UNIVERSITY *of the* WESTERN CAPE

TESTING AND EVALUATION OF ARTESIAN AQUIFERS IN TABLE MOUNTAIN GROUP AQUIFERS

Dissertation submitted to the University of the Western Cape in the fulfilment of the degree of Doctor of Philosophy

by

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DECLEARATION

I declare that **TESTING AND EVALUATION OF ARTESIAN AQUIFERS IN TABLE MOUNTAIN GROUP AQUIFERS** is my own work, and that 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.

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ABSTRACT

Testing and evaluation of artesian aquifers in Table Mountain Group Aquifers

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Keywords: Fractured rock aquifer, hydraulic properties, hydraulic test device, hydraulic testing, conceptual model, groundwater storage capacity, analytical solution, reciprocal rate derivative, artesian aquifer, Table Mountain Group, free-flowing

The Table Mountain Group (TMG) Aquifer is a huge aquifer system which may provide large bulk water supplies for local municipalities and irrigation water for agriculture in the Western Cape and Eastern Cape Provinces in South Africa. In many locations, water pressure in an aquifer may force groundwater out of ground surface so that the borehole drilled into the aquifer would produce overflow without a pump. Appropriate testing and evaluation of such artesian aquifers is very critical for sound evaluation and sustainable utilization of groundwater resources in the TMG area. However, study on this aspect of hydrogeology in TMG is limited. Although the flow and storage of TMG aquifer was conceptualised in previous studies, no specific study on artesian aquifer in TMG was made available.

There are dozens of flowing artesian boreholes in TMG in which the pressure heads in the boreholes are above ground surface locally. A common approach to estimate hydraulic properties of the aquifers underneath is to make use of free-flowing and recovery tests conducted on a flowing artesian borehole. However, such testing approach was seldom carried out in TMG due to lack of an appropriate device readily available for data collection. A special hydraulic test device was developed for data collection in this context. The test device was successfully tested at a flowing artesian borehole in TMG. The device can not only be used to measure simultaneous flow rate and pressure head at the test borehole, but also be portable and flexible for capturing the data during aquifer tests in similar conditions like artesian holes in Karoo, dolomite or other sites in which pressure head is above ground surface.

The straight-line method proposed by Jacob-Lohman is often adopted for data interpretation. However, the approach may not be able to analyse the test data from flowing artesian holes in TMG. The reason is that the TMG aquifers are often bounded by impermeable faults or folds at local or intermediate scale, which implies that some assumptions of infinite aquifer required for the straight-line method cannot be fulfilled. Boundary conditions based on the Jacob-Lohman method need to be considered during the simulation. In addition, the diagnostic plot analysis method using reciprocal rate derivative is adapted to cross-check the results from the straight-line method. The approach could help identify the flow regimes and discern the boundary conditions, of which results further provide useful information to conceptualize the aquifer and facilitate an appropriate analytical method to evaluate the aquifer properties.

Two case studies in TMG were selected to evaluate the hydraulic properties of artesian aquifers using the above methods. The transmissivities of the artesian aquifer in TMG range from 0.6 to 46.7 m^2/d based on calculations with recovery test data. Storativities range from 10^{-4} to 10^{-3} derived from free-flowing test data analysis. For the aquifer at each specific site, the transmissivity value of the artesian aquifer in Rawsonville is estimated to be 7.5–23 m^2/d, with storativity value ranging from 2.0×10^{-4} to 5.5×10^{-4}. The transmissivity value of the artesian aquifer in Oudtshoorn is approximately 37 m^2/d, with S value of 1.16×10^{-3}. The simulation results by straight-line and diagnostic plot analysis methods, not only imply the existence of negative skin zone in the vicinity of the test boreholes, but also highlight the fact that the TMG aquifers are often bounded by impermeable faults or folds at local or intermediate scale.

With the storativity values of artesian aquifers derived from data interpretation, total groundwater storage capacity of aquifers at two case studies was calculated. The figures will provide valuable information for decision-makers to plan and develop sustainable groundwater utilization of artesian aquifers in local or intermediate scales. With the hydraulic test device readily available for data collection, more aquifer tests can be carried out in other overflow artesian boreholes in TMG. It becomes feasible to determine the hydraulic properties of artesian aquifers for the entire TMG. Thereof quantification of groundwater resources of artesian aquifers in TMG at a mega-scale becomes achievable. This would also contribute towards global research initiative for quantification of groundwater resources at a mega-scale.

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ABBREVIATIONS

BH	borehole
ch	collar height
DN	diameter nominal
DPFM	Differential Pressure Flow Meter
DWA	Department of Water Affairs
GAB	great Artesian Basin
GH report	geohydrology report at the DWA
GIS	Geological Information System
GRA II	Groundwater Resource Assessment Phase II
GW	groundwater
IARF	Infinite Acting Radial Flow
L	length
Ma	million years
mamsl	meters above mean sea level
magl	meters above ground level
mbch	meters below collar height
mbgl	meters below ground level
NGDB	National Groundwater Database
PRF	Pressure Release Flowing Test
RSA	Republic of South Africa
SUP	Sustainable Utilizable Potential
TMG	Table Mountain Group
UAB	Uitenhage Artesian Basin
UFM	Ultrasonic Flow Meter

UWC University of the Western Cape

VBA Visual Basic for Applications

WL Water level

WMA Water Management Area

WRC Water Research Commission

NOTATIONS

A	The size of confined aquifer
A_{crop}	The area of TMG outcrop
B	Leakage factor
D	Diameter of pipe or the thickness of confined aquifer
D'	Saturated thickness of the aquitard
h	Artesian head of artisan aquifer above ground surface
h_{min}	The lowest water level during hydrogeological year
h_{max}	The lowest water level during hydrogeological year
K	Hydraulic conductivity
K'	Hydraulic conductivity of the aquitard for vertical flow
kPa	Kilopascal
L	Length of pipe
m	The reciprocal rate derivative
n	Porosity
Pa	Pascal
Q	Flow rate
r_i	The distance between the image borehole and barrier
r_w/r_{ew}	Effective radius of test borehole
s	Drawdown
s'	Residual drawdown
S	Storativity
S'	Storativity during recovery
S_s	Specific storage
S_w	Constant drawdown
S_y	Specific yield
t	Time since the start of free-flowing test

t'	Time since cessation of free-flowing test
T	Transmissivity
V	Total groundwater in storage
V_a	Adjustable storage
V_0	The maximum volume of groundwater released from artesian aquifer
V_p	Available pressurized storage of artesian aquifer
$W(u,r_{ew}/B)$	Hantush's borehole function for leaky aquifer

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Chapter 1

Introduction

1.1 Background

The Table Mountain Group (TMG) is a strategic aquifer system in South Africa. It is a huge aquifer system that extends from the northwest of the Western Cape to the northeast of the Eastern Cape, consisting of a suite of sedimentary hard rocks produced in the Ordovician-Devonian period. The significance of the TMG groundwater for water supply in the arid or semi-arid areas of the nation has long been stressed due to the good water quality and a big potential of water abstraction from the fractured sandstones. Studies of the TMG aquifer system have become continuous in the past 10 years as regarding the hydrogeological settings, hydraulic properties of aquifers, and accordingly the groundwater storage and circulation.

There are voluminous borehole hydraulic test data in TMG available for the analyses of aquifer properties on the traditional basis (Rosewarne, 2002). Estimation of the intrinsic aquifer properties in TMG such as hydraulic conductivity (K), transmissibility (T), and storativity (S) and specific yield (S_y) using pumping test and remote sensing etc has been well elaborated by Lin (Lin et al., 2007). These estimated aquifer parameters are very critical in groundwater resources evaluation, management, and sustainable development in TMG area. An overestimate of T and S, for instance, may lead to water level withdraw from the aquifer exceeding its normal capacity, which would cause water level drop significantly and aquifer degradation in a long-term water supply. The current studies on hydraulic properties of the TMG aquifers through field tests are mainly concentrated on the unconfined aquifer and confined aquifer, in which the water level is below ground surface. However, hydraulic testing and evaluation of artesian aquifers in TMG in which the pressure head is above ground surface have not become a systematic research yet.

A common approach to evaluate artesian aquifer properties is to make use of free-flowing and recovery tests conducted on a flowing artesian borehole drilled into the aquifer. Instantaneous flow rate and pressure head at test borehole will be measured during the tests. However, many flowing artesian boreholes in TMG cannot be tested properly using conventional pumping test approaches, due to the fact that no proper device is readily available for data collection. It is noted that flow rate and pressure of the artesian borehole change so rapidly at the beginning of the test that measurements using the conventional method can hardly be accurate. Therefore, a special hydraulic test device for data collection in this context is deemed to be critical.

With hydraulic testing data captured by the proper test device, evaluation of aquifer properties and storage of artesian aquifers in TMG become achievable. First, conceptualization of hydraulic testing at flowing artesian hole should be developed based on the local hydrogeological information. Then appropriate model can be utilized to estimate the T and S values of artesian aquifer. Further evaluation of groundwater resources in artesian aquifers in TMG can be derived with S value made available.

1.2 Research objectives

The research objectives consist of the following components, namely:

1. Literature review and introduction of artesian aquifer in TMG;
2. Development of hydraulic test device for data collection. Instantaneous flow rate and pressure head at test borehole was measured by the device during the tests;
3. Conceptualization of hydraulic testing at flowing artesian borehole;
4. Methodology and software development for interpretation of tests data;
5. Evaluation of artesian aquifer properties (T and S values) with case studies in TMG;
6. Estimation of groundwater storage capacity in artesian aquifer in TMG; and
7. Guideline development for hydraulic testing at flowing artesian borehole

1.3 Site selection

Two case studies in TMG area are selected and documented to test and evaluate hydraulic properties of artesian aquifers, namely, artesian aquifers in Rawsonville area and Oudtshoorn area. Reasons to select these two sites are listed as follows:

- The two artesian sites in TMG are the typical areas with tectonic characteristics and hydrogeological settings;
- Accessibility of the study areas; and
- Availability of relatively comprehensive data sets. A few aquifer tests were conducted in well-field in Rawsonville, by which the results are useful to develop conceptual model of the study area; while in Oudtshoorn artesian basin, a two-month free-flowing and six-month recovery tests were carried out during the dry season (Hartnady et al., 2013). Flow rates were measured manually, and the pressure head at test borehole and observation hole were captured with data logger. No data

interpretation has been completed since then. Results from data analyses will help conceptualize the artesian aquifers at local or intermediate scale.

1.4 Layout of this thesis

The abovementioned objectives can be reached with a combination of available site-specific data, related experience, and scientific knowledge of the TMG hydrogeology, geology/geological structure, and geomorphology. Characterization of hydraulic properties of artesian aquifer based on the analysis of these data requires an experienced interpretation of available data and a full understanding of the flow process during the hydraulic testing at flowing artesian borehole. This study would provide valuable information for groundwater flow conceptualization and evaluation of deep groundwater resources in TMG.

The structure of this dissertation is developed into nine chapters regarding seven objectives of this study. It begins with a brief background, the objectives expected to be achieved in this study and site selections as case studies in Chapter 1. For objective 1, based on the description of geology and hydrogeology settings, aquifer delineation and the related researches, general studies on artesian aquifer (literature review) and conceptualization of artesian aquifer in TMG are discussed in Chapter 2 and Chapter 3, respectively.

Objective 2 will be covered in Chapter 4, and Objectives 3 and 4 will be covered in Chapter 5. A special hydraulic test device is developed to measure instant flow rate and pressure head during hydraulic testing in a flowing artesian borehole. Procedures of installation of the device and hydraulic testing at flowing artesian borehole in the field are outlined in Chapter 4 in particular. Conceptualization of hydraulic testing at flowing artesian borehole is developed in Chapter 5. Different analytical models and solutions to evaluate hydraulic properties and relevant software are developed and discussed. The diagnostic plot analysis method is reviewed and applied to evaluate the artesian aquifer properties at local or intermediate scale. Noise elimination is highlighted in particular. The method using reciprocal rate (reciprocal rate derivative) is developed to cross check the results from conventional approach at the end of Chapter 5.

Chapter 6 and Chapter 7 cover objectives 5 and 6, respectively. In Chapter 6, two case studies in TMG area (Rawsonville and Oudtshoorn) are selected and documented to evaluate the artesian aquifer properties. Hydraulic testing at a flowing artesian borehole was conducted at the first case study of Rawsonville in 2012, with data captured by the test device. For the case study of Oudtshoorn, a two-month free-flowing test and six-month recovery test were carried out in 2009, with data collected manually. No proper data interpretation has been made since then. With collected data, *T* and *S* values of artesian aquifers at both study sites were estimated using a program developed in Excel using Visual Basic for Applications (VBA). Skin factor, effective radius and boundary conditions are particularly discussed. The diagnostic plot method is applied with free-flowing test data to evaluate the aquifer properties as well. The results are compared with the ones derived from conventional straight-line method. In Chapter 7, with storativity (*S*) estimate derived from data analysis, groundwater storage capacity of artesian aquifers at study sites will be evaluated.

In Chapter 8, a guide to hydraulic testing in artesian aquifer is developed, with specific reference to artesian aquifer in TMG. The guideline may be used to guide the researchers for testing and evaluation of artesian aquifer in similar conditions in future, e.g. the artesian aquifer in Karoo Aquifers in South Africa.

In Chapter 9, a comprehensive summary is made, followed by a brief conclusion and the suggestions for further work. The dissertation ends with the references and appendices.

Chapter 2
Literature review

2.1 Introduction

An aquifer is a geologic formation, either unconsolidated material like sand and gravel or permeable bedrock, which readily transmits water and is tapped for supplying groundwater to water-supply wells. In some cases, groundwater may be under pressure because the aquifer is overlain by a confining layer, such as clay or shale. The confining layer restricts the movement of groundwater and pressure can then build up within an aquifer, which refers to the confined aquifer. This condition can occur when the aquifer is recharged at a point of higher elevation than the location in which the aquifer is under pressure. When a borehole taps the underlying aquifer, the water level will rise in the borehole to a level above the top of the aquifer. This type of borehole is an artesian borehole. If the water level is above ground surface, the borehole is then called a "flowing borehole", or "flowing artesian borehole". All flowing boreholes are artesian, but not all the artesian boreholes are flowing boreholes.

Flowing artesian boreholes have intrigued mankind for centuries. This point was illustrated by Freeze and Cherry in 1979, who stated: "Flowing wells (along with springs and geysers) symbolize the presence and mystery of subsurface water, and as such they have always evoked considerable public interest". According to David and Dewiest (1966), the widespread search for artesian water that occurred after the completion of flowing boreholes in Flanders (now Belgium and Netherlands) around 1100 A.D., and later in 18th century in the northern France province of Artois, Western England, and Northern Italy, was responsible for stimulating the advancement of water well drilling technology.

Elevation and loading are two distinct hydrogeological forces that account for the development of flowing artesian boreholes. Artesian conditions can be either geologically-controlled or topographically-controlled (Fig. 2.1). For the later type of artesian condition, the free-flowing borehole can take place in unconfined aquifer condition where the hydraulic head (or pressure) value is higher than the land surface.

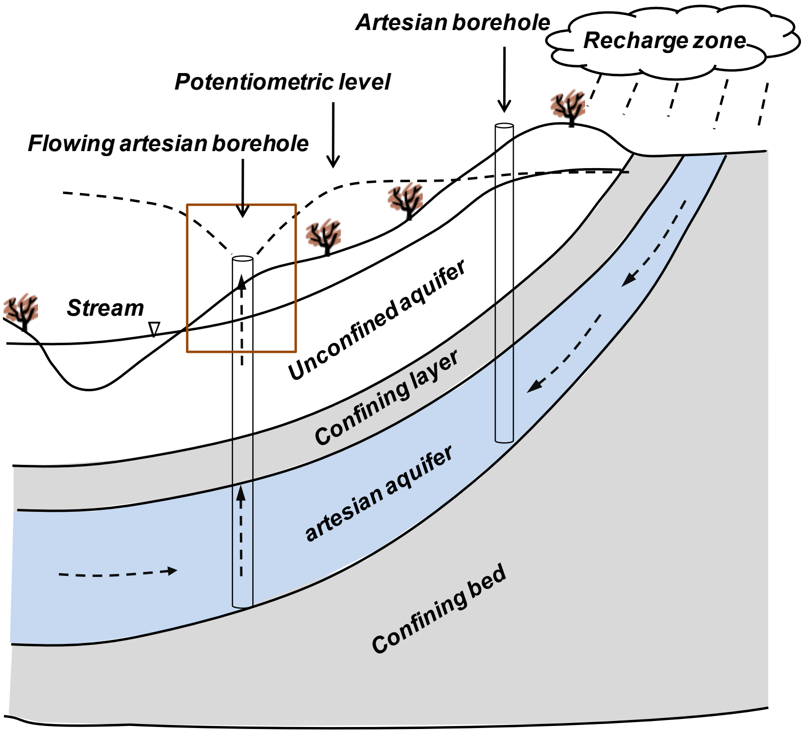


Fig. 2.1: Geologically-controlled flowing artesian borehole

Take artesian aquifer in TMG as a typical example, borehole BH-1 drilled in TMG Peninsula Formation on the Gevonden farm has a potentiometric surface well above ground surface. For this borehole, the core sample was logged and packer tests were conducted to identify specific positions of the aquifer. But aquifer test could not be applied properly as no suitable methods were available to do the intended test. This type of dilemma that we were facing in the field is not uncommon, especially in TMG area.

