10.29
9	3.9	9	10.07
10	4.08	10	9.88
12	4.38	12	9.58
15	4.82	15	9.21
20	5.34	20	8.53
25	5.67	25	8.09
30	5.98	30	7.68
40	6.23	40	6.76
50	6.65	50	6.07
60	6.94	60	5.68
70	7.16	70	5.41
80	7.35	80	5.2
90	7.56	90	5.02
100	7.75	100	4.85
120	8.06	120	4.62
150	8.47	150	4.31
200	9.12	200	3.97
250	9.63	250	3.63
300	9.99	300	3.39
400	10.71	400	3.05
500	10.99	500	5.82
600	11.33	600	2.66
700	11.6	700	2.56
800	11.85	800	2.45
900	12	900	2.28

1000	12.22	1000	2.18
1100	12.39		
1200	12.58		
1300	12.79		
1400	13.04		
1440	13.13		

KG 93/106 **04/03/94**

Borehole depth	141m
Supervisor	Rory
Datum	0.43/8m
Water level	17.35m
Pump depth	72m

	STEP 1(0.45 L/S) 162 RPM	STEP 2 (1.08 L/S) 310 RPM	STEP 3 (2.11 L/S) 550 RPM
Time	Drawdown	Drawdown	Drawdown
0.5	0.23	1.14	2.79
1	0.3	1.29	3.15
1.5	0.35	1.47	3.42
2	0.39	1.49	3.59
2.5	0.42	1.55	3.75
3	0.46	1.6	3.87
4	0.5	1.67	4.08
5	0.54	1.75	4.29
6	0.56	1.81	4.46
7	0.59	1.86	4.68
8	0.62	1.91	4.77
9	0.63	1.94	4.89
10	0.64	1.98	5
12	0.66	2.03	5.23
15	0.69	2.1	5.41
20	0.73	2.18	5.5
25	0.77	2.26	5.54
30	0.81	2.32	5.59
40	0.88	2.42	5.63
50	0.92	2.5	5.74
60	0.96	2.53	5.86

STEP 4 (3.1 L/S) 800 RPM	STEP 5 (4.3L/S)	Recovery	
Drawdown	Drawdown	Time	Residual Drawdown
6.12	11.43	0.5 2h00	21.81
6.24	11.65	1	19.68
6.36	12.18	1.5	17.66
6.41	12.93	2	16.2
6.48	13.19	2.5	15.7
6.54	13.61	3	13.81
6.74	14.28	4	11.76
6.89	14.89	5	9.98
7.05	15.43	6	8.54
7.17	15.76	7	7.27
7.33	16.09	8	6.53
7.5	16.24	9	6.24
7.64	16.55	10	5.94
7.93	17.37	12	5.33
8.31	18.24	15	4.58
8.9	19.61	20	3.78
9.37	20.71	25	3.05
9.72	21.65	30	2.74

10.32	23	40	2.25
1094	23.84	50	1.9
11.26	24.51	60	1.67
		70	1.47
		80	1.31
		90	1.22
		100	1.1
		120	1.01
		150	0.82
		200	0.69
		250	0.59

Monitoring bore hole KG 4
Static water level 17.35m
Datum 0.2m

Date	**Drawdown**
06/03/94	20.56
	20.547
07/03/94	20.54
	20.547
08/03/94	20.5
	20.46
09/03/94	20.46
	20.355
10/03/94	20.43
	20.33
11/03/94	20.6
	20.6
12/03/94	20.62
	20.59
13/03/94	20.52
	20.5
14/03/94	20.5
	20.5

Constant Discharge
1.5l/s

Time	Drawdown
0.5	0.88
1	1.14
1.5	1.34
2	1.45
2.5	1.55
3	1.65
4	1.82
5	1.96
6	2.09
7	2.19
8	2.29
9	2.39
10	2.49
12	2.79
15	3.11
20	3.41
25	3.61
30	3.77
40	4.01
50	4.16
60	4.29
70	4.38
80	4.5
90	4.56
100	4.63
120	4.74
150	4.89
200	5.03
250	5.19
300	5.29
400	5.44
500	5.57
600	5.71
700	5.74
800	5.77
900	5.83
1000	5.86
1100	5.92
1200	5.95
1300	6.01
1400	6.07
1440	6.08
1500	6.13
1600	6.17
1700	6.24
1800	6.28
1900	6.34
2000	6.38
2100	6.41
2200	6.45
2300	6.49
2400	6.53

05/03/94
Recovery after CDT

Time	Residual Drawdown
0.5	6.49
1	6.21
1.5	5.96
2	5.76
2.5	5.61
3	5.47
4	5.27
5	5.07
6	4.88
7	4.68
8	4.53
9	4.39
10	4.26
12	4.05
15	3.83
20	3.57
25	3.36
30	3.2
40	2.95
50	2.86
60	2.77
70	2.69
80	2.57
90	2.54
100	2.51
120	2.42
150	2.33
200	2.21
250	2.1
300	2.01
400	1.89
500	1.79
600	1.72
700	1.65
800	1.62
900	1.57
1000	1.54
1100	1.5
1200	1.46
1300	1.4
1400	1.38
1440	1.37

2500	6.57
2600	6.61
2700	6.65
2800	6.69
2880	6.72
2900	6.76
3000	6.78
3100	6.82
3200	6.88
3300	6.94
3400	6.98
3500	7
3600	7.02
3700	7.04
3800	7.05
3900	7.06
4000	7.07
4100	7.08
4200	7.1
4300	7.12
4320	7.13
4400	7.16
4500	7.2
4600	7.25
4700	7.29
4800	7.34
4900	7.35
5000	7.36
5100	7.37
5200	7.39
5300	7.42
5400	7.44
5500	7.47
5600	7.5
5700	7.53

Monitoring bore hole KG 4

Date	Drawdown
10/03/94	10.42
11/03/94	18.62
	18.6
12/03/94	18.57
	18.449
13/03/94	18.35
	18.135
	18.24

KG 93/107 **04/03/94**

Borehole depth	130m
Supervisor	Rory
Datum	0.49m
Water level	6.65m
Pump depth	102m

	STEP 1(1.36 L/S)	STEP 2 (2.5 L/S)	STEP 3 (4.03 L/S)
	162 RPM	310 RPM	550 RPM
Time	Drawdown	Drawdown	Drawdown
0.5	0.85	2.79	5.11
1	1.11	3.21	5.55
1.5	1.45	3.42	5.86
2	1.65	3.56	6.01
2.5	1.65	3.64	6.14
3	1.69	3.69	6.22
4	1.72	3.78	6.55
5	1.8	3.84	6.89
6	1.85	3.88	7.04
7	1.89	3.91	7.13
8	1.94	3.94	7.2
9	1.99	3.96	7.25
10	2.04	3.96	7.3
12	2.15	3.98	7.36
15	2.15	4.01	7.44
20	2.15	4.05	7.54
25	2.18	4.09	7.63
30	2.2	4.11	7.69
40	2.22	4.18	7.76
50	2.24	4.22	7.84
60	2.27	4.27	7.93

STEP 4 (6.07 L/S)	STEP 5 (8.8L/S)	STEP 6 (12.34L/S)	Recovery	
800 RPM		1620 RPM		
Drawdown	Drawdown	Drawdown	Time	Residual Drawdown
9.42	13.76	20.02	0.5	19.54
10.17	14.95	21.18	1	15.1
10.68	15.32	22.09	1.5	11.63
11	15.65	22.75	2	10.08
11.15	15.88	23.2	2.5	8.61
11.27	16.44	23.57	3	7.63
11.32	16.8	24.06	4	6.39
11.32	17.14	24.55	5	5.7
11.37	17.34	24.9	6	5.29
11.41	17.49	25.18	7	5.05
11.45	17.39	25.37	8	4.82
11.49	17.31	25.54	9	4.62
11.54	17.28	25.66	10	4.44
11.59	17.3	25.88	12	4.21
11.64	17.38	26.02	15	3.98
11.71	17.49	26.34	20	3.69
11.79	17.61	26.59	25	3.54

11.88	17.65	26.7	30	3.43
12.04	17.86	26.99	40	3.22
12.19	18.07	27.15	50	3.06
12.5	18.18	27.31	60	2.91
			70	2.22
			80	2.61
			90	2.52
			100	2.47
			120	2.31
			150	2.28
			200	2.18
			250	2.01
			300	1.69
			400	
			500	
			600	
			720	1.09
			800	
			900	
			1000	

Monitoring bore hole 93/115
Static water level
Datum 0.265m

Date	Drawdown
02/03/94	13.66
03/03/94	13.64
04/03/94	13.6
	13.61
05/03/94	13.61
	13.65
06/03/94	13.59
	13.58
07/03/94	13.59
	13.56
08/03/94	13.56
	13.54
09/03/94	13.53
	13.57
10/03/94	13.54
	13.49