Generally speaking, the sustainable management of groundwater resources is dependent on how well the aquifer system is understood. The rate of abstraction of groundwater should ensure that the long term use of the resource has minimum impact on the aquifer and its dependent ecosystems. In many cases the absence of sound estimates of critical parameters such as hydraulic conductivity and storativity results in the inaccurate estimation of resources availability. This leads to the over abstraction from boreholes and eventual dewatering and potentially deteriorating groundwater quality.

In general, estimation of aquifer hydraulic properties is achieved by pumping test. The most common form of pumping test is constant-rate pumping test in which a borehole is abstracted at a constant rate and the water level is measured in the pumping borehole itself, and, optimally, in one or more surrounding observation boreholes. However, a flowing artesian borehole spontaneously discharges water without being pumped. The conventional hydraulic testing on such a borehole and estimating of aquifer properties (where groundwater occurs in reasonable quantities, it is referred to as an aquifer) are still challenging for hydrogeologists.

In this chapter, common methods of aquifer test for non-artesian aquifer and artesian aquifer are summarized at the beginning, followed by an introduction of the conventional ways of measurements during the tests. Theories to interpret the test data are summarized. Methods for interpreting the aquifer test data in flowing artesian boreholes are highlighted in particular. Inasmuch as single borehole test is one of the most popular methods conducted on a flowing artesian borehole, methods to determine skin factor and effective radius under this context will be discussed.

2.2 Overview of aquifer tests

2.2.1 Constant-rate test

Constant-rate test as one of the most popular ones in practical can be used under either confined or unconfined aquifer condition, where the pumping borehole is pumped at a constant volumetric flow rate, and the resultant head change is monitored at the same borehole or observation borehole. Theories for analysing constant-rate aquifer test data are based on a method proposed by Theis (1935) who was the first to develop a formula for unsteady-state flow that introduces the time factor and the storativity. Based on the Theis formula, a simpler method was developed by Cooper and Jacob (1946). For most applications, the log-log curve-fitting approach (Theis method) and semi-log straight-line method (Cooper-Jacob method) are the preferred methods for analysis of pumping test data. Besides the two methods, superposition may be used to account for the effects of pumping borehole interference, aquifer discontinuities, groundwater recharge, well storage and variable pumping rates.

2.2.2 Constant-head test

Another popular pumping test approach is constant-head test. The water level of test borehole is adjusted and maintained at a constant head during the test, with discharge rate at test hole being monitored as a function of time. This pumping method is more easily conducted at a flowing artesian and a borehole drilled into an unconfined aquifer that has very low transmissivity. A specific pump and a flow meter are required to control the drawdown level and measure discharge rate for the latter case. Borehole skin effect needs to be considered as the skin zone might be caused by the mud and/or the formation damage during drilling process (Chen and Chang, 2006), and the existence of skin zone may have significant impact on the discharge from the flowing artesian borehole.

Since the test borehole is flowing artesian borehole, of which the water level is above ground surface. Constant-head test method is often preferred over constant-rate test. The advantage of this method is that there is little effect from borehole storage. From operational standpoint, free-flowing test is preferable in the artesian borehole. In this case, the water head would be dropped and maintained at ground level or the altitude of borehole rim; while instant flow rate and pressure head of borehole will be monitored during the test.

The major disadvantage with constant-head test at flowing artesian borehole is the difficulty of maintaining a constant head if the transmissivity of aquifer is low or the possibility that the available drawdown is limited due to low transmissivity, storativity or borehole construction. In such case, the test borehole should be shut-in with a cap near ground surface till the static pressure condition is built-up. Other disadvantages also include the influences from skin effect and the barometric pressure during the test (Papadopulos and Cooper, 1967; Agarwal et al., 1970). Both factors may need to be taken into account if they have significant impacts on the test data.

2.2.3 Step-drawdown test

Step-drawdown pumping test as another popular single-borehole pumping test method is often used to determine the formation loss and borehole loss constants. In addition, it may be used to determine the proper discharge rate for the subsequent aquifer tests and the hydraulic conductivity value. It is usually carried out with increased discharge rate through at least three steps, which should all be of equal duration, say from 30 minutes to 2 hours each (Kawecki, 1995).

2.2.4 Recovery test

When the pump is shut down after the pumping period, the water levels in the borehole and piezometer will start to rise. Water levels could be monitored at both test borehole and observation hole during the test, and the process is known as recovery test. It allows the transmissivity of the aquifer to be calculated based on principle of superposition. During the recovery process, it is presumed that the rate "recharge" to the borehole is constant, whereas the constant discharge-rate pumping method is often difficult to achieve in the field, therefore, recovery test could provide an independent check on the results of pumping test, moreover, the cost is very little compared with the pumping test.

It is widely acknowledged that the transmissivity derived from recovery test data analysis is often found smaller yet more reliable than the one derived with conventional pumping test data analysis. Therefore, a recovery test is invaluable if the pumping test is performed without the use of piezometers.

2.2.5 Slug test

Slug test is a popular and invaluable method for rough hydraulic conductivity estimation. The test can be completed within a few minutes or at the most a few hours with no piezometer required. If the transmissivity of the aquifer is higher than, say, 250 m^2/d, the automatic data logger might be needed to record the water level response instead of measuring manually. Although slug test is a simple test method to estimate the hydraulic conductivity of the aquifer, it cannot be regarded as a substitute of conventional pumping test, as the volume which is removed by the solid cylinder or slug is small, and the formation surrounding the borehole may have been disturbed during the borehole drilling or construction. Therefore, the result from the test can only represent the vicinity formation surrounding the borehole. Nevertheless, it could still give a fairly accurate result of hydraulic conductivity (Ramey et al., 1975; Bouwer and Rice, 1976; Moench and Hsieh, 1985).

2.2.6 Packer test

Horizontal hydraulic conductivity (K) for consolidated rock can be determined by a packer test conducted in a stable borehole. It is often used to test a section of borehole, typically a section to 1.5 or 3 m, between the borehole bottom and the packer location. With two packer systems, theoretically, the hydraulic parameters of aquifers at any position or interval could be determined in a completed borehole.

In general, analytical techniques are preferred methods to interpret the test data under one or several assumptions. With different analytical methods available, researchers often find more than one method that could reasonably approximate the field condition. However, one or several assumptions at the given condition must be taken into account and should generally represent the field condition to some extent. Besides the analytical methods described above for pumping test data analysis, numerical models can also be utilized to interpret the pumping test data.

2.2.7 Numerical models

Numerical modelling for pumping test analysis has been adopted for many projects in the past 30 years. Rushton and Booth (1976), Laksminarayana and Rajagopalan (1977, 1978), Rathod and Rushton (1984, 1991), Bennett et al. (1990), Bulter and McElwee (1990), Rutledge (1991), Reilly and Harbaugh (1993), Pandit and Aoun (1994) and Cheong et al. (2008) have applied and developed the numerical models for pumping test data analysis. Finite difference and finite element codes have been developed for pumping test in two and three dimensions. The MODFLOW and FEFLOW codes are very powerful tools to evaluate the drawdown from constant-rate test (Warren and Martin, 1997; Michael and Colin, 1998; Neil and Toya, 2011). In many cases, assumptions can be made to meet the needs of specific situation. In addition, with the parameters calibration afterwards, the results may provide the user more insight into the conceptual models of the flow systems, what is more, the significance of some parameters could be found by doing sensitivity analysis, and different scenarios can be simulated for prediction of the behaviour of the system (Butler and McElwee, 1990; Jiao, 1995).

2.2.8 Other methods

There are some other methods to determine the hydraulic conductivity of the aquifer. Like single boring method, laboratory determination and particle size analysis. For instance, the single boring method, a boring is advanced into aquifer with the water level in boring allowed to reach the static condition; water is then removed with water level versus time measurements collected in the same method as the rising head slug test. The data is then evaluated using Ernst or Hooghoudt equation to get a quick estimate of hydraulic conductivity (Ernst, 1950; Hooghoudt, 1936). For laboratory determination, an undisturbed sample of aquifer material is used in either constant head or falling head permeability test. Typically, the constant head is used for sands and gravels while the falling head is for fine sand grained soils. Particle size analysis uses Hazen method to determine the hydraulic conductivity of the saturated media. The relationship is based on observations of loose, clean sand; therefore, it is only used on unconsolidated materials having a grain-size of 10 percent finer by weight than 0.1-3.0 mm ($0.1 < D_{10} < 3.0$).

In summary, theoretically all these methods could be applied to estimate the hydraulic conductivity (K) and/or storativity (S) under certain conditions. The selection of methods depends on the required accuracy, the performable protocol and the cost, etc.

However, not all boreholes drilled in confined and semi-confined aquifers can be tested through numerical models or conventional approaches which include constant rate test, multi-rate and slug tests, etc. In reality, pumping test is still the most popular method to evaluate the aquifer properties. If the aquifer is non-artesian aquifer, the choice between constant-rate and constant-head test relies on the expected transmissivity (T) and available drawdown. For the artesian aquifer with hydraulic pressure above ground surface, constant-head test is preferred over constant-rate test for practical reasons.

2.3 Aquifer test at flowing artesian borehole

Common hydraulic testing such as constant-rate and step-drawdown tests requires a static water level at the beginning of the test, and the measurements of flow rate (fixed for a period of time) and water level are taken during the test. Such methods may be applied to a flowing artesian borehole under certain conditions. A valve needs to be adjusted to control the flow rate from artesian hole, and flow rate and pressure head can be measured during the tests. It is assumed that the flow rate remains stable over a certain period of time. Methods for data interpretation can refer to constant-rate test and step-drawdown test (Birsoy and Summers, 1980).

In practice, constant-head test as another variant in hydraulic testing is often preferred over constant-rate test and step-drawdown test for practical reasons, since maintaining a constant head is generally easier than maintaining a constant rate for such case. During the constant-head test, the test borehole is kept at a constant head, with flow rate being monitored as a function of time. Methods for data interpretation refer to Jacob and Lohman method (Jacob and Lohman, 1952), Hantush method (Hantush, 1959) and Glover method (Glover, 1978) etc.

2.3.1 Flow rate measurement

Unlike the usual constant-rate pumping test, a flowing artesian borehole drilled into an artesian aquifer in which the hydrostatic head is higher than the land surface, no pump is needed to run the aquifer test. From an operational standpoint, free-flowing and recovery tests are often adopted to estimate the hydraulic properties of artesian aquifer. The tests involve allowing the groundwater flowing freely without pumping under the artesian condition for a certain time, while measurements of discharge rate and pressure at artesian borehole are taken simultaneously. Discharge measurement is usually taken using a certain volume of bucket and timer under low flow rate conditions (flow rate = volume/time), or using the V-notch weir under high flow rate circumstances (Fig. 2.2). However, the flow and pressure of the artesian hole change so rapidly at the beginning of the free-flowing test that measurements using the conventional method can hardly be accurate. Therefore, a special hydraulic test device for data collection in this context is deemed to be critical.

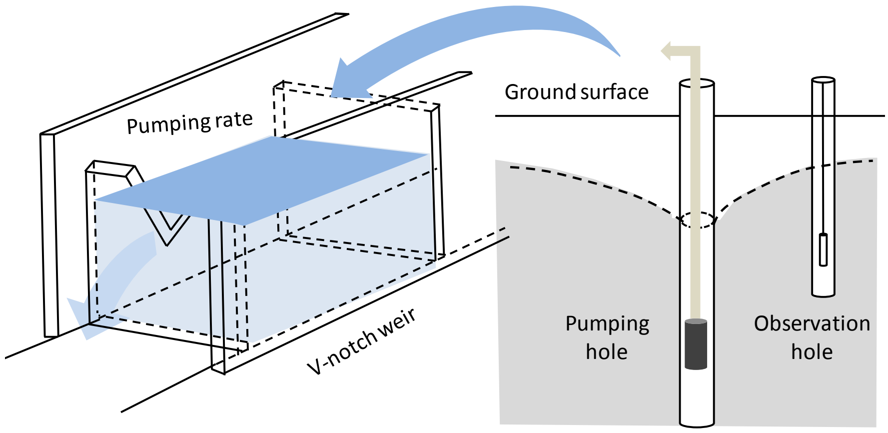
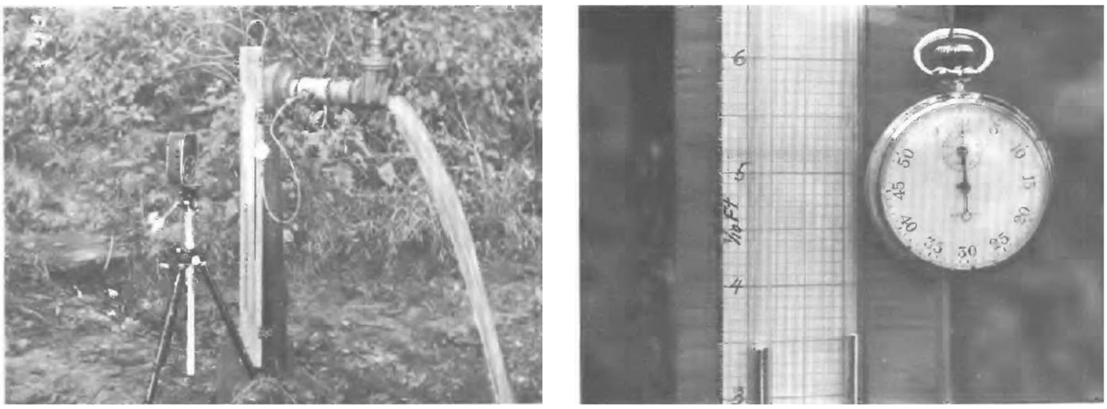


Fig. 2.2: Conventional method of flow rate as well as water level data collection from pumping test

2.3.2 Pressure head measurement

The conventional measurement of hydraulic head is often made by measuring the water level in a clear plastic hose that is connected to a tap in the borehole casing. A number of studies of data capture using such devices applied to a flowing artesian borehole have been carried out since 1960s. A mercury manometer can be used to measure the water head (Wyrick and Floyd, 1961). In 1961, a manometer tube and a stopwatch were used to capture the data from recovery test done by USGS (Fig. 2.3). An 8-mm motion-picture camera was adjusted to nominal values of 12, 16, 24 and 32 frames per second. The camera was focused to include both the manometer tube and the stopwatch in each frame and was set at the position for 24 frames per second. Thanks to the technical setting of camera, the change in pressure in the manometer tube was recorded at intervals of 1/25 second.

In 1979, an artesian aquifer test was conducted in Stanfield, Oregon (Oberlander and Almy, 1979). The test lasted for 46 hours and 8 minutes. Water level measurements were made during flowing and recovery periods with an airline and calibrated pressure gauge. Instantaneous flow rate measurements were made using a Polysonics model UFM-PD (Polysonics Portable Ultrasonic Flowmeter) calibrated at the Portland Water Works meter calibration lab and installed according to manufacturers specifications. Water level was controlled by the discharge elevation of storage reservoir. Water level in the borehole was measured using calibrated gauges installed at the borehole head. Gauges used for pressure measurements were calibrated before the test. All the boreholes involved directly in the test were required to recover at least 48 hours prior to the start of the aquifer test. No large production boreholes were known to be pumped within 7.5 km of the pumped borehole during the test. The above rule needs to be applied in any other pumping test to avoid the impact from other pumping activities.



a) typical equipment setup b) typical frame from film strip

Fig. 2.3: Photographs of equipments used in microtime measurements of groundwater recovery tests in Martin County, Florida (Wyrick and Floyd, 1961)

2.3.3 Water-level corrections

In reality, water-level fluctuations in artesian aquifer can be caused by barometric pressure or earth tidal stresses besides recharge, evapotranspiration and groundwater abstraction etc. Identifying and removing such effects in confined artesian aquifers are necessary in some cases.

2.3.3.1 Water-level changes induced by barometric pressure

It is commonly known that barometric pressure can change water-level in boreholes within confined and unconfined aquifers. Fluctuations in water levels in an open borehole due to barometric pressure changes were noted by Blaise Pascal in 1660s, who was considered as the first to propose that the earth’s atmosphere exerted a surface pressure (Pascal, 1973; Gossard and Hooke, 1975). The relationship between water-level and barometric pressure is an inverse one; increases in barometric pressure create declines in observed water-level and vice versa (Freeze and Cherry, 1979).

For unconfined aquifer, the pressure at the top of the unconfined aquifer is supported partly from the rock skeleton and partly from the water thus introducing a time lag for equilibrium to be reached in hours or days. On the contrary, the water level in the confined artesian aquifer is reached without lag. The transmission of atmospheric pressure is instantaneous both to the borehole and aquifer, being functions of the degree of confinement, matrix rigidity and specific weight of water. The schematic water-level change in artesian aquifer induced by barometric pressure variation is shown in Fig. 2.4.