Monitoring bore hole 93/110
Static water level
Datum 2.53

Date	Drawdown
02/03/94	5.43
	5.47
03/03/94	5.49
	5.46
04/03/94	5.49
	5.5
05/03/94	5.53
	5.54
06/03/94	5.515
	5.53
07/03/94	5.56
	5.55
08/03/94	5.6
	5.58
09/03/94	5.6
	5.63
10/03/94	5.65
	5.6

Monitoring bore hole 93/107
Static water level 8.25
Datum 0.19

Date	Drawdown
04/03/94	8.49
07/03/94	8.45
	8.46
08/03/94	8.45
	8.44
09/03/94	8.45
	8.43

10/03/94	8.48
	8.48
11/03/94	8.6
	8.607
12/03/94	8.615
	8.618
13/03/94	8.625
	8.604
14/03/94	8.613

Constant Discharge
5l/s

Time	Drawdown
0.5	2.24
1	5.41
1.5	6.32
2	6.85
2.5	7.22
3	7.5
4	7.84
5	8.09
6	8.25
7	8.38
8	8.48
9	8.56
10	8.91
12	8.93
15	9.22
20	9.42
25	9.51
30	9.58
40	9.66
50	9.74
60	9.84
70	9.93
80	9.99
90	10.05
100	10.11
120	10.2
150	10.49
200	10.62
250	10.77
300	10.99
400	11.46
500	11.65
600	11.79
700	11.89
800	11.98
900	12.16
1000	12.36
1100	12.54
1200	12.89
1300	13.49
1400	13.62

06/03/94
Recovery after CDT

Time	Residual Drawdown
0.5	14.29
1	12.87
1.5	12.16
2	11.7
2.5	11.39
3	11.19
4	10.91
5	10.75
6	10.63
7	10.55
8	10.48
9	10.43
10	10.39
12	10.3
15	10.2
20	10.07
25	9.95
30	9.85
40	9.67
50	9.49
60	9.31
70	9.14
80	9.05
90	8.95
100	8.83
120	8.6
150	8.31
200	7.59
250	7.5
300	7.26
400	6.77
500	6.33
600	5.94
700	5.76
800	5.33
900	5.09
1000	

1440	13.8
1500	13.96
1600	14.05
1700	14.38
1800	14.41
1900	14.58
2000	14.84
2100	15.05
2200	15.19
2300	15.31
2400	15.49
2500	15.55
2600	15.69
2700	15.83
2800	15.96
2880	16.09
2900	16.29
3000	16.48
3100	16.68
3200	16.89
3300	16.99
3400	17.15
3500	17.38
3600	17.51
3700	17.68
3800	17.79
3900	17.84
4000	17.99
4100	18.1
4200	18.29
4300	18.36
4320	18.4

Static water level	6.65m
Datum	0.44m

Monitoring bore hole KG 93/107

Date	Drawdown
10/03/94	4.74
	10.93
	10.42
11/03/94	9.74
	9.437
12/03/94	9.19
	9.017
13/03/94	8.9
	8.845
14/03/94	8.823

KG 93/216 **12/03/94**

Borehole depth	9m	
Supervisor	Rory	
Datum	0.54m	
Water level	4.26m	
Pump depth	9m	
Distance from pumping		100m

STEP 1(1 L/S) 162 RPM			STEP 2 (2 L/S) 310 RPM	STEP 3 (3 L/S) 550 RPM
Time	Pumping ra	Drawdown	Drawdown	Drawdown
0.5	1	0.07	0.2	0.37
1	1	0.08	0.21	0.37
1.5	1	0.09	0.21	0.38
2	1	0.09	0.21	0.38
2.5	1	0.09	0.22	0.38
3	1	0.09	0.22	0.38
4	1	0.09	0.25	0.38
5	1	0.09	0.25	0.38
6	1	0.09	0.25	0.38
7	1	0.1	0.25	0.38
8	1	0.1	0.25	0.38
9	1	0.1	0.25	0.38
10	1	0.1	0.25	0.38
12	1	0.11	0.25	0.38
15	1	0.11	0.25	0.38
20	1	0.12	0.26	0.39
25	1	0.12	0.27	0.4
30	1	0.12	0.27	0.4
40	1	0.12	0.27	0.4
50	1	0.12	0.27	0.41
60	1	0.13	0.27	0.41
70	1	0.13	0.27	0.42
80	1	0.13	0.27	0.42

STEP 4 (4.02 L/S) 800 RPM	STEP 5 (5.5L/S)	STEP 6 (7 L/S) 1620 RPM	Recovery	
Drawdown	Drawdown	Drawdown	Time	Residual Drawdown
0.51	0.78	1.52	0.5	0.6
0.51	0.78	1.53	1	0.32
0.51	0.78	1.57	1.5	0.3
0.51	0.78	1.61	2	0.28
0.51	0.81	1.64	2.5	0.27
0.52	0.82	1.67	3	0.25
0.53	0.82	1.72	4	0.23
0.53	0.83	1.84	5	0.22
0.54	0.83	1.88	6	0.22
0.54	0.83	1.91	7	0.2
0.55	0.83	1.94	8	0.19
0.55	0.83	2.08	9	0.18
0.55	0.83	2.37	10	0.17
0.55	0.83	2.84	12	0.17
0.55	0.84	3.58	15	0.155

0.55	0.87	3.73	20	0.135
0.55	0.89	3.75	25	0.128
0.56	0.91		30	0.114
0.57	0.98		40	
0.57	1.05		50	
0.58	1.08		60	
0.58	1.1		70	
0.59	1.14		80	
			90	
			100	
			120	
			150	
			200	
			250	
			300	

Monitoring bore hole 93/217
Static water level 4.2m
Datum

Date	**Drawdown**
12/03/94	4.26
12/03/94	4.26
12/03/94	4.26
12/03/94	4.26

KG 93/217 **14/03/94**

Borehole depth	7.3m
Supervisor	Rory
Datum	0.59m
Water level	4.17m
Pump depth	6.17m
Distance from pumping	

STEP 1(0.56 L/S) STEP 2 (1.02 L/S) Recovery
72RPM 122RPM

Time	Pumping ra	Drawdown	Drawdown	Time	Residual Drawdown
0.5	0.56	0.31	0.78	0.5	0.6
1	0.56	0.38	0.93	1	0.36
1.5	0.56	0.43	1.02	1.5	0.21
2	0.56	0.46	1.08	2	0.15
2.5	0.56	0.48	1.11	2.5	0.1
3	0.56	0.49	1.13	3	0.1
4	0.56	0.5	1.19	4	0.07
5	0.56	0.51	1.25	5	0.06
6	0.56	0.52	1.29	6	
7	0.56	0.52	1.31	7	
8	0.56	0.53	1.33	8	
9	0.56	0.53	1.36	9	
10	0.56	0.53	1.37	10	
12	0.56	0.53	1.4	12	
15	0.56	0.54	1.4	15	

20	0.56	0.55	1.4	20
25	0.56	0.55	1.4	25
30	0.56	0.55	1.4	30
40	0.56	0.56	1.4	40
50	0.56	0.56	1.4	50
60	0.56	0.56	1.4	60
70	0.56	0.56	1.4	70
80	0.56	0.57	1.4	80
80.5	1.02	0.78		
81	1.02	0.93		
81.5	1.02	1.02		
82	1.02	1.08		
82.5	1.02	1.11		
83	1.02	1.13		
84	1.02	1.19		
85	1.02	1.25		
86	1.02	1.29		
87	1.02	1.31		
88	1.02	1.33		
89	1.02	1.36		
90	1.02	1.37		
92	1.02	1.4		
95	1.02	1.4		
100	1.02	1.4		
105	1.02	1.4		
110	1.02	1.4		
120	1.02	1.4		
130	1.02	1.4		
140	1.02	1.4		
150	1.02	1.4		
160	1.02	1.4		

KG 93/218 **13/03/94**

Borehole depth	14.1m
Supervisor	Rory
Datum	0.45m
Water level	7.42m
Pump depth	12m

STEP 1(0.57 L/S) 158RPM			STEP 2 (1 L/S) 270RPM	STEP 3 (1.5 L/S) 390RPM
Time	Pumping ra	Drawdown	Drawdown	Drawdown
0.5	0.57	0.12	0.22	0.36
1	0.57	0.12	0.23	0.37
1.5	0.57	0.12	0.24	0.37
2	0.57	0.12	0.24	0.37
2.5	0.57	0.13	0.24	0.37
3	0.57	0.13	0.24	0.38
4	0.57	0.13	0.24	0.39
5	0.57	0.13	0.24	0.39
6	0.57	0.13	0.24	0.39
7	0.57	0.13	0.24	0.39
8	0.57	0.13	0.24	0.39
9	0.57	0.13	0.24	0.39
10	0.57	0.13	0.24	0.39
12	0.57	0.13	0.24	0.39
15	0.57	0.13	0.24	0.39
20	0.57	0.13	0.24	0.39
25	0.57	0.13	0.24	0.39
30	0.57	0.13	0.24	0.4
40	0.57	0.13	0.24	0.4
50	0.57	0.13	0.24	0.4
60	0.57	0.13	0.25	0.4
70	0.57	0.13	0.25	0.41
80	0.57	0.13	0.25	0.41

STEP 4 (2 L/S) 510RPM	STEP 5 (3L/S) 730RPM	STEP 6 (4.8 L/S) 960RPM	Recovery	
Drawdown	Drawdown	Drawdown	Time	Residual Drawdown
0.52	0.94	1.87	0.5	1.07
0.55	1.02	1.98	1	0.15
0.55	1.03	2.03	1.5	0.06
0.56	1.03	2.09	2	0.05
0.56	1.05	2.12	2.5	0.04
0.57	1.08	2.16	3	0.04
0.58	1.08	2.23	4	0.03
0.58	1.08	2.32	5	0.03
0.59	1.08	2.45	6	
0.6	1.09	2.64	7	
0.6	1.09	2.77	8	
0.6	0.11	2.88	9	
0.6	1.12	2.96	10	

0.61	1.14	3.22	12
0.61	1.15	3.5	15
0.61	1.18	3.77	20
0.61	1.2	3.77	25
0.61	1.23	3.77	30
0.61	1.27		40
0.61	1.29		50
0.62	1.32		60
0.62	1.36		70
0.62	1.42		80
			90
			100

KG 91/30

19/04/96

Borehole depth
Contractor
Datum
Water level
Pump depth
available dd

LONG 29 42 35 68
LAT 17 36 56 36

	STEP 1(0.714 L/S)	STEP 2 (1.09 L/S)	STEP 3 (1.47 L/S)
Time	Drawdown	Drawdown	Drawdown
0.5	0.07	0.24	0.49
1	0.08	0.26	0.5
1.5	0.08	0.27	0.51
2	0.08	0.28	0.52
2.5	0.08	0.28	0.52
3	0.08	0.28	0.52
4	0.08	0.29	0.53
5	0.08	0.3	0.53
6	0.08	0.3	0.53
7	0.08	0.31	0.54
8	0.09	0.31	0.54
9	0.1	0.32	0.55
10	0.1	0.32	0.56
12	0.1	0.33	0.57
15	0.12	0.34	0.58
20	0.13	0.35	0.6
25	0.14	0.39	0.6
30	0.15	0.39	0.61
40	0.18	0.42	0.64
50	0.2	0.45	0.67
60	0.24	0.47	0.69

STEP 4 (1.98 l/s)	STEP 5 (2.68 l/s)	STEP 6 (5.2 l/s)	**Recovery**	
Drawdown	Drawdown	Drawdown	Time	Residual Drawdown
0.4	0.89	1.33	0.5	1.36
0.39	0.88	1.35	1	1.3
0.31	0.89	1.37	1.5	1.36
0.29	0.89	1.36	2	1.35
0.3	0.9	1.36	2.5	1.33
0.3	0.9	1.36	3	1.31
0.3	0.89	1.37	4	1.28
0.39	0.89	1.37	5	1.24
0.38	0.89	1.37	6	1.22
0.44	0.9	1.38	7	1.1
0.44	0.9	1.38	8	1.07
0.45	0.9	1.4	9	1.044
0.47	0.9	1.41	10	1.02
0.48	0.92	1.42	12	0.98
0.51	0.94	1.443	15	0.953
0.54	0.97	1.49	20	0.798
0.56	0.99	1.52	25	0.734

0.59	0.99	1.55	30	0.65
0.654	1.042	1.6	40	0.576
0.72	1.06	1.64	50	0.504
0.78	1.1	1.68	60	0.452
			70	0.398
			80	0.32
			90	0.262
			100	0.18
			120	0.1

Constant Discharge

0.4l/s

Time	
0.5	0.43
0.75	0.43
1	0.45
1.5	0.48
2	0.51
2.5	0.53
3	0.533
4	0.56
5	0.58
6	0.612
7	0.64
8	0.67
9	0.68
10	0.712
12	0.75
15	0.81
20	0.9
25	0.98
30	1.04
40	1.16
50	1.268
60	1.26
70	1.45
85	1.513
100	1.59
120	1.672
140	1.755
160	1.818
185	1.85
210	1.944
240	2.004
270	2.036
300	2.062
350	2.095
400	2.116
500	2.102
600	2.142
700	2.199
850	2.223
1000	2.233

Recovery after CDT

Time	Residual Drawdown
0.5	1.594
1	1.618
1.5	1.62
2	1.576
2.5	1.559
3	1.547
4	1.508
5	1.475
6	1.45
7	1.4
8	1.352
9	1.312
10	1.262
12	1.208
15	1.168
20	1.11
25	1.048
30	0.999
40	0.952
50	0.859
60	0.79
70	0.73
80	0.652
90	0.578
100	0.49
120	0.428
150	0.27
200	0.314
250	0.282
300	0.241
350	0.204
400	0.161
500	0.141
600	0.119
700	0.091
800	0.069
850	0.054
900	0.03
1000	0

1200	2.161
1400	2.076
1440	2.066
1600	2.19

Monitoring borehole **5513D**

Time	Drawdown
0.5	0
1	0
1.5	0
2	0
2.5	0
3	0
4	0
5	0
6	0
7	0
8	0
9	0
10	0
12	0
15	0
20	0
25	0.005
30	0.3
40	0.06
50	0.098
60	0.132
70	0.185
80	0.242
85	0.312
90	0.358
100	0.392
120	0.416
140	0.436
160	0.452
250	0.456
185	0.468
210	0.484
240	1.492
270	0.502
300	0.502
350	0.512
400	0.496
500	0.522
600	0.572
700	0.51
850	0.484
1000	0.478
1200	0.492
1400	0.326
1440	0.562
1600	0.44
1850	0.458

Recovery

Time	Residual Drawdown
0.5	0.428
1	0.428
1.5	0.428
2	0.428
2.5	0.428
3	0.428
4	0.428
5	0.428
6	0.428
7	0.426
8	0.426
9	0.426
10	0.424
12	0.42
15	0.408
20	0.402
25	0.402
30	0.39
40	0.384
50	0.366
60	0.348
70	0.328
85	0.302
100	0.282
120	0.25
140	0.228
160	0.21
185	0.198
210	0.18
240	0.155
270	0.141
300	0.132
350	0.112
400	0.103
500	0.091
600	0.088
700	0.088
850	0.088
1000	0.06

2100	0.454
2400	0.448
2700	0.448
2880	0.458
3000	0.426
3400	
3800	
4320	

KOMAGGAS1

BH No **KG 91/100 (Monotoring borehole)** **08/02/94**
Conducted when steps started at **KG 92/103**

Contractor DGM/AQUACARE/DOUW
Supervisor Rory

STEP 1 Time	 Drawdown	STEP 2 Drawdown	STEP 3 Drawdown	STEP 4 Drawdown
0.5	0	-0.02	-0.053	-0.07
1	0	-0.02	-0.053	-0.07
1.5	0	-0.025	-0.053	-0.07
2	0	-0.025	-0.053	-0.07
2.5	0	-0.03	-0.053	-0.07
3	0	-0.03	-0.053	-0.07
4	0	-0.03	-0.053	-0.07
5	0	-0.03	-0.054	-0.07
6	0	-0.03	-0.054	-0.07
7	0	-0.03	-0.054	-0.07
8	0	-0.03	-0.055	-0.07
9	0	-0.03	-0.056	-0.07
10	0	-0.03	-0.056	-0.07
12	0.005	-0.035	-0.057	-0.07
15	0.005	-0.035	-0.057	-0.07
20	-0.01	-0.035	-0.06	-0.07
25	-0.01	-0.035	-0.06	
30	-0.01	-0.037	-0.06	
40	-0.015	-0.04	-0.065	
50	-0.018	-0.045	-0.07	
60	-0.02	-0.053	-0.07	

BH No KG 92/103 **Pumping borehole** **08/02/94**

Datum Level above casing	
Casing Height (mbgl)	
BH Diameter	
BH Depth	153.5m
Water Level (mbgl)	9.14m
Depth of Pump	132m

Two holes ? apart.