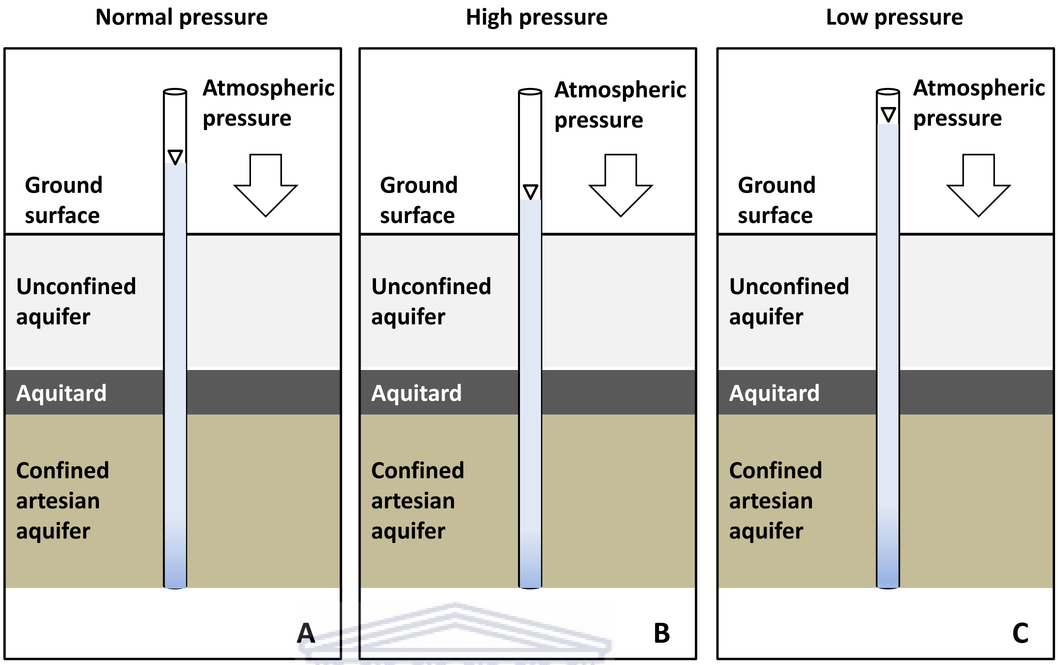


Fig. 2.4: Schematic water-level change in artesian aquifer induced by a barometric pressure variation

Method for identifying and removing barometric pressure effects in confined and unconfined aquifers is well elaborated by Rasmussen and Crawford (Rasmussen and Crawford, 1997). It is proved that removal of barometric effects is useful when trying to identify the hydraulic response to rainfall or during aquifer tests. In most cases, residual water levels are shown to behave more smoothly when barometric effects are removed. In some occasions, if the water-level changes caused by barometric pressure is insignificant compared with drawdown induced by abstraction during the aquifer test, the barometric effects can be ignored.

2.3.3.2 Water-level changes induced by earth tide

Earth tidal stresses could also change groundwater level in an aquifer (Bredehoeft, 1967; Hsieh et al., 1987). The variations of water levels, which are clearly periodic, result from the elastic behavior of the aquifer skeleton. As the Sun and Moon pass over a point on the Earth, gravitational forces generate a dilation of the bedrock, increasing pore space, and decreasing the potential of groundwater in the aquifer. After the Sun and Moon pass, the force decreases, the aquifer will contract, thus increasing the pore water potential. The more easily the aquifer deforms to gravitational stresses (less rigid), the greater the magnitude of potential change (Hsieh et al., 1987).

Each tidal component is likely to have a different influence due to the vector force applied. For instance, the Moon on the horizon exerts force in a different direction than when it is overhead. Referring to rock fractures, a tangential force will have a smaller effect on apertures than a normal force. Thus, a Moon overhead may affect horizontal fractures while vertical ones are affected when the Moon is on the horizon.

2.3.3.3 Water-level changes induced by ocean tide

Hydrogeologists in early 20th century realized that ocean tides could cause corresponding fluctuations in heads in boreholes and started to pursue the goal of using the natural processes to deduce information about the aquifer properties. Papers by Jacob (1940) and Ferris (1951) were among the first to describe the use of tidally influenced heads to estimate aquifer properties. Various methods for using water-level fluctuations caused by tidal or aperiodic natural forces to estimate aquifer properties are described and evaluated in numerous articles (Van der Kamp, 1972; Li and Jiao, 2001a; Bredehoeft, 1967; Hsieh et al., 1988; Jacob, 1940; Robinson and Bell, 1971; Van der Kamp and Gale, 1983; Rojstaczer and Agnew, 1989; Desbarats et al., 1999).

Ocean tides may also affect the groundwater levels through direct head changes in an aquifer or as loads applied through confining unit (Merritt, 2004). It is better to approximate with a nearby tidal gage that also incorporates wind and coastal geometry effects in addition to direct gravitational forcing. Ocean tides occurring in mid-continent boreholes could change the porosity and cause measurable water level fluctuations of as much as 2 cm or more in boreholes penetrating aquifers with small storage coefficients (Bredehoeft, 1967; Marine, 1975; Narasimham et al., 1984). In TMG area, as most of flowing artesian boreholes are far away from coast, the impact from ocean tides may not need to be taken into account.

Since drawdown caused by abstraction during the aquifer test is usually at least 2 orders of magnitude more than the water-level fluctuations caused by barometric pressure changes, earth tide and ocean tide, the effects from these factors will not be considered in this study. However, evaluation of aquifer properties could be applied in a location in which there are comprehensive data available. The results are independent and could be compared with values derived from aquifer test data analysis.

2.3.4 Water quality

In general, the water quality of flowing artesian boreholes is excellent. For instance, the water quality of artesian aquifer in most parts of TMG aquifers and the Great Artesian

Basin in Australia (GAB) (Herczeg, 2008) is quite good. The groundwater in Uitenhage Artesian Basin (UAB) is of an excellent quality with salinities generally less than 15 mS/m and is fit for drinking in its raw state (Maclear, 2001); with good groundwater quality, the GAB is an important water supply for cattle stations, irrigation, and livestock and domestic usage, and is a vital life line for rural Australia. Due to its low fluoride content, however, addition of fluoride, and/or blending of groundwater with surface water are needed if it is to be used as a sole long-term drinking supply. In addition, water hardening is required to lower pH as is the case at the Uitenhage Springs.

In some cases, some artesian waters may be of very poor quality and cause serious damage to the surface water or contaminate an overlaying aquifer. Generally water quality can be affected by the depth of the borehole or geological settings. For instance, a deeper flowing artesian borehole may have poorer water quality than a shallower flowing borehole. Water from bedrock formations, such as deep sandstone formations, may contain concentrations of arsenic that could pose a health concern. In such cases, artesian boreholes with poor quality water should be permanently closed (SEPA, 2010).

With regard to bacterial contamination, because of the protected nature of the confined artesian aquifer, flowing artesian boreholes are less prone to be polluted. Furthermore, the positive artesian pressure can minimize entry of surface contaminants into the borehole or aquifer. Contamination introduced during the drilling process can be flushed out by the continuous discharge of water at the beginning.

2.4 Theory of aquifer tests for artesian aquifer

There are quite a few researchers concentrating on methods of estimating the hydraulic parameters of the artesian aquifers (Hantush, 1959; Mishra and Guyonnet, 1992; Hiller and Levy, 1994; Murdoch and Franco, 1994; Chen and Chang, 2002). Methods include analytical methods and numerical methods (Fig. 2.5). The constant-head test method is particularly adopted to deal with artesian aquifer. Since the flowing artesian borehole will flow under natural condition, it would be operational to measure the discharge rate and water level as a function of time. The first analytical solution of the borehole discharge for a constant-head test in a confined aquifer was devised to estimate the storage coefficient and the transmissivity by Jacob and Lohman (1952). Hantush (1964) obtained a similar solution for a constant-head test in leaky aquifer. The latter method is usually based on the stratigraphy of the aquifer, and is very useful when the transmissivity of aquifer is relative small (Jones et al., 1992; Jones, 1993).

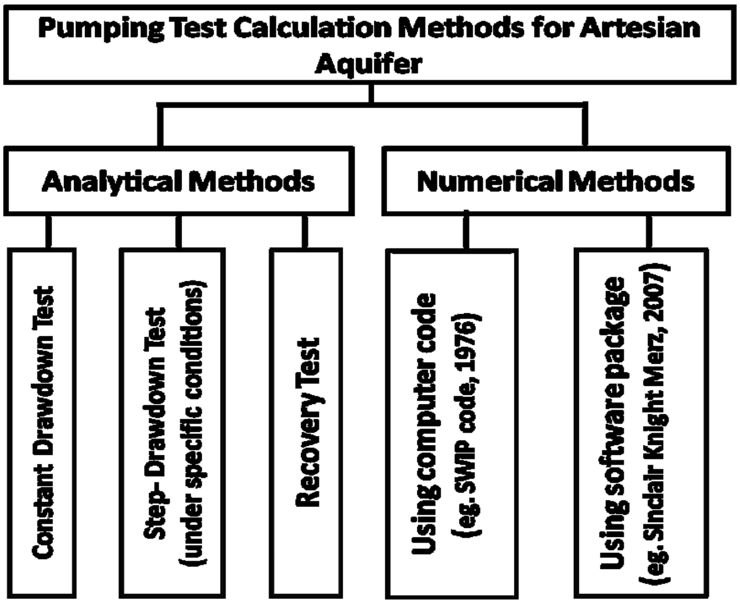


Fig. 2.5: Methods of pumping test conducted at flowing artesian borehole

Analytical methods are the priority to estimate the hydraulic parameters of artesian aquifer using constant-head pumping test. A commonly used method of estimating transmissivity from artesian flow rates and their variation with time was developed by Jacob and Lohman (1952). For application of this method, a flowing borehole is capped or a stand pipe placed above the ground to measure the initial water level or pressure head. It is then allowed to flow. The outlet elevation is kept at constant head and the discharge gradually decreases. This is also known as a constant drawdown variable discharge test.

Jacob-Lohman semi-log approximation for constant-head case could be adopted either in single borehole test or interference test (with one monitoring borehole); the observation borehole data could provide important information regarding to the connection between those two boreholes. The procedure for interpreting observation borehole data when the head was kept constant at the pumping borehole was proved to be feasible, but the inter-well distance should be approximately two orders of magnitude larger than the wellbore radius, which was satisfied in most of the situation (Mishra and Guyonnet, 1992).

A variation of methods based on the Jacob-Lohman method was adopted to estimate the transmissivity afterwards. Table 2.1 presents several methods for analysing the drawdown data for fully penetrating borehole in artesian aquifer. Aron and Scott (1965) show that when $r^2/4KDt_n$ < 0.01, the drawdown at observation borehole could be divided in two parts, one is caused by average discharge at time t_n, and another part is the excess drawdown caused by the earlier higher discharge. The method is analogous to the Jacob method, it could be adopted if the discharge rate decrease with time, the sharpest decrease occurring soon after the start of pumping, and the flow to borehole is unsteady flow and $r^2/4KDt_n < 0.01$ with the basic assumptions for confined aquifers.

Table 2.1: Classification of methods applied for fully penetrating borehole in artesian aquifer

Method	Application		Remarks
	Number of Boreholes	**Flow condition**	
Theis, 1935	Single BH or Pumping BH with piezometer	Transient	Recovery test after constant drawdown test: 1. Rate of recharge during the recovery test is equal to rate of discharge 2. Pumping time $t_p > (25r^2S)/KD$ (T, pumping duration) $T' > (25r^2S')/KD$
Jacob and Lohman (1952)	Single BH or pumping BH with piezometer	Transient	Constant drawdown test: 1. The value of effective radius needs to be determined 2. Variable discharge
Hantush and Hantush-De Glee (1959, 1964)	Pumping BH with piezometer	1. Transient for Hantush 2. Steady for Hantush-De Glee	Constant drawdown test: 1. Variable discharge 2. $L > 3D$ for Hantush-De Glee
Aron and Scott (1965)	Pumping BH with piezometer	Transient	Variable discharge test: 1. $r^2S/4KDt_n < 0.01$ 2. Variable discharge
Jacob (1947); Rorabaugh (1953)	Single BH or Pumping BH with piezometer	Transient	Step-drawdown test: 1. Determine optimum yield 2. Evaluate the skin factor 3. Estimate the transmissivity
Theis method (1935) Matthews and Russell (1967)	Single BH or Pumping BH with piezometer	Transient	Recovery test: 1. Evaluate the skin factor 2. Evaluate effective radius 3. Estimate the transmissivity

The Hantush's method (1959, 1964) for unsteady-state flow and Hantush-De Glee method (1959) for steady-state flow in a leaky aquifer are based on the condition that the hydraulic head in borehole is constant and that the discharge decreases with time; it requires one monitoring borehole. Both methods are used under the following assumptions, 1) drawdown starts instantaneously; 2) the drawdown is constant and its discharge is variable. The former method requires groundwater flow under unsteady-state; while the latter one requires that it is under steady-state condition, and $L > 3D$ (The term of L is the distance between pumped borehole and piezometer, D the thickness of the aquifer).

The recovery data of borehole after closing the cap (pumping process) could be used to estimate the transmissivity and evaluate the effective radius under certain assumptions. The analysis of recovery data involves the measurement of the rise in water levels, also referred as residual drawdown, following the cessation of a period of pumping at a constant rate. It is based on Theis theory and applies to unconfined as well as confined aquifers with fully penetrating borehole.

2.4.1 Constant-head test without vertical leakage

Constant-drawdown pumping test method was first devised by Jacob and Lohman (1952). In 1979, Lohman rewrote the equation for use in analysis of transmissivity, and the equation for the discharge of a flowing borehole is delineated as follows:

$$Q = 2\pi T S_w G(u_w) = 4\pi T S_w \frac{1}{W(u_w)} \quad \text{or} \quad \frac{s_w}{Q} = \frac{W(u_w)}{4\pi T} \qquad (2\text{-}1)$$

With

$$u_w = \frac{r_{ew}^2 S}{4Tt}$$

Where s_w is constant drawdown in the borehole (difference between static head measured during shut-in of the borehole and the outflow opening of the borehole), $G(u_w)$ Jacob-Lohman's free-flowing borehole discharge function for confined aquifers, $W(u_w)$ Theis's well function, and r_{ew} effective radius of the borehole.

According to Jacob and Lohman, the borehole discharge function can be approximated by $2/W(u_w)$ for all but extremely small values of T.

If $u_w \leq 1$, then the Equation can be expressed as:

$$W(u_w) = -\ln u - 0.5572 + u - 0.2499u^2 + 0.0552u^3 - 0.0098u^4 + 0.0011u^5 \qquad (2\text{-}2)$$

And

$$W(u_w) \approx \frac{e^{-u}}{u} \frac{a_0 + a_1 u_w + a_2 u_w^2 + a_3 u_w^3 + u_w^4}{b_0 + b_1 u_w + b_2 u_w^2 + b_3 u_w^3 + u_w^4} \quad 1 \leq u_w < \infty \qquad (2\text{-}3)$$

$$\frac{s_w}{Q_1} = \frac{2.3}{4\pi T} \log \frac{2.25 K D t_1}{r_{ew}^2 S}$$

$$\frac{s_w}{Q_2} = \frac{2.3}{4\pi T} \log \frac{2.25 K D t_2}{r_{ew}^2 S} \qquad (2\text{-}4)$$

(2-3)-(2-4), then

$$T = \frac{2.3}{4\pi \Delta(\frac{s_w}{Q})} \log \frac{t_1}{t_2} \quad \text{or} \quad T = \frac{2.3}{4\pi \Delta(\frac{s_w}{Q})} \; (\text{if } \frac{t_1}{t_2} = 10) \qquad (2\text{-}5)$$

According to Eqs (2-4) and (2-5), storativity can be calculated from:

$$S = \frac{2.25KDt_0}{r_{ew}^2} \quad (2\text{-}6)$$

Where t_0 is the interception point of time-axis where s_w/Q is zero. It has been shown that the Jacob-Lohman method is only fit during rather limited duration of the test in artesian aquifers, and long-duration test period as the drawdown and flow rate of artesian borehole are governed by transmissivity of the aquifer and storage in the area. If the transmissivity is very large and the duration of test lasts long, further adjustments may be necessary for the analysis of results.

Numerous studies have been carried out to improve the accuracy of $G(u_w)$. Based on the Jacob-Lohman method, a number of methods to interpret free-flowing test data are listed as follows.

Swamee simplified expressions (2000)

There are several improved methods based on the Equation (2-3) given by Jacob and Lohman (1952) using numerical methods to avoid mathematical complexities of the solutions or inconvenience in interpolations of the tabulated values. The tabulated values of *G(α)* can be fitted to the following equation (Swamee et al., 2000):

$$G(\alpha) = \frac{1}{\sqrt{\pi\alpha}} + 2\left\{\ln\left[(1+4e^{-\gamma}\alpha)(1+30\alpha^{-0.45})\right]\right\}^{-1} \quad (2\text{-}7)$$

Where γ is Euler's constant = 0.577216, $\alpha = 1/4u_w$. The maximum error involved in the equation is 2.32% at $\alpha = 0.03$ with mean absolute error about 0.66%.

As long as *G(α)* is determined, the estimation of parameters *T* and *S* can be done with Eqs (2-5) and (2-6).