Contractor DGM/AQUACARE/DOUW
Supervisor Rory

STEP 1(1.12L/S) 220RPM Time	 Drawdown	STEP 2 (2.03 L/S) 280 RPM Drawdown	STEP 3 (3.46 L/S) 600 RPM Drawdown	STEP 4 (4.4 L/S) Drawdown
0.5	1.65	5.84	9.29	37.61
1	2.36	6.44	9.64	42.11
1.5	2.81	6.89	11	44.26
2	3.16	7.24	11.91	46.75
2.5	3.46	7.45	12.76	50.41
3	3.68	7.6	13.09	55.16
4	3.87	7.87	13.89	60.74

5	4.17	8.06	14.53	64.92
6	4.32	8.42	15.71	69.43
7	4.43	8.6	16.52	74.52
8	4.52	8.78	17.1	78.17
9	4.58	8.88	17.67	80.94
10	4.63	8.95	18.54	83.19
12	4.71	9.01	20.16	88.94
15	4.76	9.06	21.74	96.23
20	4.79	9.1	23.1	100
25	4.82	9.13	23.75	
30	4.86	9.14	24.16	
40	4.87	9.17	24.51	
50	4.92	9.21	31.9	
60	5	9.28	36.63	

Recovery

Time	Residual Drawdown
0.5	90.25
1	76.99
1.5	67.91
2	63.53
2.5	56.49
3	50.11
4	39.24
5	28.49
6	18.55
7	13.45
8	9.72
9	5.88
10	5.05
12	3.14
15	2.17
20	1.42
25	1.12
30	1.02
40	0.93
50	0.86
60	0.81
70	0.78
80	0.76
90	0.73
100	0.71
120	0.7
150	0.68
200	0.65
250	0.61
300	0.55

21/02/94
Monitoring hole

Time	Drawdown	Residual drawdown
0.5	0	8.36
1	0	7.04
1.5	0	5.99
2	0	5.29
2.5	0	4.75
3	0	4.48
4	0	3.96
5	0	3.66
6	0	3.56
7	0	3.39
8	0	3.32
9	0	3.27
10	0	3.24
12	0	3.19
15	0	3.15
20	0	3.1
25	0	3.07
30	0	3.04
40	0	2.99
50	0	2.95
60	0	2.9
70	0	2.86
80	0	2.83
90	0	2.84
100	0	2.79
120	0	2.75
150	0	2.71
200	0	2.68
250	0	2.68
300	0	2.68
400	0	2.37
500	0	2.27
600	0	2.19
700	0	2.08
800	0	2.06
900	0	2.01
1000	0	
1200	0.07	
1320	0.07	
1440	0.15	
1800	0.15	
2280	0.15	
2880	0.19	
3480	0.31	
3900	0.37	
4320	0.44	

Pump inlet deoth 132m
Static water level 9.54
borehole depth 155m
Datum above ground 0.47
Date 21/02/94
RPM 240
1.5l/s

Time	Drawdown
0.5	2.08
1	3.48
1.5	4.54
2	5.24
2.5	5.87
3	6.34
4	6.44
5	6.52
6	6.66
7	6.81
8	7.15
9	7.27
10	7.52
12	7.63
15	7.64
20	7.64
25	7.64
30	7.64
40	7.65
50	7.68
60	7.7
70	7.71
80	7.72
90	7.73
100	7.74
120	7.74
150	7.76
200	7.78
250	7.8
300	7.82
400	7.85
500	7.86
600	7.87
700	7.89
800	7.91
900	7.93
1000	8.07
1100	8.14
1200	8.2
1300	8.26
1400	8.34
1440	8.39
1500	8.44
1600	8.53
1700	8.61
1800	8.68

1900	8.76
2000	8.82
2100	8.89
2200	8.96
2300	8.99
2400	9.04
2500	9.1
2600	9.14
2700	9.19
2800	9.25
2880	9.28
2900	9.31
3000	9.37
3100	9.43
3200	9.48
3300	9.53
3400	9.56
3500	9.59
3600	9.63
3700	9.67
3800	9.69
3900	9.73
4000	9.78
4100	9.86
4200	9.98
4300	10.11
4320	

KG 93/108

BH Depth	132.2m
Datum	0.15m
Water level	10.03m
Pump depth	120m

	STEP 1(1.4L/S)	STEP 2 (2.8 L/S)	STEP 3 (4.55 L/S)
	220RPM	420 RPM	700 RPM
Time	Drawdown	Drawdown	Drawdown
0.5	1.23	10.47	22.38
1	1.93	11.24	23.41
1.5	2.57	11.83	24.17
2	3.21	12.31	24.88
2.5	3.92	12.76	25.55
3	4.1	13.25	25.96
4	4.86	13.87	26.8
5	5.41	14.73	28.42
6	5.84	15.22	28.99
7	6.2	16.03	29.92
8	6.53	16.69	30.88
9	6.89	17.04	31.71
10	7.08	17.69	32.42
12	7.44	18.37	33.61
15	7.91	19.07	35.32
20	8.4	19.76	36.12
25	8.74	20.52	36.97
30	8.96	20.56	37.42
40	9.22	21.17	38.3
50	9.35	21.55	38.66
60	9.5	21.75	38.86

STEP 4 (6.92 L/S)	STEP 5 (8.5 L/S)	Recovery	
1000 RPM			
Drawdown	Drawdown	Time	Residual Drawdown
39.89	72	0.5 22h12	89.84
41.25	72.5	1	83.96
42.34	73.95	1.5	77.92
43.36	75.31	2	72.25
44.23	77.29	2.5	67.17
44.94	78.95	3	62.14
45.72	82.69	4	53.77
47.5	84.96	5	50.09
49.07	87.44	6	46.08
50.64	89.31	7	43.14
51.68	90.9	8	38.84
53.08	92.24	9	36.7
54.22	94	10	32.23
57.41	96.8	12	28.31
61.55		15	18.24
66.3		20	14.33
69.22		25	9.92
70.81		30	8.19
72.63		40	4.89
70.83		50	3.77
70.9		60	3.35

70		2.7
80		2.3
90		1.95
100		1.74
120		1.4
150		1.19
200		0.99
250		0.74
300		0.57
400		0.5
500	6h45	
600		
700		
800		
900		
1000		

Locality within village E
Inlet depth 120m
static water level 10.03
Recorder Erie
Monitoring BH No KG 92/103 - 92/100
Borehole Depth 132.20
Datum above ground 0.51
Date 27/01/94
4.42 L/S

Time		Drawdown	Time	**Recovery** Residual Drawdown
0.5	12H30	2.69	0.5	42.01
1		4.49	1	36.16
1.5		5.9	1.5	31.89
2		6.85	2	29.08
2.5		8.32	2.5	27.77
3		10.85	3	26.21
4		13.58	4	24.14
5		16.67	5	22.16
6		16.77	6	20.5
7		18	7	18.76
8		22.4	8	17.18
9		25.76	9	16
10		26.84	10	15.08
12		28.11	12	12.87
15		30.07	15	11.2
20		32.26	20	9.36
25		34.83	25	7.67
30		36.16	30	6.89
40		37.67	40	6.23
50		38.51	50	5.45
60		40.97	60	4.8
70		41.75	70	4.6
80		42.2	80	4.5
90		42.37	90	4.4
100		42.44	100	4.2
120		42.57	120	3.91
150		42.8	150	3.74

200		43.85	200	3.56
250		45.28	250	3.39
300		45.55	300	3.25
400		45.76	400	3.04
500		46.08	500	2.91
600		46.43	600	2.8
700		46.54	700	2.7
800		46.56	800	2.61
900		46.58	900	2.54
1000		46.6	1000	
1100		46.61		
1200		46.62		
1300		46.63		
1400		46.65		
1440		46.7		
1500		46.8		
1600		46.9		
1700		47		
1800		47.7		
1900		47.18		
2000		47.24		
2100		47.32		
2200		47.4		
2300		47.42		
2400		47.44		
2500		47.46		
2600		47.46		
2700		47.48		
2800		47.5		
2880		47.81		
2900		48.01		
3000		48.25		
3100		48.37		
3200		48.43		
3300		48.64		
3400	7H30	48.89		
3500				
3600				
3700				
3800				
3900				
4000				
4100				
4200				
4300				
4320				

KG 93/115

BH Depth 118.8m

Datum	0.74
Water level	12.46
Pump depth	86m

	STEP 1(0.28L/S)	STEP 2 (1.0 L/S)	STEP 3 (2.1 L/S)
	170RPM	350 RPM	700 RPM
Time	Drawdown	Drawdown	Drawdown
0.5	0.13	1	3.44
1	0.15	1.14	3.75
1.5	0.17	1.24	3.95
2	0.2	1.34	4.14
2.5	0.21	1.42	4.3
3	0.25	1.5	4.43
4	0.26	1.66	4.62
5	0.28	1.74	4.78
6	0.34	1.83	4.93
7	0.37	1.91	5.09
8	0.4	1.97	5.18
9	0.42	2.05	5.28
10	0.43	2.1	5.37
12	0.47	2.22	5.55
15	0.5	2.35	5.78
20	0.59	2.53	6.11
25	0.64	2.67	6.37
30	0.68	2.77	6.6
40	0.75	2.81	6.94
50	0.77	3.02	7.2
60	0.81	3.3	7.31

STEP 4 (3.15 L/S)	STEP 4.5 L/S)	Recovery	
1000 RPM			
Drawdown	Drawdown	Time	Residual Drawdown
7.52	11.4	0.5	24.67
7.78	11.56	1	23.41
7.98	11.67	1.5	22.42
8.14	11.7	2	21.69
8.28	11.76	2.5	20.93
8.42	12.05	3	20.32
8.64	12.51	4	19.27
8.83	13.09	5	18.37
9	13.64	6	17.5
9.2	14.15	7	16.67
9.4	14.5	8	15.16
9.66	14.82	9	14.81
9.7	15.17	10	14.48
9.93	15.89	12	13.22
10.21	16.85	15	11.79
10.58	18.35	20	10.87
10.73	19.67	25	9.46
10.73	20.81	30	8.07
10.73	23.2	40	5.92
10.8	25.35	50	4.42
11.2	27.27	60	3.65
		70	2.95
		80	2.38
		90	1.94
		100	1.66
		120	1.37
		150	1.12
		200	0.98
		250	0.84
		300	0.65
		840	0.45

Constant Discharge
2.5l/s

Time	Drawdown
0.5	1.39
1	1.89
1.5	2.22
2	2.56
2.5	2.85
3	3.12
4	3.59
5	3.99
6	4.34
7	4.68
8	4.94
9	5.18
10	5.45
12	5.82
15	6.35
20	6.98
25	7.53
30	8.15
40	8.67
50	9.2
60	9.64
70	10.04
80	10.33
90	10.58
100	10.74
120	10.78
150	11.27
200	12.12
250	13.15
300	13.7
400	14.49
500	15.24
600	16.09
700	16.89
800	17.07
900	17.41
1000	18.21
1100	18.45
1200	19
1300	19.74
1400	20.41
1440	20.81
1500	21.19
1600	21.82
1700	22.86
1800	23.6
1900	24.23
2000	25
2100	25.78
2200	26.12
2300	26.79

2400	27.51
2500	27.92
2600	28.45
2700	28.85
2800	29.11
2880	29.79
2900	29.92
3000	30.25
3100	30.99
3200	31.27
3300	31.86
3400	32.38
3500	32.79
3600	33.22
3700	33.75
3800	34.09
3900	34.49
4000	35.16
4100	35.69
4200	36.15
4300	36.45
4320	36.49

LF 98/312

01/02/98

Borehole depth	153.5m	
Contractor	Pumpcor	(borehole type: BP30H)
Datum	0.66m	
Water level	artesian	
Pump depth	99.42m	
Available dd	99.42m	

	STEP 1(0.85m L/S) 165 RPM	STEP 2 (1.2m L/S) 216 RPM	STEP 3 (1.95 L/S) 378 RPM	
Time	Drawdown	Drawdown	Drawdown	
1	2.102	13.996	26.1	
2	3.314	14.974	28.93	
3	4.294	15.728	31.396	
5	5.698	16.916	35.552	
7	6.73	17.71	38.778	
10	7.74	18.616	42.818	
15	8.958	19.546	46.748	
20	9.728	20.172	49.564	
30	10.664	21.006	55.246	24
40	11.248	21.526	58.364	
50	11.654	21.9	60.226	
60	11.948	22.19	61.606	
70	12.188	22.446	63.36	
80	12.376	22.63	64.384	
90	12.562	22.814	65.286	

STEP 4 (2.4 L/S)	**Recovery**	
Drawdown	Time	Residual Drawdown
68.112	1	75.95
70.248	2	63.86
72.296	3	55.476
76.148	5	42.396
79.228	7	33.132
82.674	10	24.72
86.28	15	17.234
89.15	20	12.76
92	30	7.304
	40	4.178
	50	2.004
	60	0.528
	70	0

Available dd 99.42m

Constant Discharge

1.02 l/s

Time	Drawdown
1	2.966
2	4.914
3	6.436
5	9.084
7	11.262
10	13.386
15	15.366
20	16.626
30	18.274
40	19.3
60	20.43
90	21.346
120	21.874
150	22.234
180	22.542
210	22.714
240	22.86
300	23.118
380	23.314
420	23.434
480	23.578
540	23.712
600	23.768
720	23.854
840	24.006
960	24.218
1080	24.386
1200	24.494
1320	24.544
1440	24.508
1600	24.64
1850	24.972
2100	25.212
2480	25.408
2700	25.718
3140	25.598

02/02/98

Recovery after CDT

Time	Residual Drawdown
1	20.732
2	16.954
3	14.504
5	11.666
7	9.804
10	8.356
15	6.564
20	5.332
30	3.476
40	2.204
60	0.706
78	0

LF 98/311 **31/01/98**

Borehole depth	149.3m	
Contractor	Pumpcor	(borehole type: BP30H)
Datum	0.75m	
Water level	17.486m	
Pump depth	82.2m	
Available dd	64.71m	

	STEP 1(0.65 L/S) 160 RPM	STEP 2 (1.19 L/S) 235 RPM	STEP 3 (2.18 L/S) 405 RPM
Time	Drawdown	Drawdown	Drawdown
1	0.184	1.178	2.418
2	0.272	1.212	2.53
3	0.318	1.264	2.63
5	0.374	1.326	2.794
7	0.418	1.38	2.916
10	0.478	1.452	3.074
15	0.578	1.536	3.282
20	0.654	1.612	3.45
30	0.766	1.74	3.71
40	0.848	1.84	3.94
50	0.908	1.918	4.136
60	0.95	2.004	4.31
70	1.006	2.072	4.472
80	1.044	2.134	4.622
90	1.082	2.202	4.784

STEP 4 (4.11 L/S) 741 RPM	STEP 5 (5.98L/S) 1025 RPM	STEP 6 (8 L/S) 1368 RPM	**Recovery**	
Drawdown	Drawdown	Drawdown	Time	Residual Drawdown
5.218	10.038	15.1	1	18.59
5.45	10.156	15.24	2	18.354
5.606	10.244	15.374	3	18.124
5.864	10.416	15.534	5	17.8
6.054	10.562	15.61	7	17.502
6.328	10.75	15.62	10	17.228
6.668	11.014	15.632	15	16.778
6.946	11.268	15.768	20	16.356
7.526	11.764	16.686	30	15.652
7.978	12.238	17.35	40	15.134
8.39	12.78	17.902	50	14.648
8.73	13.278	18.546	60	14.18
9.054	13.68	19.138	70	13.852
9.354	14.032	19.6	80	13.534
9.632	14.344	19.998	90	13.166
			100	12.754
			110	12.552
			120	12.218
			130	11.53
			180	11.098
			210	10.364
			240	10.126

270	9.486
300	8.664
12 hrs	5.442
14 hrs	4.95

Available dd 29.16m

Constant Discharge

3.3 l/s

Time	Drawdown
1	5.466
2	5.64
3	5.776
5	6.06
7	6.366
10	6.722
15	7.182
20	7.55
30	8.09
40	8.51
60	9.166
90	10.004
120	10.694
150	14.356
180	11.906
210	12.458
240	12.972
300	13.778
380	14.455
420	15.104
480	15.466
540	15.964
600	16.44
720	17.32
840	18.598
960	19.654
1080	21.098
1200	21.56
1320	23.032
1440	24.156
1600	↓
1850	
2100	
2480	24.844
2700	↓
3140	
3400	
3800	
4320	

01/02/98

Recovery after CDT

Time	Residaul Drawdown
1	24.21
2	24.158
3	24.138
5	24.082
7	24.06
10	24.018
15	23.956
20	23.888
30	23.782
40	23.69
60	23.496
90	23.322
120	23.188
150	22.914
180	22.586
210	22.298
240	22.004
300	21.55
380	21.042
420	20.59
480	20.158
540	
600	19.454
720	18.734
840	18.136
960	17.528
1080	16.78
1200	16.208
1320	15.34
1440	
	8.843
	6.054
	2.1813

GARIES 2

BH No	**G 45781**	**Pumping bore hole**	**13-01-01**
Datum Level above casing		360mm	
Casing Height (mbgl)		335mm	
BH Diameter		165mm	
BH Depth		118m	
Water Level (mbgl)		2.28m	
Depth of Pump		72m	

	STEP 1 (1L/S)	STEP 2 (2L/S)	STEP 3 (2.5L/S)	STEP 4 (3L/S)
	16S/25L (100 RPM)	12S/25L (140 RPM)	10S/25L (160 RPM)	8S/25L (195 RPM)
Time	Drawdown (s)	Drawdown (s)	Drawdown (s)	Drawdown (s)
1	0	21.63	33.21	42.9
2	2.06	22.33	33.53	45.38
3	4.47	22.95	34.71	47.35
5	5.57	24.2	37.38	43.8
7	6.12	25.09	39.4	46.14
9	6.43	26.12	41.17	46.36
12	8.13	27.78	42.79	52.1
15	9.46	28.68	44.13	57.54
20	13.46	29.82	45.25	62.32
25	16.86	30.26	45.35	67.32
30	17.99	30.83	45.68	77.42
40	18.63	31.77	47.77	Pomp 11h30
50	19.43	32.36	48.91	
60	19.93	32.91	49.72	

Recovery

Time	Residual Drawdown
1	55.8
2	46.05
3	39.66
5	26.01
7	18.02
9	11.88
12	7.44
15	6.13
20	5.15
25	4.75
30	4.43
40	4.01
50	3.75
60	3.5
80	3.17
100	2.92
120	2.73
150	2.49
180	1.99
210	2.02
240	2.09