For the borehole production function *H(α)*, from the tabulated values of *H(α)* (Glover, 1978) and given the values of α ranging from 20.5 to 2.5×10^7 and computed values obtained from Equation (2-3) for the ranges $10^{-4} \le \alpha < 2.25$ and $2.5\times10^7 < \alpha \le 10^{12}$, the equation of *H(α)* can be written as:

$$H(\alpha) = \sqrt{\frac{4\alpha}{\pi}} + 2\alpha(1+0.088\alpha^{-0.03})\cdot\left\{\ln\left[(1+4e^{-\gamma}\alpha)(1+30\alpha^{-0.45})\right]\right\}^{-1} \quad (2\text{-}8)$$

The maximum error with the above equation is 2.45% at $\alpha = 0.5$ and 0.77% while $\alpha = 400$.

Singh simplified approximations (2007)

The borehole function of *G(α)* can be developed as follows (Singh, 2007):

$$G(\alpha) = \frac{2}{\ln(2.246\alpha)}[1 + (\frac{11}{40000\alpha})^{2/5}]^{-12} \quad (2\text{-}9)$$

According to the above equation, the maximum error in *G(α)* is 0.75% for $1\times10^2 \le \alpha \le 1\times10^{12}$. The $\alpha < 10^2$ is practically not observed for a small diameter borehole. If $\alpha > 1\times10^5$, the above equation can be truncated with maximum error of 0.9% as:

$$G(\alpha) = \frac{2}{\ln(2.246\alpha)} \quad (2\text{-}10)$$

From tabulated values of *H(α)*, the approximation for *H(α)* can be developed as:

$$H(\alpha) = [\frac{10\sqrt{\pi}}{9}\ln(\alpha) + \frac{5\pi}{99}]^{-1} \quad (2\text{-}11)$$

The maximum error in *H(α)* using the above equation is 0.7% for $\alpha > 100$. For most cases of a small diameter borehole, $\alpha > 100$.

When the above methods are applied for estimation of aquifer parameters, the curve-matching method can be adopted to minimize the errors. To remove the subjectivity during the calculation, the two equations below, using absolute error *E* and integral squared error *F,* can be used to minimize the error:

$$E = \frac{1}{n}\sum_{i=1}^{n}\left|Q_i - 2\pi T s_w G(\alpha_i)\right| \quad (2\text{-}12)$$

Or

$$F = \frac{1}{n}\sum_{i=1}^{n}(Q_i - 2\pi T s_w G(\alpha_i))^2 \quad (2\text{-}13)$$

Where *E* is absolute error, Q_i observed discharge at time t_i, *n* number of observations and *F* integral squared error.

The utilization of the above approaches is based on the following assumptions and conditions:

- The aquifer is confined;
- The aquifer has seemingly infinite areal extent;
- The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by the test;
- Prior to pumping, the piezometric surface is horizontal (or nearly so) over the area that will be influenced by the test;
- At the start of the test ($t = 0$), the water level in the free-flowing borehole drops instantaneously. At $t > 0$, the drawdown in the borehole is constant, and its discharge is variable;

- The borehole is screened throughout the main aquifer only;
- The flow to the borehole is in an unsteady state.

Free-flowing test with observation borehole

A conclusion that the drawdown at the observation borehole, normalized by the flow rate at the test borehole is the same for both constant rate and constant head at the test borehole conditions was made in a paper by Mishra and Guyonnet (1992). Therefore, recalling the Theis and Cooper-Jacob solutions, the equation for the constant head test can be written as:

$$\frac{s}{Q} = \frac{1}{4\pi T}\ln\left(\frac{2.25Tt}{r^2 S}\right) \tag{2-14}$$

Where Q is the discharge rate at the flowing artesian borehole, s the drawdown at the observation borehole, and r the distance from free-flowing borehole to observation borehole.

2.4.2 Constant-head test with vertical leakage

It is rare in nature to find borehole-confined aquifers, especially in TMG area. Leaky aquifers occur far more frequently than the perfectly confined aquifers. Confining layers overlying or underlying an aquifer are seldom completely impermeable; instead, most of them leak to some extent. When a borehole in a leaky aquifer is pumped, water is contributed from relatively less permeable confining units in addition to the aquifer. A careful review of the present literature shows that there are limited researches on the constant-head test in leaky aquifer with a finite-thickness skin zone. A recent research done about leaky aquifer indicates that low dimensionless transmissivity of aquitard has little effect on the borehole discharge (Zhang et al., 2011). Most of the researches done about leaky aquifer were based on the Hantush method (Hantush and Jacob, 1955; Wilson and Miller, 1978; Hunt, 1978; Hantush, 1959). The method applied on free-flowing borehole is expressed as:

$$s_w = \frac{Q}{4\pi KD} W(u, r_{ew}/B) \quad \text{or} \quad Q = \frac{4\pi KD s_w}{W(u, r_{ew}/B)} \tag{2-15}$$

With

$$W(u, r_{ew}/B) = \int_u^{\infty} \frac{1}{y}\exp\left(-y - \frac{r^2}{4B^2 y}\right)dy \cong \left(\frac{\pi B}{2r}\right)^{1/2} e^{(-r/B)} erfc\left(-\frac{r/B - 2u}{2u^{1/2}}\right) \tag{2-16}$$

Where

Q = variable discharge rate from artesian borehole in m^3/d

s_w = constant drawdown in artesian borehole in m

$W(u, r_{ew}/B)$ = Hantush's borehole function for leaky aquifers

$u = r_{ew}^2 S/(4Tt)$

$B = \sqrt{KDc}$: leakage factor in m

$c = D'/K'$: hydraulic resistance of the aquitard in d

D' = saturated thickness of the aquitard in m

K' = hydraulic conductivity of the aquitard for vertical flow in m/d

The Hantush method for determining a leaky aquifer's parameters KD, S and c should be applied with known effective borehole radius r_{ew}. The values of S and c cannot be obtained without effective radius. The effective radius of artesian borehole can be determined using recovery test data (Matthews and Russell, 1967). The following conditions need to be added:

- The flow to the borehole is in an unsteady state;
- The aquitard is incompressible, i.e. changes in aquitard storage are negligible.

2.4.3 Boundary conditions

In a location in which there is no-flow barrier surrounding the flowing artesian borehole, flow rate during the overflow test would reduce significantly. Given that some of the faults in the TMG area are impermeable layers, these may be defined as barrier boundaries. According to Ferris et al. (1962), there are four types of no-flow boundary conditions (shown in Fig. 2.6).

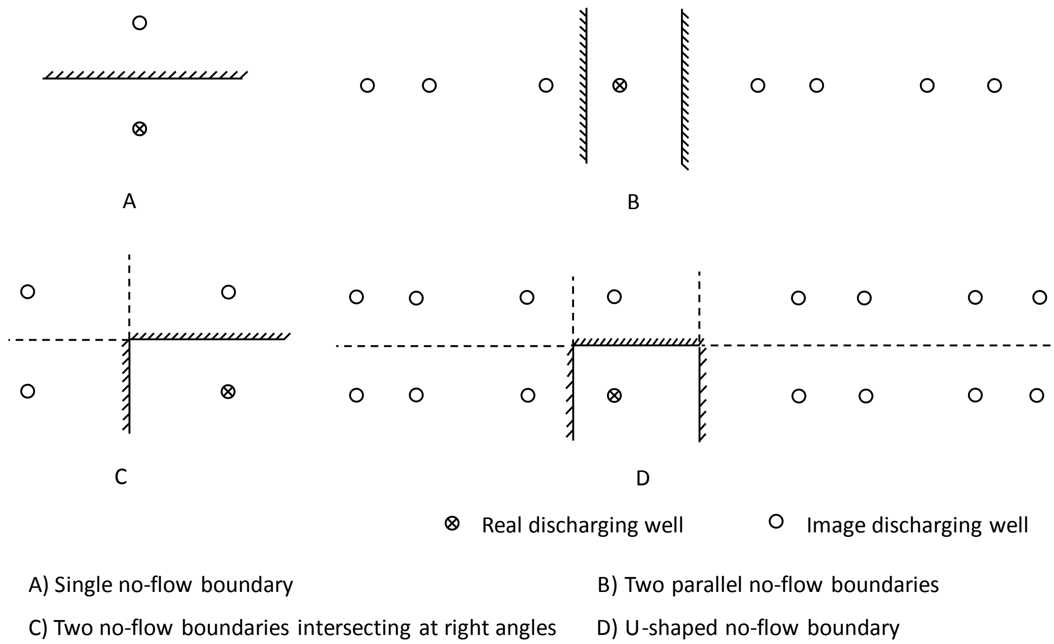


Fig. 2.6: Four types of no-flow boundary conditions (after Ferris et al., 1962)

The influence of the barrier boundary could be described by constructing an image borehole, which is located on the other side of the boundary at the same distance as between the boundary and the test borehole. Therefore image borehole method is introduced to the estimation of the hydraulic properties (Ferris et al., 1962). The flow rate in the test borehole that is due to the barrier boundary can be expressed as:

$$Q = \frac{4\pi T s_w}{W(u) + W(r_{r1}^2 u) + W(r_{r2}^2 u) + ...W(r_{rn}^2 u)}$$

$$\frac{1}{Q} = \frac{W(u) + W(r_{r1}^2 u) + W(r_{r2}^2 u) + ...W(r_{rn}^2 u)}{4\pi T s_w} \qquad (2\text{-}17)$$

Where Q is the flow rate from artesian borehole, r_w the radius of artesian borehole, r_i the distance between the image borehole and barrier, and their ratio $r_i/r_w = r_r$. Compared with the Equation 2-14, the $1/Q$ will increase due to the interference from the boundary.

One no-flow boundary condition:

$$Q = \frac{4\pi T s_w}{W(u) + W({}_{r1}^2 u)}$$

$$\frac{1}{Q} = \frac{W(u) + W({}_{r1}^2 u)}{4\pi T s_w} = \frac{\ln(\frac{2.25Tt}{r_w{}^2 S}) + \ln(\frac{2.25Tt}{r_{r1}^2 r_w{}^2 S})}{4\pi T s_w} = \frac{2\ln(\frac{2.25Tt}{r_w{}^2 S}) - 2\ln(r_{r1})}{4\pi T s_w} \qquad (2\text{-}18)$$

Two straight boundaries at right angles to each other:

$$Q = \frac{4\pi T s_w}{W(u) + W({}_{r1}^2 u) + W({}_{r2}^2 u) + W({}_{r3}^2 u)}$$

$$\frac{1}{Q} = \frac{W(u) + W({}_{r1}^2 u) + W({}_{r2}^2 u) + W({}_{r3}^2 u)}{4\pi T s_w} = \frac{\ln(\frac{2.25Tt}{r_w{}^2 S}) + \sum_{i=1}^{3} \ln(\frac{2.25Tt}{r_{ri}^2 r_w{}^2 S})}{4\pi T s_w} = \frac{4\ln(\frac{2.25Tt}{r_w{}^2 S}) - -2\sum_{i=1}^{3} \ln(r_{ri})}{4\pi T s_w} \qquad (2\text{-}19)$$

Two parallel boundaries:

$$Q = \frac{4\pi T s_w}{W(u) + W({}_{r1}^2 u) + W({}_{r2}^2 u) + ... + W({}_{r7}^2 u)}$$

$$\frac{1}{Q} = \frac{W(u) + W({}_{r1}^2 u) + W({}_{r2}^2 u) + ... + W({}_{r7}^2 u)}{4\pi T s_w} = \frac{\ln(\frac{2.25Tt}{r_w{}^2 S}) + \sum_{i=1}^{7} \ln(\frac{2.25Tt}{r_{ri}^2 r_w{}^2 S})}{4\pi T s_w} = \frac{8\ln(\frac{2.25Tt}{r_w{}^2 S}) - 2\sum_{i=1}^{7} \ln(r_{ri})}{4\pi T s_w} \qquad (2\text{-}20)$$

U-shape boundaries condition

$$Q = \frac{4\pi T s_w}{W(u) + W(r_1^2 u) + W(r_2^2 u) + \ldots + W(r_{15}^2 u)}$$

$$\frac{1}{Q} = \frac{W(u) + W(r_1^2 u) + W(r_2^2 u) + \ldots + W(r_{15}^2 u)}{4\pi T s_w} = \frac{\ln(\frac{2.25Tt}{r_w{}^2 S}) + \sum_{i=1}^{15} \ln(\frac{2.25Tt}{r_{ri}^2 r_w{}^2 S})}{4\pi T s_w} = \frac{16\ln(\frac{2.25Tt}{r_w{}^2 S}) - 2\sum_{i=1}^{15} \ln(r_{ri})}{4\pi T s_w} \qquad (2\text{-}21)$$

2.4.4 Recovery test

In reality, there is a difficulty that when the condition of constant drawdown is reached, the change in discharge at later stage of flowing test is so subtle that the measurements can become problematic, and the estimates of aquifer parameters using these data may be unreliable. This suggests that the method of recovery data could be a more convenient way to check on the magnitude of the transmissivity. Numerous studies have proven that the estimate of T is smaller by recovery test method compared with pumping test method, yet the result from recovery test data analysis is more reliable.

When the valve is shut down after free-flowing test, the water head in the artesian borehole and the piezometer will start to rise. The rise in water levels is known as residual drawdown (*s'*). Theis recovery method can be applied for artesian borehole. Under this situation, the residual drawdown after free-flowing test is defined as:

$$s' = \frac{Q}{4\pi KD}\{W(u) - W(u')\} \qquad (2\text{-}22)$$

Where

$$u = \frac{r_{ew}{}^2 S}{4KDt} \text{ and } u' = \frac{r_{ew}{}^2 S'}{4KDt'} \qquad (2\text{-}23)$$

When u and u' are sufficiently small (for instance, $u < 0.01$), the Equation (2-22) can be approximated by:

$$s' = \frac{Q}{4\pi KD}(\ln\frac{4KDt}{r_{ew}{}^2 S} - \ln\frac{4KDt'}{r_{ew}{}^2 S'}) \text{ or } s' = \frac{2.30Q}{4\pi KD}\log\frac{t}{t'} \qquad (2\text{-}24)$$

Where

s' = residual drawdown in m

r_{ew} = effective radius of free-flowing borehole in m

KD = transmissivity of the aquifer in m^2/d

S' = storativity during recovery, dimensionless

S = storativity during free-flowing, dimensionless

t = time since the start of free-flowing in d

t' = time since cessation of free-flowing in d

Q = flow rate at the end of free-flowing test in m^3/d

During the free-flowing test, the discharge rate Q does not remain constant, it decreases with time. Jacob and Lohman (1952) suggested that a weighted average value of discharge be used for recovery test data analysis, which is incorrect; the discharge at the end of free-flowing test phase should be used instead (Rushton and Rathod, 1980). The reason is that the constant discharge required to produce a drawdown s at a specified time is identical to the overflowing discharge due to the constant drawdown s_w at this specified time.

A plot of *s'* versus *t/t'* on semi-log paper will yield a straight line. When *S* and *S'* are constant and equal, and *KD* is constant. The slope of the line can be derived as:

$$\Delta s' = \frac{2.30Q}{4\pi KD} \tag{2-25}$$

$$T = KD = \frac{2.30Q}{4\pi\Delta s'} \tag{2-26}$$

Where *Δs'* is residual drawdown difference per log cycle of *t/t'*. Storativity is difficult to be estimated by Theis method. However, when *S* and *S'* are constant, but unequal, the ratio of *S* and *S'* can be approximated; the straight line through the plotted points intercepts the time axis where *s'* = 0 at a point *t/t'* = $(t/t')_0$. At this point, Equation (2-24) becomes:

$$0 = \frac{2.30Q}{4\pi KD}[\log(\frac{t}{t'})_0 - \log(\frac{S}{S'})] \tag{2-27}$$

As 2.30$Q/(4KD)$ = 0, $(t/t')_0 = S/S'$, which determines the relative change of *S*.

2.4.5 Numerical models

Generally speaking, the analytical methods are practical to interpret field data with certain assumptions made and the adequacy of model checked. However, these methods do not take into account the influence of friction loss on flow rate, which varies with the flow rate and distance to the aquifer boundaries. On some occasions, the friction losses in the wellbore and casing are not negligible. These difficulties indicate that there can be appreciable uncertainty in estimates made with the constant drawdown formula; furthermore, some assumptions might not represent the physical boundary conditions well. Therefore, numerical method may be chosen as an additional tool to cross-check the results.

Numerical modelling capabilities for pumping test analysis have been available for more than 20 years; however, they are seldom adopted for artesian aquifers. SWIP code (Intercomp Resource Development and Engineering, Inc. (1976)) as a resource was adopted in the development of the three-dimensional integrated finite-difference code

HST3D, which is applied to deal with the problems of groundwater flow as well as solute and thermal transport. The estimation of transmissivity was 91% less than that determined by constant drawdown analysis, while the former estimate is assumed to be better as the simulation provides a realistic depiction of the aquifer flow system. The reason is that a realistic representation of the variable drawdown and its relation to the rate of flow required consideration of several boundaries at varying distances from the well. Available analytical solutions that accounted for boundaries were considered not to have sufficient generally for such a representation; while the numerical model is able to achieve this (Merritt, 1997). The self-designed code is complicated and time-consuming. It is not highly recommended for practical use for quick estimation of hydraulic parameters.

Another popular numerical method uses computer package, such as MODFLOW and FEFLOW, etc. The hydrogeological parameters used in the model are normally from analytical models. Sensitivity analysis can be carried out on the calibrated model to demonstrate the effects of higher and lower values of hydraulic conductivity (K) on model calibration hydrographs after flow simulation is done. During the calibration process, conductivity is considered to be the most sensitive parameter; therefore it is often doubled and halved across the model to evaluate its sensitivity.

Numerical models of pumping tests provide three major advantages. They may give reasonable results and explanations under certain assumptions and after calibrating some of parameters; the user can selectively choose some properties to calibrate and the assumptions to make; and also through informal analysis with trial and error inverse solution, they would provide insights into the conceptual models of the groundwater flow system and some of the uncertainties. Strictly speaking, numerical methods are practical for characterising the hydrogeological system rather than estimating the hydrogeological parameters.

Despite the advantages of numerical methods for pumping test analysis, most researchers tend to favor curve-fitting techniques. Numerical models require more data sets and parameters for input, and need the feasible conceptual models even before entering the appropriate parameters. Even more, it takes time to calibrate and run the models. This is certainly more complicated than selecting and applying a curve-fitting method.

2.5 Skin factor and effective radius

In groundwater hydraulics, when single-borehole pumping test is conducted, discussion of skin effect is inevitable. The effect of skin zone on the response of pumping tests has been recognized for a long time in the petroleum industry. From hydrogeological aspect, the concept of skin effect was introduced by van Everdingen (1953). The skin effect is defined as the difference between the total drawdown observed in a borehole and the aquifer loss component, assuming that the non-linear borehole losses are negligible. Hawkins (1956) defined a skin effect which was related to external and altered permeability further. Streltsova and McKinley (1984) considered an infinitesimal skin and used a skin factor to represent the skin effect.

A finite thickness of borehole skin may be produced due to the borehole construction as a result of drilling through mud or extensive borehole development. The skin thickness may range from a few millimeters to several meters and thus it should be considered in the single aquifer test (Novakowski, 1989). If the hydraulic conductivity of skin zone around pumping borehole is bigger than that of the zone out of the skin zone, it is defined as negative skin. A positive skin could indicate either a damaged borehole or an undamaged borehole with partial penetration; a negative skin characterizes a stimulated borehole that could be acidized, hydraulically fractured, or that intersects a natural fracture to enhance the yield. Van Everdingen (1953) presented a method to compute the pressure drop due to the reduction of the permeability of the formation around the borehole.

The recovery test after constant rate pumping test could be implemented into recovery test after constant head test. The following equation for the drawdown in a borehole that fully penetrates a confined aquifer can be applied to estimate the skin factor:

$$s_w = \frac{2.30Q}{4\pi KD}\ln\frac{2.25KDt}{r_w^2 S} + (skin)\frac{Q}{2\pi KD} = \frac{Q}{4\pi KD}[\ln\frac{2.25KDt}{r_w^2 S} + 2(skin)] \tag{2-28}$$

Where *skin (Q/2πKD)* = skin effect in m

skin = skin factor (dimensionless)

r_w = radius of the borehole screen in m

After the tap is closed, the residual drawdown s_w' in the borehole for $t' > 25r_w^2S/KD$ is:

$$s_w' = \frac{2.30Q}{4\pi KD}[\ln\frac{2.25KDt}{r_w^2 S} + 2skin] - \frac{Q}{2\pi KD}[\ln\frac{2.25KDt'}{r_w^2 S} + 2skin] = \frac{2.3Q}{4\pi KD}\log\frac{t}{t'} \tag{2-29}$$

Where t = time since free-flowing started *t'* = time since free-flowing ceased

for $t' > 25\ r_w^2 S/KD$, a semi-log plot of s_w' versus t/t' will yield a straight line. The transmissivity of the aquifer can be calculated from the slope of this line. For time $t = t_p$ (total free-flowing time), the Equation (2-28) becomes:

$$s_w(t_p) = \frac{Q}{4\pi KD}\ln\frac{2.25KDt}{r_w^2 S} + (skin)\frac{Q}{2\pi KD} \tag{2-30}$$

The difference between $s_w(t_p)$ and the residual drawdown s_w' at any time t', is

$$s_w(t_p) - s_w' = \frac{Q}{4\pi KD}\ln\frac{2.25KDt_p}{r_w^2 S} + (skin)\frac{Q}{2\pi KD} - \frac{Q}{4\pi KD}\ln\frac{t_p + t'}{t'} \tag{2-31}$$

For $\frac{t_p + t'}{t'} = \frac{2.25KDt_p}{r_w^2 S}$ (2-32)

Equation (2-31) reduces to:

$$s_w(t_p) - s_w' = skin(\frac{Q}{2\pi KD}) \tag{2-33}$$

$$r_{ew} = r_w e^{-skin} \tag{2-34}$$

r_{ew} is effective radius of artesian borehole in m.The procedures for determining the *T* value have been described in Section 2.4.1 and Section 2.4.4. After the *T* value is determined, the skin factor can be calculated with the following procedures:

- Determine the ratio $(t_p+t_i')/t_i'$ by substituting the values of the total free-flowing time t_p, the calculated *T*, the known value of r_w, and an assumed value of *S* into Equation (2-32).
- Read the value of s_w' corresponding to the calculated value of $(t_p+t_i')/t_i'$ from the extrapolated straight line of the data plot s_w' versus t/t'.

Substitute the observed value of $s_w(t_p)$ corresponding to free-flowing time $t = t_p$, and the known values of s_w', *Q* and *T* into Equation (2-33) and solve for the skin factor. Thereafter, the effective radius value can be calculated with Equation (2-34).

2.6 Discussion and summary

As the pressure head of strong artesian aquifer is above ground surface, the conventional constant-rate test is hardly applied under the situation. A commonly used method of estimating transmissivity and storativity of artesian aquifer is done through constant-head test. During the test, flow rate from the test borehole gradually drops, and pressure head immediately drops from the initial height to collar height (CH) or ground level. Flow rate and pressure head data need to be captured. However, it is noticed that the data collection was usually done manually. Conventional way of measurements using the bucket and timer during the test is cumbersome, yet the data may not be accurate if the flow rate is too high, particularly at the beginning of the flowing test. A device to capture such data is deemed to be important to enhance the accuracy. It is anticipated that the hydraulic test device will be devised to mount on a pressurized borehole on ground measuring potentiometric height (water head) and the concomitant flow rate that is induced by the potentiometric height.

Analytical solutions based on certain assumptions are useful tools to evaluate aquifer properties. The very first method to interpret constant-head test data is the Jacob-Lohman method. A variation of methods was developed based on the fundamental equation. Inasmuch as the aquifer test at flowing artesian borehole is single-borehole test, skin factor and effective radius have to be considered, which can be done using an appropriate analytical method (Matthews and Russell, 1967). A basic software package supporting the interpretation of test data obtained from artesian borehole can be developed for obtaining aquifer parameters including T and S values. However, methods to identify the boundary condition and flow regimes during the constant-head test have not been addressed yet, for instance, most of confined aquifers in TMG are bounded by impermeable faults or folds. It is known that the diagnostic plot method can help improve understanding the constant-rate pumping test and provide a description of different hydrogeological formations using drawdown data (Djebbar and Kuman, 1980). The method can be reviewed further and adapted to evaluate the artesian aquifer properties with reciprocal rate and reciprocal rate derivative data.

The study is not only innovated in nature but also has the potential to be widely applicable, bearing far reaching implications both scientifically and economically.

Chapter 3
Artesian aquifer in TMG

3.1 Introduction

Understanding the hydrogeological settings of TMG aquifers is very important for planning sustainable groundwater utilization. Generally the TMG consists of the Peninsula Formation, which is the major fractured-rock aquifer, and the Nardouw Subgroup (comprised of the Skurweberg and Baviaanskloof Formations, the latter including the Kareedouw Member), which forms a separate, upper TMG aquifers with two subaquifer divisions. The two main formations are separated by Goudini Formation, which often performs as impermeable layer. The outcrop of TMG covers an area of some 37,000 km^2 (shown in Fig. 3.1), which is considered as recharge zone for TMG Aquifer (Xu et al., 2009).

In the locations of South Africa underneath the pressure head of the Peninsula Aquifer is above ground surface. Such aquifer in TMG can be defined as strong artesian aquifer.

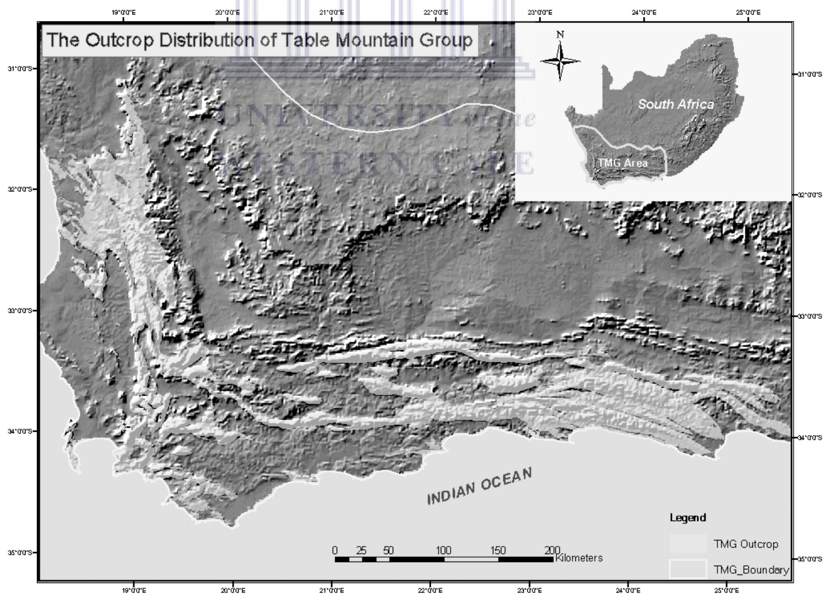


Fig. 3.1: Extension of the TMG in South Africa with outcrop shown in light grey (Lin, 2007)

In this chapter, aquifer media and geological background of TMG is described, which is followed by a discussion of characteristics of flowing artesian borehole in TMG. Conceptualization of artesian aquifer in TMG is developed, which would help further develop conceptual model for data interpretation later on.

3.2 Aquifer media in TMG

On a local scale, the TMG aquifer system is a heterogeneous and anisotropic entity, but on a regional scale it can be regarded as homogeneous and isotropic in most cases. Thin section studies have proven that even in pure quartzitic sandstones from unfolded beds of the TMG, intergranular pore spaces are completely filled by secondary quartz overgrowths, making these host rocks nearly impermeable (Hälbich and Cornell, 1983; De Beer, 2002). It is only where they are fractured by folding, and/or faulting that the rocks develop a secondary porosity and become fractured aquifer media. This point is also supported by the thin section analysis of sandstone samples from both Peninsula Formation and Nardouw Formation.

Fractures are referred to as joints and faults, as well as varied discontinuities over different scales and lithologies due to crustal tectonic driving forces (Pollard and Aydin, 1988). They can act as either groundwater conduits or barriers to groundwater flow.

It is well acknowledged that faults to a big extent play a key role in the occurrence of groundwater in the TMG sandstones. So far, almost all the major wellfields for water supply schemes in the TMG area are developed in the vicinity of fault zones, such as Vermaaks River (Kotze, 2002), Boschkloof (Hartnady et al., 2012a), St Francis Bay (Rosewarne, 1993a), Ceres (Rosewarne, 1993b), and so on. Where the faults intersect the regionally oriented structure, they may become a preferred locality for the production boreholes. This suggested that the secondary splays of regional faults are currently major zones for groundwater targeting. Therefore, most common types of TMG aquifers are confined or locally-confined aquifers. Recharge areas for artesian aquifer are located outside the confined zone, which often appears as outcrop (Fig. 3.1).

However, through field investigation of the Vermaaks River fault, Hälbich and Greef (1995) found that there were hard breccias and cataclasites widely developed in both the 9 km long fault and its secondary splays. In Eastern Cape the Coega Fault cutting southeastward through the Uitenhage artesian basin results in separating the basin into two different groundwater systems (Maclear, 2001). The same situation happens in Rawsonville area as well, where groundwater system is separated into two systems by an impermeable fault (Lin, 2007). One of the aquifer systems appears to be artesian with pressure head above ground surface. In fact, most fault zones found in the TMG sandstones and siltstones are evidenced to be lithified acting as aquitards (Newton et al., 2006), such as Klein Bavaria fault north of Plettenberg Bay, Brandvlei – Eikenhofdam fault, and Kango fault etc.

Of particular interest to borehole for groundwater development is the architecture of fault which could have a big effect on the mode of groundwater occurrence. Generally, to distinguish from the country rocks, the elements of a fault include fault core and fracture zones at both walls (Ciane et al., 1996). Current state of a fault is the result of geological processes; especially neotectonic activities might have an additional impact on the fault fabrics. However detailed information of neotectonics is not yet available except that some evidences show that the area has undergone a relatively low magnitude of fault reactivation, for instance, evidenced by earthquake events in the western and southern branches of the Cape Fold Belt. Three types of fault architecture are categorized in TMG according to the permeability, porosity and connectivity of pore spaces or fractures of faults, which depends on the nature of fault zone material (Antonellini and Aydin, 1994; Caine et al., 1996):

- Hydraulic conduit
- Localized barrier
- Composite barrier and conduit

The majority of the TMG faults fall in last category where the fault cores are largely recemented and often serve as groundwater barriers, whilst the fracture zones act as the conduits. This sheds light on localized groundwater targeting, but more detailed work needs to be done for a better understanding of the mega-faults, such as the Worcester and Kango Faults which are apparently related to the occurrence of hot springs in the Cape Fold Belt.

3.3 Geological background

3.3.1 Stratigraphy

The stratigraphy and lithology of the TMG have been depicted in details by Du Toit (1954), Rust (1967; 1973), and De Beer (2002). Main stratigraphic units involved from the bottom to the top in the TMG aquifer system are Piekenierskloof, Graafwater, Peninsula, Pakhuis, Cedarburg Formation, and Nardouw Formation (listed in Table 3.1). The basal Piekenierskloof Formation, lying unconformably on basement rocks, consists of litharenites and rudites and is overlain by the semi-confining Graafwater shale/siltstone formation. These two units are only found in the western branch of the TMG. The most significant and thickest Peninsula Formation is composed entirely of quartzitic arenites and has been proved to have a great potential for water supply. This formation occurs across the whole extent of the TMG with a thickness ranging from 1000 - 2000 m. A thin shale siltstone layer with an average thickness of 70 m makes up the Cedarberg Formation. As extensive as the underlying

Peninsula, Cedarberg Formation acts as a confining layer or aquitard and effectively separates the lower and upper aquifers. The topmost of the TMG is the Nardouw subgroup, which is divided into three members of interlayered shale, sandstone, siltstone and quartzite because of its variable composition. In many cases, it is found that the pressure in Peninsula Aquifer is higher than ground level. Conceptualization of such aquifer can be developed (Fig. 3.2).

Table 3.1: Stratigraphical succession of Table Mountain Group (after Lin, 2007)

Group	Subgroup	Formation	Geological symbol	Thickness (m) subtotal	Thickness (m)	Lithology
Bokkeveld			D	4000		Siltstones, shales, sandstones
Table Mountain	Nardouw	Rietvlei/Baviaa-nskloof	Dr/ S–Db	1200	300	Feldspathic quartz arenite
		Skurneberg	Ss		500	Quartz arenites
		Goudini	Sg		400	Arenite, minor siltstone, shale
		Cedarberg	O–Sc	70	50-150	Silty shales and shaly siltstone
	Peninsula	Parkhuis	Opa	2500-3100	100-150	Tillite, diamictite, quartz arenites
		Penninsula	Ope		1500-2000	Largely thick-bedded, coarse-grained quartzitic arenites
		Graafwater	Og		65-150	Thin-bedded sandstone, siltstone, shale and mudstone
		Piekenierskloof	Op		800	Quartzitic sandstone with coarse-grained to gritty zones and rudites
Basement		Underlying the TMG are the Malmesbury shales, the Gamtoos and the Kaaimans argillites, comprising a suite of moderately to lightly metamorphic sedimentary rocks; and cape granite suite.				