Observation borehole

Water leve 3.62m

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Time	STEP 1	STEP 2	STEP 3	STEP 4
1	0.13	1.1	2.7	3.96
2	0.13	1.15	2.73	3.99
3	0.13	1.2	2.77	4.01
5	0.12	1.22	2.77	4.03
7	0.21	1.24	2.83	4.06
9	0.27	1.3	2.86	4.07
12	0.36	1.37	3.13	4.09
15	0.44	1.55	3.1	4.13
20	0.59	1.76	3.19	4.22
25	0.72	1.89	3.21	4.41
30	0.79	2.23	3.24	4.53
40	0.74	2.49	3.46	
50	0.88	2.59	3.64	
60	1	2.66	3.84	

Recovery

Time	Residual Drawdown
1	4.46
2	4.44
3	4.42
5	4.41
7	4.38
9	4.31
12	4.17
15	4.06
20	3.87
25	3.73
30	3.59
40	3.38
50	3.13
60	2.88
80	2.61
100	2.33
120	1.98
150	1.8
180	1.58
210	1.58

SPOEGRIVIER

BH No	**G 45805**	**Pumping bore hole**	**21-01-01**
Datum Level above casing		780mm	
Casing Height (mbgl)		425mm	
BH Diameter		180mm	
BH Depth		119m	
Water Level (mbgl)		3.47m	
Depth of Pump		98m	

2 holes are 20 m apart.

Time	STEP 1 (1L/S) Drawdown (s)	STEP 2 (1.5L/S) Drawdown (s)	STEP 3 (2L/S) Drawdown (s)
1	1.81	45.6	81.96
2	2.78	46.61	82.3
3	3.77	47.71	82.78
5	5.27	49.73	83.27
7	6.96	51.63	83.88
9	8.37	53.52	84.31
12	10.81	56.13	85.01
15	13.04	58.64	85.59
20	17.66	62.53	86.35
25	21.96	65.93	87
30	25.57	69.27	87.73
40	33.19	74.49	88.64
50	39.58	78.73	89.53
60	44.26	81.38	90.35

Recovery Time	
1	89.64
2	89.42
3	89.23
5	88.83
7	88.39
9	88.09
12	87.49
15	86.88
20	85.78
25	85.48
30	83.03
40	79.18
50	74.61
60	70.17
80	63.06
100	56.35
120	50.77
150	42.61
180	32.99
210	26.48
240	23.26
300	19.57
360	16.47

BH No **G 45807** **Observation borehole**

Time	STEP 1	STEP 2	STEP 3
1	2.57	2.39	2.4
2	2.57	2.38	2.42
3	2.57	2.38	2.41
5	2.55	2.38	2.41
7	2.55	2.38	2.42
9	2.56	2.38	2.44
12	2.53	2.38	2.44
15	2.54	2.35	2.45
20	2.47	2.35	2.46
25	2.46	2.35	2.48
30	2.44	2.35	2.51
40	2.41	2.36	2.52
50	2.39	2.38	2.54
60	2.35	2.4	2.58

Recovery

Time	Residual D
1	2.58
2	2.59
3	2.59
5	2.6
7	2.61
9	2.61
12	2.62
15	2.64
20	2.64
25	2.66
30	2.67
40	2.71
50	2.75
60	2.79
80	2.84
100	2.9
120	2.97
150	3.05
180	3.12
210	3.17
240	3.21
300	3.31
360	3.36

GARIES 1

BH No	**G 445779 Pumping bore hole**	**11-01-01**
Datum Level above casing	9.65mm	
Casing Height (mbgl)	180mm	
BH Diameter	165mm	
BH Depth	86m	
Water Level (mbgl)	9.61m	
Depth of Pump	82m	

Two holes 90m apart.

Time	STEP 1 (2L/S) 150 RPM Drawdown	STEP 2 (2.5L/S) 225 RPM Drawdown	STEP 3 (3L/S) 230 RPM Drawdown
1	3.74	39.84	56.11
2	5.67	40.54	56.61
3	7.24	41.47	57.12
5	10.19	42.82	57.76
7	12.51	43.72	57.93
9	15.19	44.34	58.14
12	18.3	45.02	58.45
15	21.33	46.11	58.67
20	25.91	47.91	64.71
25	28.95	49.25	69.7
30	31.39	50.35	
40	34.99	52.81	
50	37.05	53.88	
60	38.57	54.55	

Recovery

Time	Residual drawdown
1	57.63
2	56.12
3	54.93
5	51.07
7	49.66
9	48.76
12	47.65
15	46.69
20	45.53
25	44.27
30	43.36
40	41.25
50	39.56
60	37.36
80	34.46
100	32.43
120	30.38
150	28.2
180	26.94
210	25.85
240	24.77
300	23.27
360	20.8

Observation borehole **########**

Water leve 0.43m

Casing Height (mbgl) 0.42m

	STEP 1	STEP 2	STEP 3	**Recovery**	
Time	Drawdown	Drawdown	Drawdown	Time	Residual drawdown
1	0	0.01	0.01	1	0.01
2	0.01	0.01	0.01	2	0.01
3	0.01	0.01	0.01	3	0.01
5	0.01	0.01	0.01	5	0.01
7	0.01	0.01	0.01	7	0.01
9	0.01	0.01	0.01	9	0.01
12	0.01	0.01	0.01	12	0.01
15	0.01	0.01	0.01	15	0.01
20	0.01	0.01	0.01	20	0.01
25	0.01	0.01	0.01	25	0.01
30	0.01	0.01	0.01	30	0.01
40	0.01	0.01	0.01	40	0.01
50	0.01	0.01	0.01	50	0.01
60	0.01	0.01	0.01	60	0.01
				80	0.01
				100	0.01
				120	0.01
				150	0.01
				180	0.01
				210	0.01
				240	0.01
				300	0.01
				360	0.01

TEST STARTED 12/01/2001 AT 08H00 AM
TEST COMPLETED 13/01/2001 AT 02H00 AM
Water level 15m

Constant Discharge test

Pumping

Time (min)	Drawdown	**Recovery**
1	1.38	75.74
2	3.22	72.16
3	3.96	69.72
5	5.3	68.48
7	7.34	67.94
9	8.67	67.92
12	10.35	66.93
15	11.83	66.22
20	14.59	65.16
25	17.02	64.31
30	19.06	63.29
40	21.97	61.84
50	23.94	60.48
60	25.51	59.76
80	27.8	57.03
100	29.7	55.98
120	30.77	55.71
150	33.04	55.33
180	34.69	53.53
210	36.17	53.41
240	38.03	53.39
300	38.77	52.14
360	39.85	50.72
420	41.44	48.93
480	43.32	46.65
540	43.64	43.21
600	44.28	41.35
720	46.09	40.11
840	49.04	37.16
960	52.38	35.06
1080	64.74	32.94
1200		32.48
1320		25.36
1440		22.1
1800		17.77
2280		15.29
2880		13.85
3480		13.48
3900		13.05

Observation

Time (min)	Drawdown	**Recovery**
1	3.97	4.97
2	3.97	4.97
3	3.97	4.97
5	3.97	4.97
7	3.97	4.67
9	3.97	4.67
12	3.97	4.67
15	3.97	4.67
20	3.97	4.67
25	3.97	4.67
30	3.97	4.67
40	3.97	4.67
50	3.97	4.67
60	3.97	4.67
80	3.97	4.67
100	3.97	4.67
120	3.97	4.67
150	4.17	4.67
180	4.27	4.67
210	4.57	4.67
240	4.77	4.27
300	4.87	4.27
360	4.97	4.27
420	5.07	4.27
480	5.07	4.27
540	4.77	4.27
600	5.05	4.27
720	4.97	4.27
840	4.97	5.57
960	4.97	3.87
1080	4.97	4.57
1200		4.37
1320		4.67
1440		5.17
1800		4.27
2280		4.37
2880		4.37
3480		
3900		

Paulshoek **(G 45816)** **A & B Pumps**

Type installation	BP 22	Waterlevel (mbgl)	0
Borehole depth (m)	132.89	Datum level above casing (m)	0.34
Pump depth (m)	65.82	Casing Height (magl)	0.31
Date and time started	29/10/01(14h20)	Diam pump inlet (mm)	165
Date and time completed	29/10/01(17h35)		

STEP TEST

Time: 14h20

Time	Drawdown	Yield
1	0.88	
2	1.75	
3	2.44	
5	3.20	0.47
7	4.08	
10	4.66	0.46
15	5.49	
20	5.93	0.43
30	6.43	
40	6.72	0.43
50	6.95	
60	7.06	
61	7.20	
62	7.33	
63	7.50	
65	8.19	0.55
67	9.05	0.64
70	9.86	
75	10.82	
80	11.46	0.64
90	12.23	
100	12.67	0.63
110	12.98	
120	13.20	
121	14.95	
122	16.86	1.45
123	18.36	
125	21.11	1.42
127	23.36	
130	26.17	1.42
135	30.32	
140	33.90	1.43
150	39.86	
160	44.10	1.40
170	47.85	
180	54.00	
181	63.80	2.40
182	65.82	