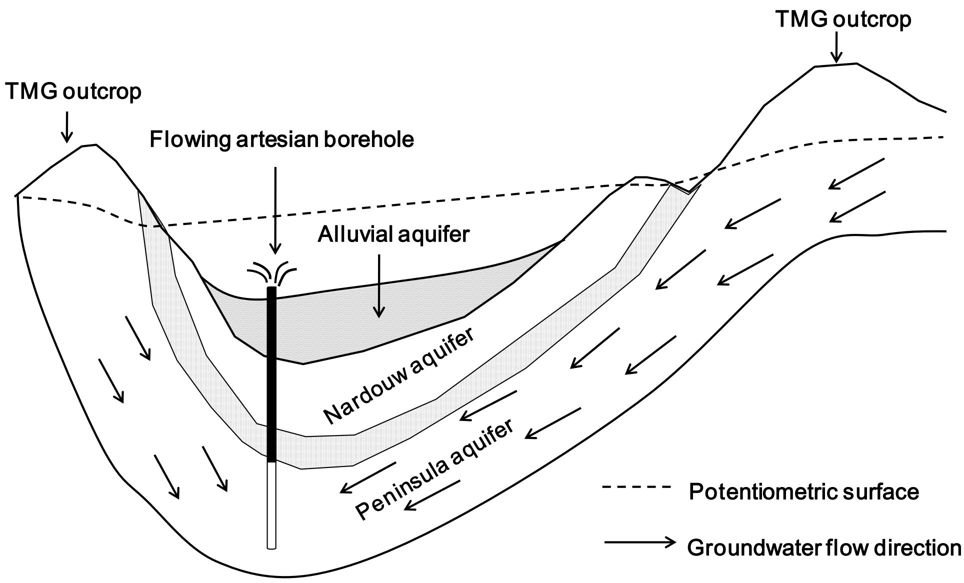


Fig. 3.2: Cross-section of an artesian basin in the TMG

3.3.2 Geological structure

The TMG rocks have been reconstructed by several phases of crustal movements from the Permian to the Cretaceous, which created various types of discontinuities in the form of joints, faults and unconformities. Some of the discontinuities have been reactivated since the post Karoo tectogenesis which complicated the existing fracture systems or zones. These structural voids in TMG sandstones and siltstones constitute most of the fracture spaces allowing groundwater storage and movement.

The normal faults developed in the TMG have long been the targets for groundwater exploration and exploitation. This is the case for Quaternary active faults where the fault core materials are mostly uncemented, but misperception may arise when the fault zones are cemented and act as groundwater barriers. In such case, the fault often divides the Peninsula Aquifer into two independent aquifers. One aquifer is confined aquifer, yet the pressure head is below ground surface. The other aquifer on the other side is artesian aquifer, where the pressure head is higher than ground level (Fig. 3.3). In fact, most fault zones developed in the TMG sandstones and siltstones are evidenced to be lithified and act as aquitards (Newton et al., 2006), such as Klein Bavaria fault north of Plettenberg Bay, Brandvlei – Eikenhofdam fault, and Kango fault etc. Flowing artesian boreholes are often encountered during borehole drilling process.

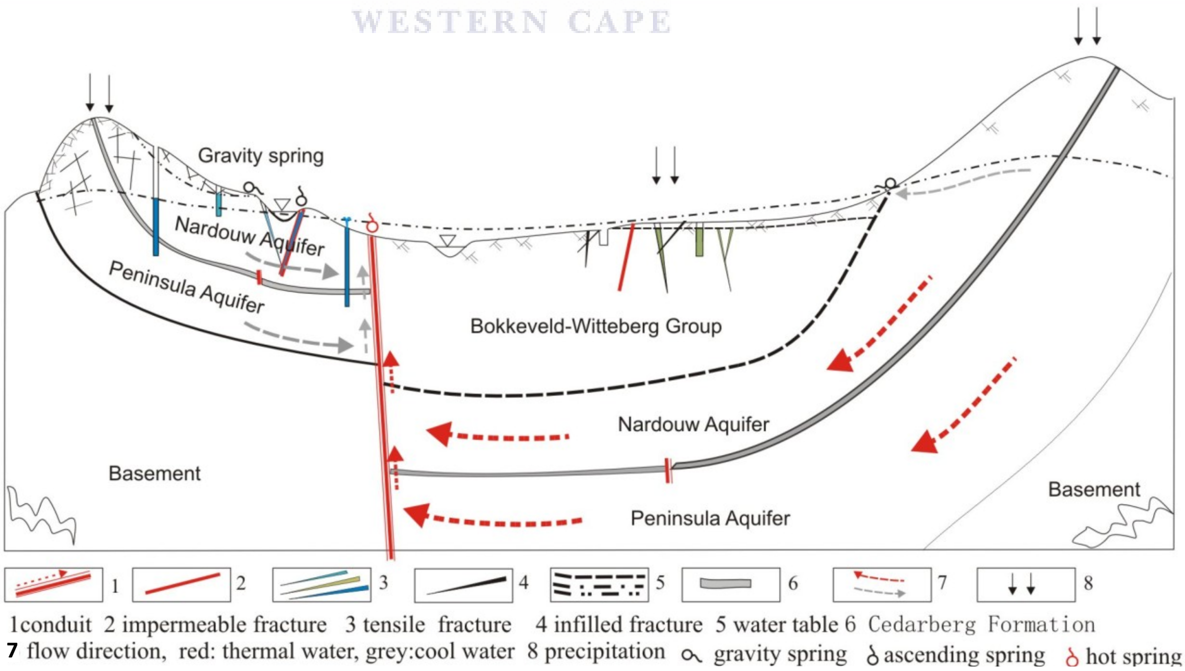


Fig. 3.3: Conceptualization of artesian aquifer with fault nearby in TMG (after Wu, 2005)

3.4 *Flowing artesian borehole in TMG*

3.4.1 Characteristics of flowing artesian borehole

As discussed in Chapter 2, an artesian borehole is a borehole that taps into a confined aquifer where the water level rises above the top of the aquifer, but does not necessarily reach the ground surface. A flowing artesian borehole is one in which the water level rises to a height that is greater than that of the ground surface (Fig. 3.4). Flowing artesian boreholes can flow on an intermittent or continuous basis and originate from unconsolidated aquifers, karst aquifers or fractured rock aquifers.

It is noted that the potentiometric surface is an imaginary surface above the aquifer, to which water from an artesian aquifer would rise in a pipe. The term potentiometric surface means head- or potential-indicating surface and is preferable to the term piezometric surface (Freeze and Cherry, 1979; Domenico and Schwartz, 1990), which is found in some of the literature.

Pressure head of a flowing artesian borehole is defined as the vertical distance from the ground surface to the potentiometric level, and can be measured either by extended casing or a pressure gauge installed on top of the borehole (Fig. 3.4). The pressure can be converted to pressure head in meters using the following equation (Weight, 2008):

$$L = \frac{P}{\rho g} \tag{3-1}$$

Where: L is the pressure head of the artesian aquifer in meters, P the pressure in kPa, ρ the density of water (10^3 kg/m^3), and g the gravitational acceleration (9.8 m/s^2).

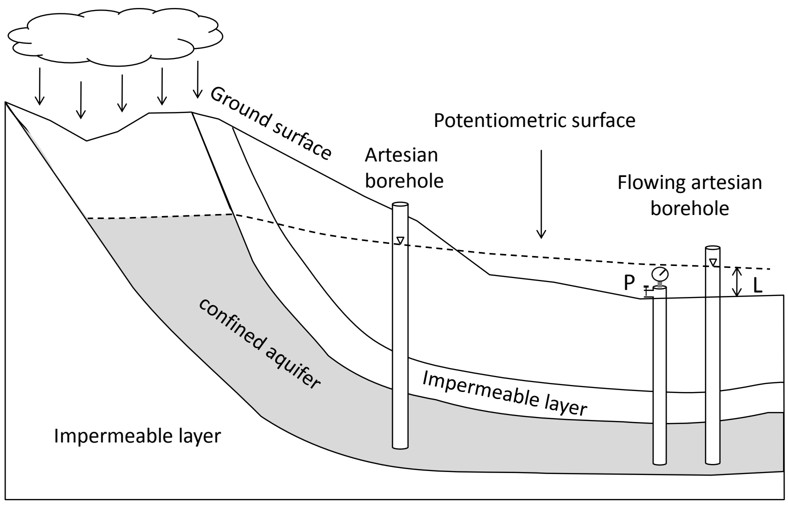


Fig. 3.4: Flowing artesian boreholes and methods of measuring pressure head

A major difference between unconfined and artesian aquifers is that an artesian aquifer has volume elasticity. Under artesian conditions, the artesian aquifer remains saturated with water as the potentiometric surface declines, the water withdrawn from storage is released both by compression of the aquifer and by expansion of the water, and reduction in storage may be permanent (inelastic) as well as elastic (Meinzer and Hard, 1925; Meinzer, 1928; Thompson, 1929). This was considered the first lucid statement on storage in an artesian system (Meinzer and Hard, 1925).

Another large difference between unconfined and artesian aquifers is the rate of spreading of the cone of depression. In an unconfined aquifer, a large volume of water drains slowly by gravity from the sediment within the spreading cone. In an elastic artesian aquifer, the pressure change traverses the aquifer at the speed of sound; the cone of depression and the area of influence grow very rapidly, but at a gradually diminishing rate. The area of influence of the cone of depression in an artesian aquifer pressure surface is commonly several thousand times larger than that in an unconfined aquifer (Lohman, 1965). For instance, elaborate aquifer tests in an artesian basin in Utah and a non-artesian basin in Nebraska, United States, were conducted to explore the transmission of pressure and the extending rate of the cone of depression, respectively (Leggette and Taylor, 1934; Wenzel, 1936). Even though the effects of pressure changes in the artesian aquifer were transmitted at different rates according to varying conditions, in all cases the transmission occurred at a much more rapid rate than for the tests under non-artesian conditions, where the rim of the cone of depression reached 150 m from the production borehole in 2 hrs, 270 m in 6 hrs, and about 360 m in 12 hrs. In the Utah tests, the opening of the artesian borehole affected the artesian pressure head in an observation borehole 855 m distant in 7 mins; the opening of another artesian borehole 1,155 m distant affected the head in the observation borehole in 57 mins. In other tests, changes of pressure were transmitted a distance of 3.2 km in 3 to 13 hrs.

3.4.2 Distribution of artesian boreholes

According to the elements of a hydrodynamic system and the boundary conditions of groundwater storage and flow, the TMG aquifer system can be divided into 15 hydrogeological units (Lin, 2007). Most of the flowing artesian boreholes are located at Bokkeveldberg, Worcester-Grabouw, Oudtshoorn-George and Uitenhage groundwater subareas, only a few are situated in Graafwater and Cape Flat groundwater subareas (Fig. 3.5). All these artesian boreholes are distributed in four primary catchments in TMG aquifer system. Detailed information of the flowing artesian boreholes in TMG is attached in appendix A.

One of the most important artesian groundwater basins is the Uitenhage Artesian Basin (UAB), and the other site is Oudtshoorn Artesian Basin. Water level as well as water quality data collected in artesian boreholes in Boschkloof indicates the characteristics of high yielding and excellent water quality in artesian aquifer. The studies at these sites focus on hydraulic pressure monitoring, conceptual model development and/or aquifer test data collection manually. A basin-scale hydrogeological characterisation of UAB was carried out in early 2000, and a conceptual model of artesian system was built locally (Maclear, 2001). Another significant artesian basin is situated in the semi-arid region in Klein Karoo, 55 km north of the coastal town of George in the Western Cape Province. Free-flowing test was carried out in Oudtshoorn on 22 September 2009. The test involved allowing the groundwater to flow freely without pumping under the artesian conditions for approximately 2 months. During the test, due to no automatic flow-meter or data-logger, flow rate, pressure changes at artesian borehole, the temperature of discharge water and water levels in all other boreholes were measured manually. These valuable data can be utilized to evaluate the hydraulic properties of artesian aquifer.

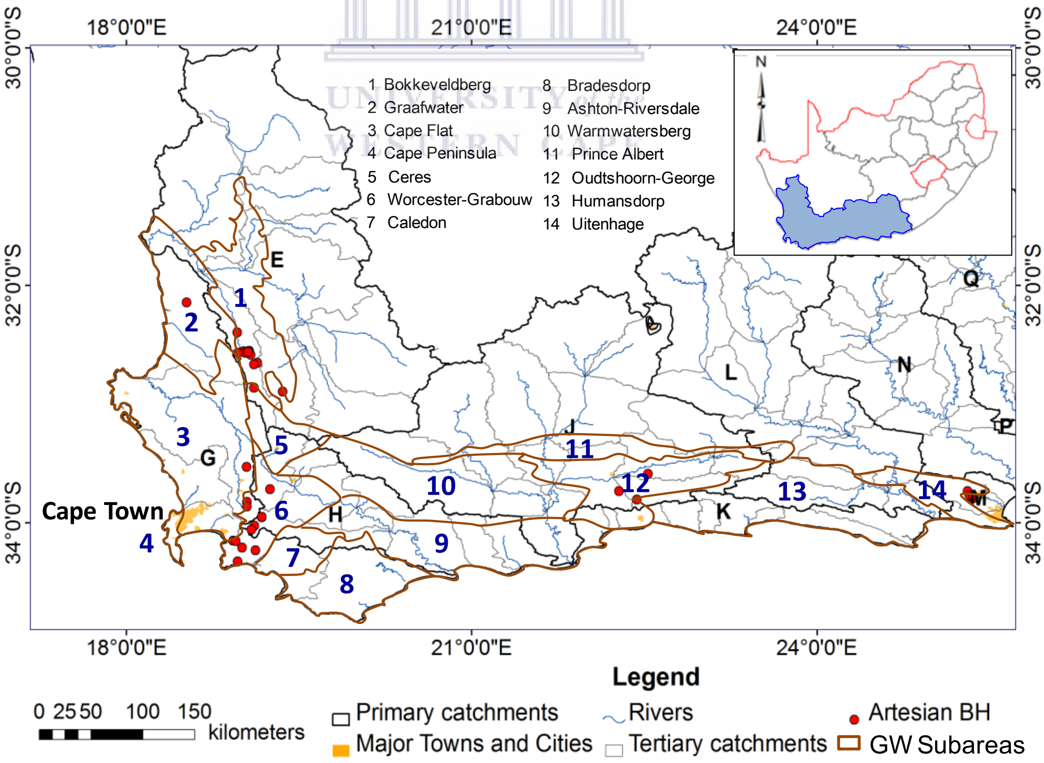


Fig. 3.5: Map of flowing artesian boreholes in TMG aquifer system

3.4.3 Artesian pressure of artesian borehole

Fractured rocks in TMG aquifers, reconstructed by several phases of crustal movements from the Permian to the Cretaceous, created various types of discontinuities in the form of joints, faults and unconformities. The largest fractures, that are associated with the deep-seated tectonic movements in the earth's crust, provide a route for deep circulating large volumes of groundwater under artesian pressure. In terms of pressure head, flowing artesian boreholes drilled into artesian aquifer in TMG can be classified into three categories:

- Weak artesian: pressure head is below or slightly above ground surface during or after wet season (- 0 m).
- Medium artesian: pressure head ranges from 0 to 20 m. For instance, pressure head of an artesian borehole in Rawsonville is approximately 10 m.
- Strong artesian: pressure head is more than 20 m. For instance, the pressure head of two artesian boreholes in Oudtshoorn is more than 45 m (UMVOTO, 2009). In such a case, the pressure head is usually measured by pressure gauge.

A large portion of flowing artesian boreholes in the TMG fall within the 'medium' or 'strong' artesian pressure categories (Riemann and Hartnady, 2013; GEOSS, 2010). To evaluate artesian aquifer properties, a free-flowing and recovery tests are often preferred over a constant-rate pumping tests since no pump will be needed. During the tests, simultaneous flow rate and pressure head are measured over time.

3.4.4 Current studies in TMG

A number of studies on artesian aquifer in TMG have been carried out in the past 20 years (Bush, 1985; GEOSS, 2003; UMVOTO, 2005). The information of those artesian boreholes and their locations are summarized in Fig. 3.5 and appendix A. A manual of pumping test data analysis in fractured rock aquifer was developed in 2002 as a step-by-step guide to assist the researcher in planning and executing pumping test in general (Xu, 2002). In 2005 to 2006, a groundwater research and monitoring site with a five-borehole network in Rawsonville was established in the TMG fractured aquifer. Borehole BH-1 is a flowing artesian borehole. Several studies referring to borehole core logging, groundwater level observations, hydraulic tests and tracer tests were done to explore the characteristics of fractured rock aquifer and the flow dynamics at local and regional scales (Xu et al., 2009). The results from Borehore BH-1 differing from other boreholes indicate that the flow system in borehole BH-1 is not connected to other aquifers. Due to the high pressure in confined aquifer, this artesian borehole was capped since it was completed in December, 2005, and limited studies on artesian borehole have been done besides one incomplete packer test done in 2006 (Lin, 2007).

During the free-flowing of artesian borehole in a confined aquifer, water flow to the borehole is the result of compression of the aquifer matrix and a lowering of potentiometric surface. Due to the fact of existing impermeable folds and identified as well as unidentified faults in TMG, the assumption of infinite aquifer cannot be fulfilled. Results from previous studies on non-artesian aquifer in TMG indicate the impact of fault or folds (Lin et al., 2014). All these information will help conceptualize the artesian aquifer in TMG.

Storativities of artesian aquifer in TMG ranging from 10^{-6} to 10^{-1} were obtained by conventional methods without considering the boundary conditions (Riemann and Hartnady 2013). The method adopted was based on an assumption that the flow during a certain time was constant (constant-rate test), which is problematic. Such a wide range of S values could also provide little information for evaluation of groundwater resources and planning for sustainable groundwater exploration in artesian aquifers in TMG area. It is hence critical to narrow down the wide range of S values.

3.5 Summary

In conclusion, the deep Peninsula Aquifer in TMG is often pressurized due to the overlying confining layer (Goudini Formation). The aquifer is compartmentalized into various hydrogeological units, bounded by large faults, lithologies, and topographies. In many locations, the pressure in Peninsula Aquifer is above ground surface. Boreholes drilled into such aquifer would become flowing boreholes. There are at least 37 flowing artesian boreholes in the TMG area, which are mainly located in four hydrogeological units (out of fifteen).

Characterization and storage determination of TMG aquifers were carried out by UMVOTO Africa and Water Research Commission (WRC) in the past few years. Various methods were used to determine the hydraulic properties and storage capacity of TMG aquifers (Non-artesian aquifer). There are very limited studies on artesian aquifers. It is well known that flow and pressure of flowing artesian boreholes during flowing tests change so rapidly that measurements taken manually can be unreliable. Thereof a special hydraulic test device for data collection in this context is deemed to be critical.

Another main issue related to artesian aquifer in TMG is that there is no comprehensive method available to evaluate the hydraulic properties (transmissivity and storativity).

Inasmuch as impermeable faults or folds in TMG, the current data interpretation method assuming the homogenous and isotropic of aquifer can be problematic. A method needs to be developed to address such issue. With storativity value derived from data interpretation, quantification of groundwater resources in artesian aquifers of TMG can be determined at a confidence level required for sustainable utilization by users including City of Cape Town Metropolitan Municipality. In summary, evaluation of aquifer properties and groundwater resources in TMG artesian aquifers can provide valuable information for decision-makers to develop sustainable groundwater utilization programme.

Chapter 4
Hydraulic test device

4.1 Introduction

Accurate data collection during the pumping test is very essential. The most serious shortcomings of the test methods are insufficient accuracy of measurements and incomplete control of certain variables. The conventional way of measuring discharge rate using bucket and timer or V-notch weir method is inefficient, and in the artesian borehole with free-flowing status, the above approach is cumbersome, and data might be inaccurate. Therefore, fabrication of hydraulic test device for data collection is deemed to be critical yet it must be carefully designed so that the measured data are accurate enough to be used for analysis.

Based on unique characteristics of flowing artesian borehole, the device needs to be designed to achieve and maintain the pressure head as a constant, meanwhile the discharge rate and pressure changes need to be simultaneously measured and recorded over a period of testing time.

The dedicated equipment should be adopted for a flowing artesian borehole, and the first way to do so is to use a valve to control the discharge from flowing borehole. However, this approach usually renders a poor way to maintain the pressure head, let alone the labor-intensive and tedious work to adjust the valve frequently during the test. The valve can be fine adjusted once the constant-head has been achieved, however, it may cause pressure-head and flow rate varying more widely than desired, creating ineffective data. With this in mind, it is hence recommended that maintaining the hydraulic head as zero is preferential if the pressure and flow rate are not high. In this case only discharge rate needs to be measured during the free-flowing period, while pressure head can be measured by pressure gauge or data logger during recovery period. It is less time-consuming, and the data are more accurate.

The objective of this chapter is to develop and present a hydraulic test device, which is used to take measurements of flow rate and hydraulic pressure at flowing artesian borehole simultaneously during free-flowing and recovery tests. Procedures to install and operate hydraulic testing on a flowing artesian borehole are highlighted in particular.

4.2 Main units and configuration

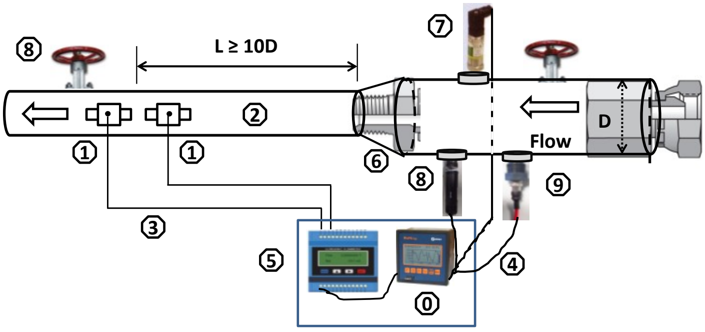
4.2.1 Ultrasonic flow meter (UFM) and pressure transmitter

The designed test device should be able to show the dynamic heads on scales and record flow rate simultaneously (at certain time interval). It must be fit to the flowing artesian borehole, the artesian hole BH-1 in Rawsonville in particular (Fig. 4.1). Individual proper flow meter and pressure gauge unit can be jointly used to achieve the goals. In consideration of field applications, the pipe material should be changed to stainless steel instead of plastic, and the test device should be portable and flexible for free-flowing test in other sites as well.

Fig. 4.1: The artesian borehole BH-1 in Rawsonville

According to the above-discussed requirements, a use of ultrasonic technology is made in the flow meter to measure the accurate discharge rate and flow velocity through the transducers mounted on the pipe surface. A pressure transmitter is used to measure the pressure head of artesian borehole. All the measured data saved by data logger can be downloaded to PC for data interpretation later on.

The flowmeter is used to measure the discharge rate simultaneously at two different points of pipe without direct contact with discharging water. The flow transducers are attached to the end of the pipe or casing where the free-flowing water comes out, and the location of transducers should be set at the right location according to JEMIS 032-1987 (Table 4.1). The configuration of the test device and the detailed information of each component are shown in Fig. 4.2 and Table 4.2, respectively.



① Transducer (mounted outside)
② Testing pipe
③ Transducer cable
④ Cable (link to data logger)
⑤ Ultrasonic flowmeter
⑥ Adapter (link to outlet)
⑦ Pressure transducer
⑧ pH probe
⑨ EC probe
⓪ Data logger

Fig. 4.2: The configuration of test device with ultrasonic flow meter (UFM) and pressure transmitter for measurements of continuous flow rate, pressure, *pH* and *EC*

Table 4.1: Requested pipe conditions and locations (D-Diameter, and L-Length. JEMIS 032-1987)

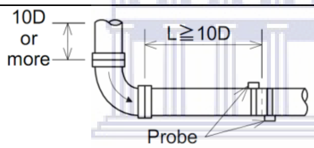
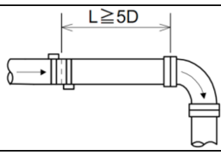
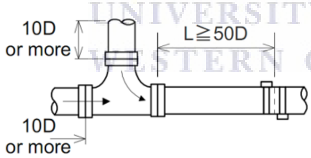
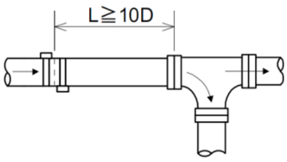
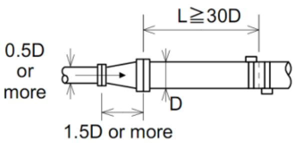
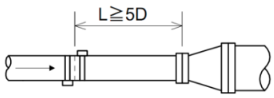
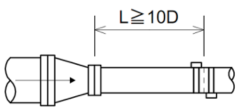
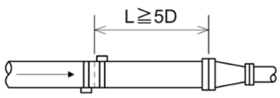
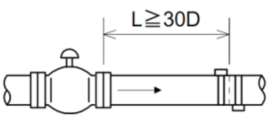
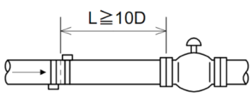
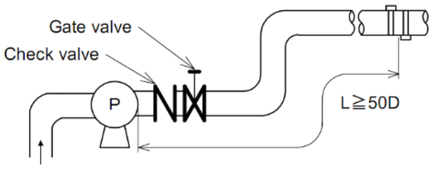
Section	Upstream straight pipe length	Downstream straight pipe length
90° bend		
T		
Expanding pipe		
Contracting pipe		
Various valves	 When flow volume is adjusted at the upstream valve.	 When flow volume is adjusted at the downstream valve
Pump		

Table 4.2: Detailed information of each component, function and rough cost of UFM and transmitter test device

Component of test device	Function	Range	Description/Requirement	Price (USD)
Adapter to casing	link the casing to test device	-	It should be attached to the casing smoothly without leaking.	10-20
Flow meter transducer	Ultrasonic transmitter-receiver sensors	-	Transducers need to be attached onto the surface of pipe. The location of transducers refers to JEMIS 032-1987 (Table 4.1).	1500-7000
Transducer cable	Transmit the ultrasonic signal to flowmeter main unit	-	-	
Cable	Link from flowmeter to laptop/PC to download data	-	-	
Portable flowmeter main unit	Flow rate measurement	0.01-32 m/s (velocity)	Parameter input prior to the test (pipe diameter, unit of flow rate and range etc).	
Pressure transmitter	Pressure measurement	0-300 psi	Parameter input prior to the test (unit and range).	200
pH probe	pH measurement	0-14	It needs to be calibrated for the first time.	150
EC probe	EC measurement	0-1000 us	-	250
Data logger plus software	Record the instant flow rate and pressure, pH and EC		It could display the instantaneous values, and the data could be exported to PC later.	1300
Adapter to outlet	link test device to outlet	-	It should be attached to the outlet smoothly without leaking.	10-20
Valve	Control the free-flowing	-	The valve should be closed slowly to avoid water hammer effect.	20
Testing pipe	Provide flow path through the test device	-	Materials allow stable transit of ultrasonic waves.	20-30
				Total: 3400-10000

Due to the very low flow rate of borehole BH 1 in Rawsonville (0.1 l/s-3 l/s), a smaller pipe with diameter of 25 mm was linked to the casing of borehole to ensure the pipe fully-filled with water. The data logger with a monitor will be attached to the flowmeter and transmitter to display and record the flow rate and pressure data.

4.2.2 Integrated differential pressure flow meter (DPFM) and pressure transducer

Alternatively, a V-Cone differential pressure flow meter and pressure transducer can be jointly used to measure and record the instant flow rate and pressure changes (Fig. 4.3). The

V-Cone flow meter is a device that accurately measures flow over a wide range of Reynolds numbers, under all kinds of conditions and for a variety of fluids. It operates on the same physical principle as other differential pressure-type flow meters, using the theorem of conservation of energy in fluid flow through a pipe. The V-Cone flow meter features a centrally-located cone inside the tube. The cone interacts with the fluid flow, reshaping the fluid's velocity profile and creating a region of lower pressure immediately downstream of itself. The pressure difference, exhibited between the static line pressure and the low pressure created downstream of the cone, can be measured via two pressure sensing taps. One tap is placed slightly upstream of the cone, and the other is located in the downstream face of the cone itself. The pressure difference can then be incorporated into a derivation of the Bernoulli equation to determine the fluid flow rate. The cone's central position in the line optimizes the velocity profile of the flow at the point of measurement, assuring accurate and reliable flow measurement regardless of the condition of the flow upstream of the meter (Dyer, 2009).

Flow integrator uses large screen liquid crystal display, which can display six digit instant flow rate and pressure changes with an accuracy of two digits to right of decimal point or one digit. The detailed specifications of the test device are listed in Table 4.3.

Flow computer adopts a micropower single-chip-microcomputer (power consumption is less than or equal to 400 uA); use industrial lithium battery DC3.6 V to supply power with service life of two to three years.

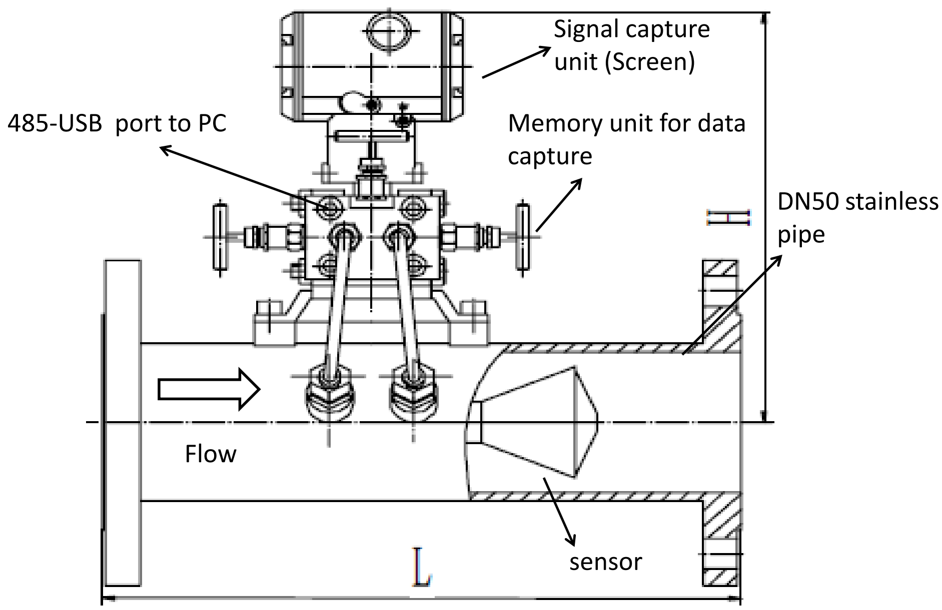


Fig. 4.3: The configuration of test device with DPFM and pressure transducer for measurement of continuous flow rate and pressure

Table 4.3: Detailed information of each component, its function and rough cost for integrated differential pressure flow meter (DPFM) and pressure transducer

Component of test device	Function	Range	Description/Requirement	Price (USD)
V-Cone differential pressure flow meter	Flow rate measurement	0.1-10 m/s	Parameter input prior to the test	3500
Pressure transducer	Pressure measurement	0-300 psi	-	925
Flow computer	Data collect and output	-	Flow computer is connected to V-Cone differential pressure flow meter.	1200
Data Cable	Link from flow computer to laptop/PC.	-	485 data cable between flow computer and laptop/PC.	
485-USB adaptor	An adaptor for 485/USB data converting	-	An adaptor for 485/USB data converting	3000
Flow meter manager software	Data processing and analysis software	-	Data processing and analysis software. Excel format is supported for data output.	
DN50 stainless pipe	Link to BH	-	With 80 cm length at each side of test device	1050
Multiple parameter memory unit	Save the flow rate and pressure data	-	The memory unit will be linked to PC to download data after the test	2200
Temperature probe	Temperature measurement	-	-	225
				Total: 12100

4.2.3 Test device selection and configuration

The two designed test devices, namely, UFM and pressure transmitter test device and integrated DPFM and pressure transducer test device, can both be used to measure as well as record the instantaneous flow rate and pressure. However, there are some advantages and disadvantages for each device. Table 4.4 lists the comparison of these two test devices from different aspects.

Table 4.4: Comparison of UFM and pressure transmitter test device and integrated DPFM and pressure transducer test device

Test device / Comparison	UFM and pressure transmitter test device	Integrated DPFM and pressure transducer test device
Portable	Yes	Yes
Range	It can be used widely in other artesian boreholes with high flow rate/velocity.	It may not be used in artesian borehole with high free-flowing rate.
Power supply	It needs external power supply. However, portable Li-ion battery can be used for power supply.	It comes with rechargeable battery.
Data storage/processing	Data is saved by data logger	Data is stored in microcomputer
Time to make the test device	Short (1-2 weeks)	Long (6-8 weeks)
Maintenance	Easy	Difficult
Principle	Easy	Complicated
Accuracy	High	High
Cost	Low-Medium	High

Considering of the characteristics of these two test devices listed in Table 4.4, together with the cost and the potential application for the other free-flowing boreholes in South Africa, the idea of developing UFM and pressure transmitter test device is adopted for data collection. According to the idea shown in Fig. 4.2, the hydraulic test device is developed and fabricated as follows (Fig. 4.4):

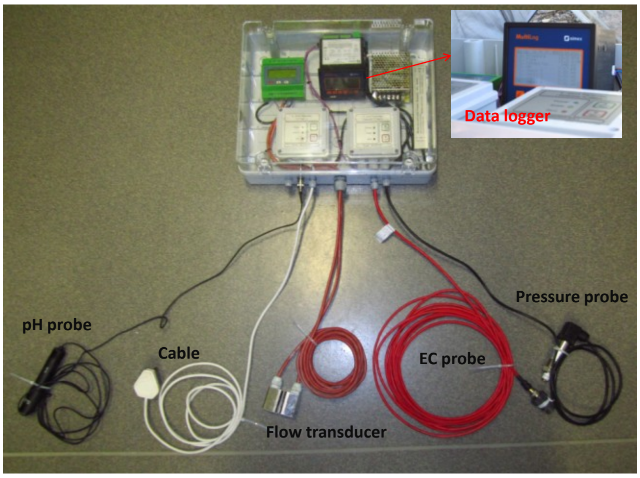


Fig. 4.4: Configuration of the test device for measurements of continuous flow rate, pressure, *pH* and *EC*

4.3 Calibration and installation of test device

4.3.1 Parameters input and calibration

Before installation of the test device in the field, sampling interval and technical parameters related to flow rate, pressure, *pH* and *EC* need to be entered and calibrated from data logger. For instance, pipe material, pipe diameter, thickness of pipe, units and ranges etc. It may take a couple of hours in the lab to finish this task. The sampling interval is recommended to be 1 minute, 2 minutes or 5 minutes. The units and ranges related to flow rate and pressure depend on the physical conditions in the study area. For lower flow rate, unit of l/min is recommended, while unit of l/s is recommended for high flow rate situation.

Procedures to calibrate the *pH* and *EC* parameters can be found from relevant manual or reports (Todd et al., 2000). It will not be described in the following section. The configuration of flowmeter in the field will be highlighted due to its significant role for data collection.