Recovery

Time	Residual Drawdown
1	60.66
2	56.76
3	52.68
5	43.50
7	36.47
10	29.53
15	22.92
20	16.48
30	8.80
40	5.35
50	3.98
60	3.30
70	2.66
80	2.15
90	1.75
100	1.30
110	0.98
120	0.67
150	0.00

CONSTANT DISCHARGE TEST

Date 30/10/01 Time:07h15

Time	Drawdown	Yield
1	0.97	
2	2.10	0.69
3	3.14	
5	4.45	
7	5.46	0.64
10	6.94	
15	7.72	0.65
20	8.67	
30	9.42	0.62
40	9.84	
60	10.30	0.61
90	11.60	
120	12.32	0.62
150	13.04	
180	13.80	0.64
210	14.22	
240	14.48	0.62
300	14.94	
360	15.20	0.61
420	15.76	
480	16.00	0.60
540	16.22	
600	16.41	0.60
720	16.67	0.61
840	16.84	0.61
960	16.98	0.60
1080	17.04	0.62
1200	17.10	0.60
1320	17.16	0.61
1440	17.25	0.60
1560	17.37	0.60
1680	17.40	0.61
1800	17.49	0.60
1920	17.64	0.62
2040	17.89	0.64
2160	18.08	0.62
2280	18.17	0.60
2400	18.28	0.60
2520	18.39	0.61
2640	18.48	0.60
2760	18.57	0.62
2880	18.68	0.61

Recovery

Time	Residual Drawdown
1	16.72
2	15.18
3	14.82
5	12.00
7	10.58
10	9.35
15	7.92
20	6.94
30	5.82
40	5.20
60	4.34
90	3.29
120	2.46
150	1.70
180	1.00
210	0.48
240	0.00

Paulshoek **G 45815** **A & B Pumps**

Type installation	Mono toe BP16	Waterlevel (mbgl)	7.16
Borehole depth (m)	66.1	Datum level above casing (m)	0.3
Pump depth (m)	59	Casing Height (magl)	0.19
Date and time started	2001-01-11 (08h55)	Diam pump inlet (mm)	165
Date and time completed	2001-01-11 (16h29)		

STEP TEST

Time: 03h55

Time	Drawdown	Yield
1	0.20	
2	0.15	
3	0.21	
5	0.29	
7	0.33	
10	0.34	
15	0.50	0.33
20	0.54	
30	0.57	0.33
40	0.59	
50	0.60	0.32
60	0.62	
61	1.38	
62	1.58	
63	1.70	0.87
65	1.81	
67	1.88	
70	1.96	
75	1.99	0.89
80	2.03	
90	2.07	0.88
100	2.09	
110	2.13	0.88
120	2.15	
121	3.40	
122	3.87	
123	4.21	
125	4.56	1.66
127	4.75	
130	4.89	
135	4.99	1.65
140	5.06	
150	5.15	1.66
160	5.20	
170	5.24	
180	5.28	
181	7.59	
182	8.28	
183	9.04	
185	10.02	2.67
187	10.57	
190	10.90	
195	11.25	2.69
200	11.46	
210	11.74	2.69

Recovery

Time	Residual Drawdown
1	19.14
2	12.53
3	8.20
5	3.92
7	2.36
10	1.61
15	1.29
20	1.14
30	1.01
40	0.84
50	0.76
60	0.70
70	0.64
80	0.61
90	0.58
100	0.55
110	0.52
120	0.50
150	0.45
180	0.39
210	0.33
240	0.27

220	11.90	
230	12.02	2.70
240	12.12	
241	12.71	
242	14.28	
243	16.76	4.20
245	19.23	
247	21.03	
250	24.85	4.20

CONSTANT DISCHARGE TEST

Date 30/10/01 Time: 07h15

Time	Drawdown	Yield
1	1.99	
2	3.26	
3	3.72	
5	4.37	
7	5.21	2.07
10	6.41	
15	7.72	
20	8.47	2.09
30	8.72	
40	8.91	
60	9.05	2.09
90	9.20	2.09
120	9.26	2.08
150	9.33	2.08
180	9.46	2.08
210	9.53	2.08
240	9.62	
300	9.77	2.09
360	9.89	
420	9.99	
480	10.06	
540	10.12	
600	10.20	
720	10.47	
840	10.83	
960	11.21	
1080	11.52	2.09
1200	11.60	
1320	11.66	
1440	11.69	
1560	11.75	2.07
1680	11.86	2.09
1800	11.92	2.09
1920	11.98	2.09
2040	12.09	2.08
2160	12.17	2.08
2280	12.21	2.08
2400	12.29	2.08
2520	12.37	2.08
2640	12.49	2.08
2760	12.55	2.08
2880	12.58	2.08

Recovery

Time	Residual Drawdown
1	7.93
2	6.01
3	4.73
5	4.09
7	3.92
10	3.80
15	3.72
20	3.66
30	3.54
40	3.45
60	3.36
90	3.23
120	3.12
150	3.02
180	2.96
210	2.84
240	2.78
300	2.67
360	2.57
420	2.50
480	2.39
540	2.30
600	2.24
720	2.16
840	2.09
960	2.03
1080	2.00
1200	1.96
1320	1.90
1440	1.85
1560	1.81
1680	1.76
1800	1.70
1920	1.65
2040	1.62
2160	1.59
2280	1.56
2400	1.54
2520	1.52
2640	1.50
2760	1.49
2880	1.47

Paulshoek **G 45820** **A & B Pumps**

Type installation	BP 22	Waterlevel (mbgl)	3.72
Borehole depth (m)	132.97	Datum level above casing (m)	0.38
Pump depth (m)	120	Casing Height (magl)	0.28
Date and time started	2001-04-11 (12h30)	Diam pump inlet (mm)	165
Date and time completed	2001-09-11 (07h00)		

STEP TEST

Time: 12h30

Time	Drawdown	Yield
1	0.98	
2	1.17	
3	1.25	
5	1.48	
7	1.60	0.79
10	1.73	
15	1.85	0.81
20	1.96	
30	2.08	
40	2.17	0.80
50	2.23	
60	2.28	
61	2.79	
62	3.04	1.20
63	3.36	1.45
65	3.90	
67	4.18	1.44
70	4.39	
75	4.70	
80	4.86	
90	5.08	1.45
100	5.25	
110	5.39	1.46
120	5.54	
121	8.74	
122	10.72	2.79
123	12.31	
125	14.19	
127	15.44	
130	16.78	
135	18.14	2.79
140	18.90	
150	20.14	
160	21.12	2.80
170	21.77	
180	22.18	
181	25.27	
182	28.57	4.43
183	31.49	
185	36.29	4.42
187	39.76	4.43
190	44.06	
195	49.33	

Recovery

Time	Residual Drawdown
1	53.97
2	43.38
3	34.49
5	21.69
7	13.13
10	7.55
15	5.15
20	4.21
30	3.13
40	2.56
50	2.29
60	2.14
70	2.02
80	1.91
90	1.85
100	1.78
110	1.72
120	1.66
150	1.52
180	1.38
210	1.26
240	1.17
300	1.02
360	0.82
420	0.73
480	0.64
540	0.56

200	52.80	4.39
210	57.54	
220	62.17	
230	64.65	4.40
240	65.45	

CONSTANT DISCHARGE TEST

Date: 05/11/01 Time: 07h00

Time	Drawdown	Yield
1	3.98	
2	5.50	
3	7.94	
5	10.25	2.27
7	12.23	2.52
10	14.30	
15	16.04	
20	16.91	2.53
30	17.82	
40	18.52	2.52
60	19.14	
90	19.78	
120	20.20	2.53
150	20.66	
180	20.99	
210	21.36	2.52
240	21.62	
300	22.10	2.53
360	22.65	
420	23.22	2.51
480	24.12	
540	24.34	2.52
600	24.76	
720	25.25	
840	25.46	2.50
960	25.73	2.53
1080	25.94	2.54
1200	26.27	2.51
1320	26.46	2.53
1440	26.87	2.51
1560	27.54	2.53
1680	28.68	2.50
1800	29.04	2.54
1920	29.28	2.54
2040	29.28	2.52
2160	29.34	2.55
2280	29.41	2.50
2400	29.49	2.52
2520	29.60	2.53
2640	29.73	2.51
2760	29.94	2.54
2880	30.05	2.50

Recovery

Time	Residual Drawdown
1	23.20
2	18.14
3	14.56
5	11.34
7	10.47
10	9.77
15	9.03
20	8.53
30	7.90
40	7.52
60	7.06
90	6.57
120	6.13
150	5.86
180	5.57
210	5.18
240	4.93
300	4.51
360	4.16
420	3.81
480	3.48
540	3.19
600	2.92
720	2.43
840	2.17
960	1.91
1080	1.65
1200	1.39
1320	1.10
1440	0.96
1560	0.81
1680	0.68
1800	0.60
1920	0.54
2040	0.50
2160	0.45
2280	0.39
2400	0.33
2520	0.27
2640	0.24
2760	0.22
2880	0.18

[redacted]

Kamassies 91/1

Type installation	Mono pump (BP 22)
Borehole depth (m)	147
Pump depth (m)	78
Date and time started	2001-09-11 (16H30
Date and time completed	2001-12-11 (7H00)

A & B Pumps

Waterlevel (mbgl)	5.24
Datum level above casing (m)	0.66
Casing Height (magl)	0.08
Diam pump inlet (mm)	165

STEP TEST

Time: 16H30

Time	Drawdown	Yield
1	0.60	
2	1.36	
3	1.94	
5	2.81	
7	3.53	
10	4.31	0.49
15	5.20	
20	5.88	
30	6.81	
40	7.44	0.48
50	7.90	
60	8.28	0.48
61	8.64	
62	9.11	
63	9.45	0.85
65	10.07	
67	10.55	0.87
70	11.05	
75	13.59	
80	15.46	0.86
90	18.48	
100	20.52	
110	21.73	0.87
120	22.45	
121	23.83	
122	25.63	1.49
123	27.58	
125	31.56	1.66
127	35.77	
130	40.90	
135	46.05	
140	49.37	1.65
150	56.38	
160	61.33	
170	64.96	1.65
180	67.25	
181	68.94	
182	69.45	
183	71.75	2.12

Recovery

Time	Residual Drawdown
1	65.55
2	61.27
3	56.51
5	48.65
7	41.18
10	34.37
15	23.76
20	14.27
30	9.70
40	7.44
50	6.12
60	4.80
70	3.94
80	3.08
90	2.22
100	1.98
110	1.74
120	1.20
150	0.96
180	0.57
210	0.28
240	0.09
300	0.00

185	73.05	
187	73.78	
190	73.79	
		1.53
		1.47

CONSTANT DISCHARGE TEST

Date: 10/11/01 Time: 07h00

Time	Drawdown	Yield
1	0.15	
2	0.65	
3	1.42	
5	2.95	
7	4.25	0.81
10	6.11	
15	8.12	0.79
20	9.01	0.72
30	10.57	
40	12.00	
60	16.27	0.73
90	19.95	
120	19.59	
150	19.85	0.72
180	20.12	
210	20.38	
240	20.65	0.71
300	20.72	
360	20.80	0.72
420	20.88	
480	21.16	0.71
540	21.44	
600	21.49	0.71
720	21.70	
840	21.76	0.72
960	21.97	
1080	22.18	0.71
1200	22.39	
1320	22.60	0.72
1440	22.92	
1560	23.22	0.72
1680	23.60	
1800	23.79	0.72
1920	23.87	
2040	23.96	0.71
2160	24.17	
2280	24.31	0.72
2400	24.59	
2520	24.71	0.71
2640	24.83	
2760	24.95	0.72
2880	25.16	0.72

Recovery

Time	Residual Drawdown
1	21.83
2	19.26
3	17.72
5	14.26
7	11.99
10	10.92
15	10.43
20	10.08
30	9.57
40	9.03
60	7.75
90	5.50
120	4.23
150	3.14
180	2.20
210	1.69
240	1.33
300	0.99
360	0.65
420	0.40
480	0.22
540	0.08
600	0.00

Leliefontein ?

Type installation	Mono pump (BP 16)
Borehole depth (m)	45.8
Pump depth (m)	41
Date and time started	14/11/01 14h30
Date and time completed	

A & B Pumps

Waterlevel (mbgl)	3.51
Datum level above casing (m)	0.73
Casing Height (magl)	0
Diam pump inlet (mm)	165

STEP TEST

Time: 14H30

Time	Drawdown	Yield
1	0.60	
2	0.83	
3	1.00	
5	1.15	
7	1.28	
10	1.37	
15	1.48	
20	1.54	0.20
30	1.64	
40	1.68	0.21
50	1.71	0.22
60	1.73	
61	2.05	
62	2.34	
63	2.56	0.41
65	2.78	
67	2.92	
70	3.02	0.42
75	3.14	
80	3.22	
90	3.30	0.40
100	3.35	
110	3.40	0.41
120	3.43	
121	4.00	
122	4.90	0.98
123	5.29	
125	6.65	
127	8.20	
130	11.33	0.97
135	14.89	
140	16.67	0.97
150	19.80	
160	21.72	0.93
170	23.85	
180	26.50	
181	28.40	
182	31.89	1.74
183	38.08	
185	38.38	
187 pis		0.93
190		0.87

Recovery

Time	Residual Drawdown
1	32.48
2	29.10
3	27.85
5	24.82
7	20.40
10	14.59
15	7.00
20	4.86
30	2.16
40	1.31
50	0.92
60	0.70
70	0.60
80	0.53
90	0.47
100	0.45
110	0.41
120	0.37
150	0.35
180	0.33
210	0.31
240	0.31
300	0.29
360	0.27
420	0.25

CONSTANT DISCHARGE TEST

Date: 15/11/01 Time: 08h20

Time	Drawdown	Yield
1	0.55	
2	0.86	
3	1.00	
5	1.33	0.46
7	1.52	
10	1.67	
15	2.77	
20	3.80	0.52
30	4.35	
40	4.62	0.53
60	4.80	
90	4.94	0.52
120	5.46	
150	5.71	0.50
180	5.82	
210	6.10	0.50
240	6.20	
300	6.61	0.49
360	6.94	
420	7.00	0.51
480	7.07	
540	7.18	0.50
600	7.51	0.49
720	7.88	0.50
840	8.94	0.51
960	9.70	0.50
1080	10.62	0.50
1200	11.15	0.52
1320	11.46	0.50
1440		0.50

Recovery

Time	Residual Drawdown
1	6.90
2	6.71
3	6.48
5	5.73
7	5.15
10	4.48
15	3.15
20	2.46
30	1.90
40	1.60
60	1.31
90	1.14
120	1.07
150	1.02
180	0.98
210	0.94
240	0.90
300	0.83
360	0.78
420	0.72
480	0.70
540	0.68
600	0.66
720	0.59
840	0.56
960	0.52
1080	0.48
1200	0.46
1320	0.42
1440	0.40

Nourivier G45839

DWAF-Mr Willie Koetsee

Type installation	Mono R2
Borehole depth (m)	108
Pump depth (m)	100
Date and time started	2001-09-11
Date and time completed	

Waterlevel (mbgl)	5.79
Datum level above casing (m)	?
Casing Height (magl)	0.18
Diam pump inlet (mm)	165

STEP TEST

Time: ?

Time	Drawdown	Yield
1	5.70	
2	6.58	
3	7.09	0.25
5	7.83	
7	8.48	
10	9.49	
15	10.45	
20	11.22	
30	12.34	
40	13.10	
50	13.72	
60	14.11	
61	14.63	
62	15.00	0.42
63		
65	15.56	
67	16.36	
70	17.76	
75	19.42	
80	20.52	
90	21.84	
100	22.95	
110	23.73	
120	24.31	
121	25.79	
122	26.74	0.60
123	27.44	
125	29.15	
127	30.19	
130	30.86	
135	32.17	
140	33.23	
150	35.81	
160	37.47	
170	38.35	
180	39.13	
181	40.35	1.00
182	41.50	
183	42.46	
185	43.94	
187	45.28	
190	47.02	
195	49.58	

Recovery

Time	Residual Drawdown
1	58.98
2	57.12
3	55.19
5	52.40
7	49.16
10	45.63
15	41.40
20	37.21
30	32.83
40	27.70
50	26.59
60	25.79
70	24.25
80	23.20
90	22.25
100	21.41
110	20.65
120	20.16
150	18.82
180	17.45
210	16.48
240	15.40
	14.82
	14.28
	13.70
	13.25
10-Nov	6.51
10-Nov	6.51

200	52.03
210	55.63
220	58.59
230	61.34
240	64.22

CONSTANT DISCHARGE TEST

Date: 12/11/01		Time:?	**Recovery**	
Time	Drawdown	Yield	Time	Residual Drawdown
1	7.32	0.25	1	31.18
2	8.71		2	30.70
3	10.00		3	30.12
5	11.93		5	29.31
7	13.38		7	28.56
10	15.21		10	27.69
15	17.28		15	26.50
20	19.41		20	25.58
30	20.39		30	24.14
40	24.31		40	23.17
60	21.97		60	21.96
90	23.61		90	20.17
120	24.70		120	19.13
150	25.60		150	18.12
180	26.31		180	17.30
210	26.97		210	16.00
240	27.85		240	16.45
300	28.95		300	15.39
360	29.68			
420	30.25			
480	30.70			
540	31.40			
600	31.99			
		13-Nov	11.23	