Steps to configure the parameters related to flow rate

In order to make the UFM work properly and enhance the accuracy of measurements, the following steps to configure the system parameters are formulated:

1. Calculate the transducer spacing. The pipe materials, the size of outer diameter and wall thickness of pipe need to be entered into unit of flowmeter. Transducer-*S* needs to be chosen as transducer type. The flowmeter will calculate the transducer spacing automatically, which will be shown on the screen. Mark the transducer installation spots on the pipe according to the spacing value.
2. Locate an optimal position where the straight pipe is sufficient (see Table 4.1) and no rust covers the pipe. Polish the pipe outer surface. A sander is recommended if the pipe surface is not smooth.
3. Apply adequate ultrasonic couplant (grease, gel or Vaseline) onto the transducer surface as well as the installation area on the pipe surface.
4. Strap on the transducers and make sure there is no gap between the transducer surface and the pipe surface. Transducer mounting methods (the V-method and Z-method are the common methods. N-method is suitable for small pipe. The introduction of these methods will be depicted in next section).
5. Fine tune the transducers' position until the triplet, signal strength *S*, signal quality *Q* and transit-time ratio *R* have the best readings and those readings are in their operational ranges.

4.3.2 Installation of test device

The first step in the installation process is to select an optional location for installing the flow transducers in order to make the measurements accurate and reliable. A basic knowledge about piping would be advisable. An optional location would be defined as a long straight pipe line full of liquid that is to be measured. The pipe can be in vertical or horizontal position. Principles to select an optimal location are described as follows:

- Pipe must be full of water at the measurement side;
- Must be in a safe location;
- No heavy corrosion or deposition inside of the pipe. Select a relative new straight pipe if it is possible. Old pipe tends to have corrosions and depositions, which will affect the results;
- The straight pipe should be long enough to eliminate irregular flow-induced error. Therefore, it is better to avoid valve, outlet and bend etc. Typically, the length of the straight pipe should be at least 15 times the pipe diameter. The longer the pipe is, the better the accuracy.

Transducer mounting allocation

Follow the steps mentioned above to configure the parameters related to flow rate, and write down the spacing value for two transducers. Three transducer mounting methods are available, namely, V method, Z method and N method. The V method is primarily used on small pipes (DN 100-300 mm). The Z method is used in applications where the V method cannot work due to poor signal detected. In addition, the Z method generally works better on larger diameter pipes (DN over 300 mm) or cast iron pipes. The N method is an uncommonly used method. It is used on smaller diameter pipes (DN below 50 mm).

V method

The V method is considered as the standard method. It usually gives a more accurate reading when it is used on pipe with diameters ranging from 50 mm to 400 mm. It is convenient to use, but still requires proper installation of the transducers, contact on the pipe at the pipe's centerline and equal spacing on either side of the centerline. The configuration of two transducers is shown in Fig. 4.5.

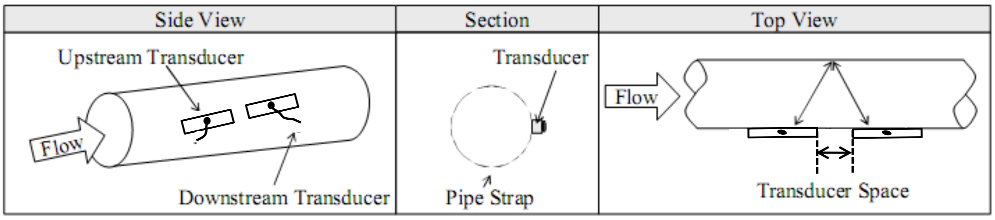


Fig. 4.5: The configuration of transducers of flowmeter using V method

Z method

The signal transmitted in a Z method installation has less attenuation than a signal transmitted with the V method. This is because the Z method utilizes a directly transmitted (rather than reflected) signal which transverses the liquid only once. The Z method is able to measure on pipe diameters ranging from 300 mm to 1200 mm approximately. Fig. 4.6 shows the configuration of transducers with Z method.

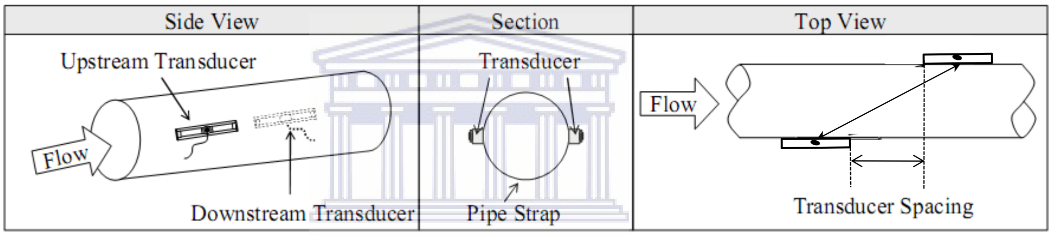


Fig. 4.6: The configuration of transducers of flowmeter using Z method

N method

For the N method, the sound waves traverse the fluid twice and bounce three times off the pipe walls. It is suitable for small diameter measurement.

The measurement accuracy can be improved by extending the transit distance with the N method (uncommonly used). The configuration of transducers is shown in Fig. 4.7.

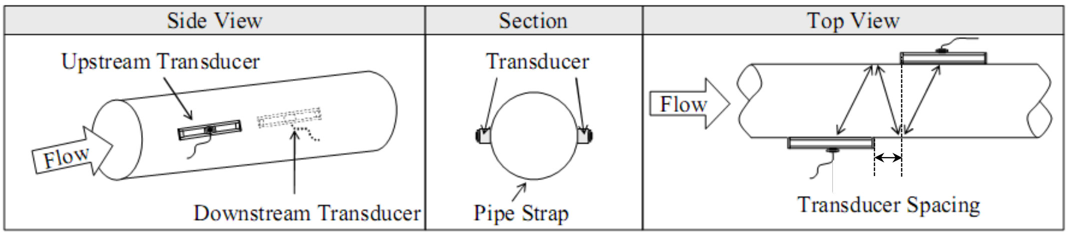


Fig. 4.7: The configuration of transducers of flowmeter using N method

4.3.3 Installation check-up

After proper installation of transducers, the user should check the following items before opening the valve: the range of pressure, *pH*, *EC* and parameters related to flow rate, including the receiving signal strength *S*, the signal quality *Q* value and the transit time ratio *R* displayed on the screen of control unit. As such, the flow meter will be fairly working properly and the results are accurate and reliable. After all the check-up are done, the free-flowing test can be started by opening the valve. The data changes would be shown on the screen of data logger. Minor adjustment of transducers might be needed to stabilize the signal.

4.4 Hydraulic testing on an artesian borehole

4.4.1 Prior to test

It is noted that the water would flow out of any free-flowing artesian borehole under nature condition; therefore, the artesian borehole must be sealed. Before start free-flowing test, the borehole needs to be shut in to build enough pressure, and the observation of pressure in artesian aquifer is necessary. In addition, it is recommended that water level or pressure head of other boreholes nearby be monitored before the test.

4.4.2 Free-flowing borehole without observation hole

When free-flowing test is carried out in flowing artesian borehole, discharge rate and pressure head will be measured with UFM and pressure transmitter, respectively. The data would be saved by the data logger. Alternatively, the data can be captured manually or by other devices.

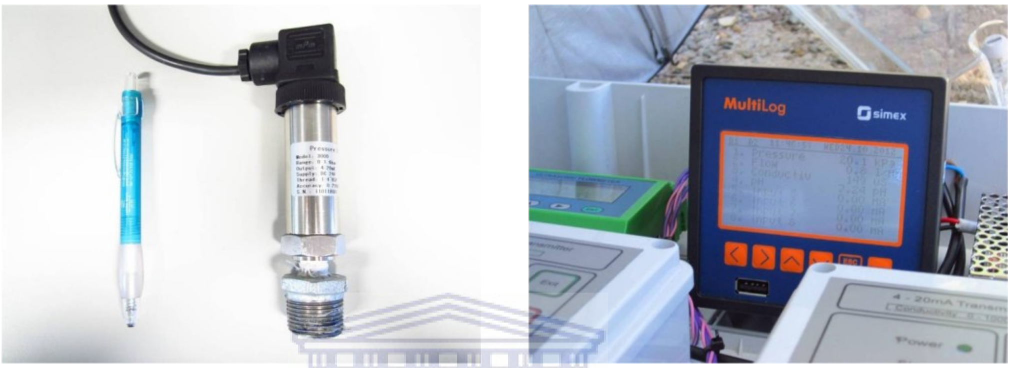
Two factors must be taken into consideration during the test. Water level or pressure head at other boreholes in the study area should be measured occasionally to check whether there is any significant leakage in upper or lower part of the testing aquifer. The free-flowing water from test borehole must be deposited to a place where it is not linked to the artesian aquifer.

4.4.3 Free-flowing borehole with observation hole

Capturing data of constant-head variation is different from that of the conventional constant-rate test. In the condition where there is an observation borehole, as soon as the free-flowing test starts, pressure head and discharge rate at free-flowing borehole and pressure head at observation borehole need to be measured simultaneously. The measurement of pressure head at observation hole can be taken using a pressure gauge or pressure transmitter.

4.4.4 Recovery test data collection

After free-flowing ceases with the valve shut down, recovery of the pressure head will start. The duration of recovery process depends on local aquifer properties (*T* value in particular) and the duration of flowing period. Pressure head will be captured by the pressure transmitter and data logger during recovery test. The value will also be displayed on screen of data logger. The main components of test device to capture pressure head at artesian borehole are shown in Fig. 4.8.



A Pressure transmitter ***B*** Data logger linked to pressure transmitter

Fig. 4.8: Photographs of equipment used for data capture during recovery test at artesian borehole

4.5 Hydraulic testing with test device

Three aquifer tests on artesian borehole BH-1 in Rawsonville were conducted in 2012. The first free-flowing test was conducted on 18^{th}, March, with duration of 18 hrs. No automatic flow-meter or data logger was available for data collection. All the data were measured manually (Fig. 4.9). During the test, the following measurements were taken:

a) Pressure
b) Discharge rate with a 15 L bucket and timer
c) Temperature, *EC* and *pH* parameters

Fig. 4.9: Free-flowing test data capture manually in Rawsonville

Fig. 4.9 shows the set-up of the area. Before starting the test, hydraulic pressure of artesian borehole was 94 kPa; during the 18 hours test, the tap was partially open, the pressure was maintained at 40 kPa by adjusting the tap manually, and the flow rate was measured with 15 L bucket and a timer (flow rate = volume/time). The water was discharged into the stream nearby which is disconnected from the local confined aquifer systems. The flow rate data versus time was plotted at semi-log scale shown in Fig. 4.10.

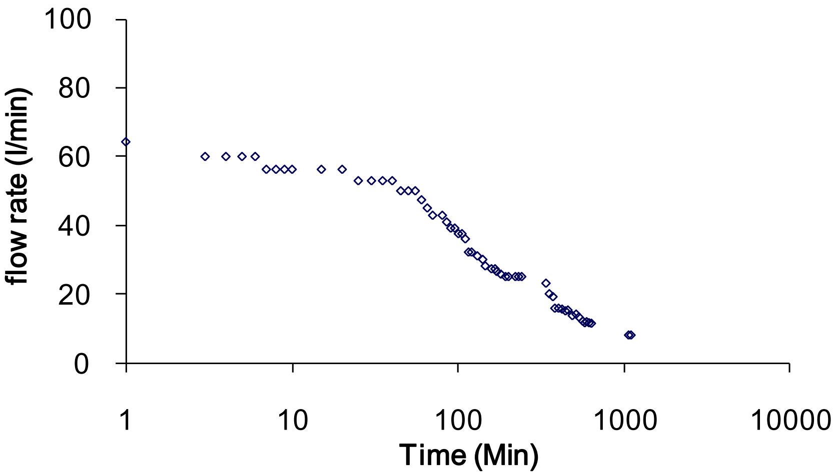


Fig. 4.10: Flow rate measured manually at test borehole BH-1 in Rawsonville

The flow rate decreased slowly in the first 100 minutes. After that, it dropped sharply, and tended to be stable at the end of the test. To help evaluate the aquifer properties at later stage, the results of constant drawdown over flow rate during 18 hrs test period were plotted on semi-log scale shown in Fig. 4.11.

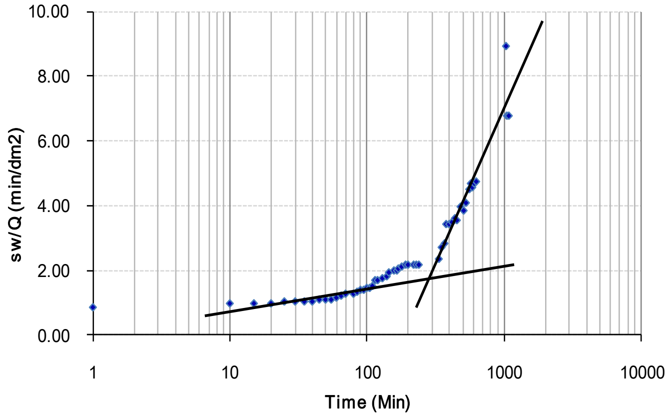
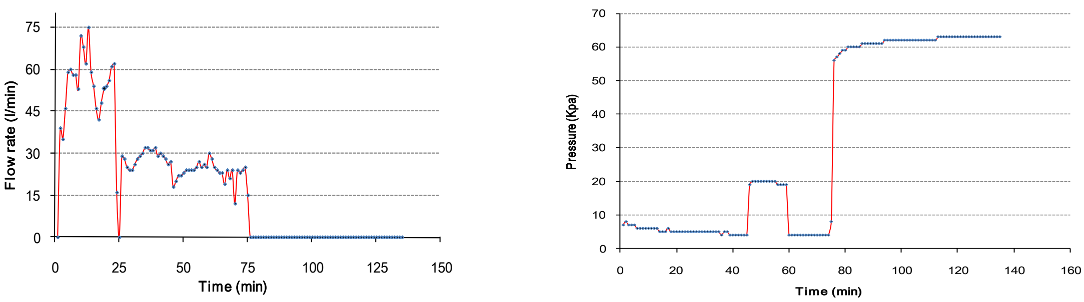


Fig. 4.11: s_w/Q over time with data measured manually at test borehole in Rawsonville (s_w-constant drawdown, Q-flow rate)

The second test was conducted to test the designed equipment for measuring the flow rate and hydraulic pressure in early November, 2012. The set-up of the equipment was shown in Fig. 4.12.

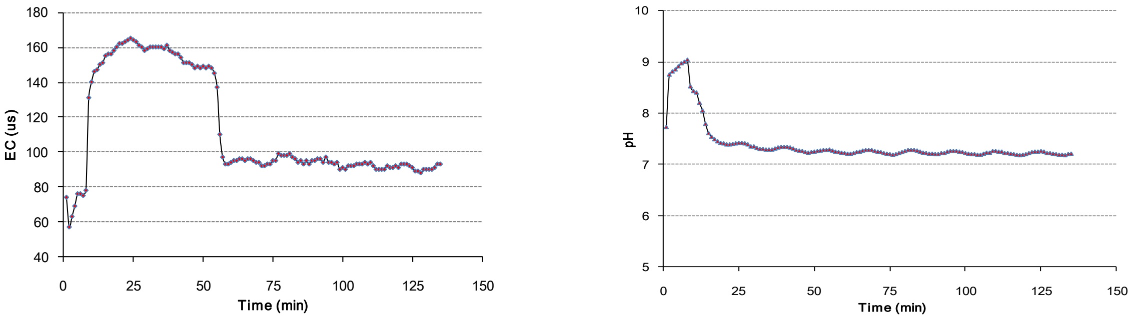
Fig. 4.12: The set-up of equipment test for measuring the flow rate and pressure of artesian borehole in Rawsonville

The duration of equipment test was about 2 hrs, with pressure, flow rate, *EC* and *pH* parameters recorded by data logger. The data were presented in Fig. 4.13.



a) flow rate changes

b) pressure changes

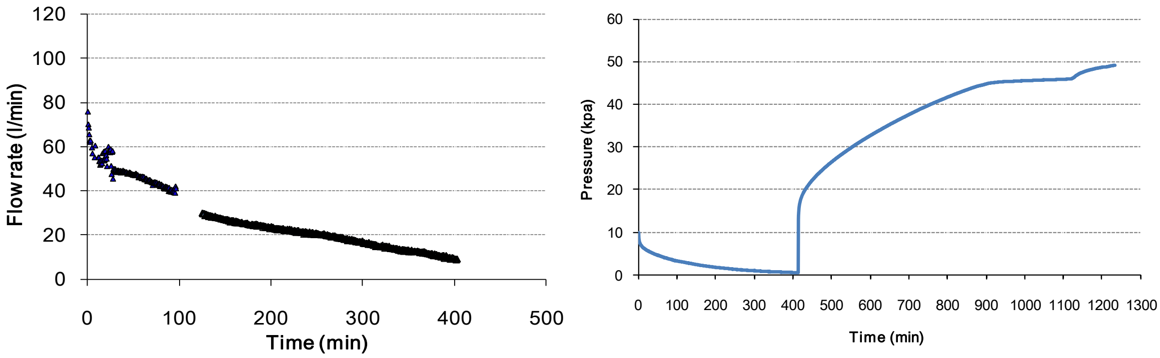


c) EC changes d) pH changes

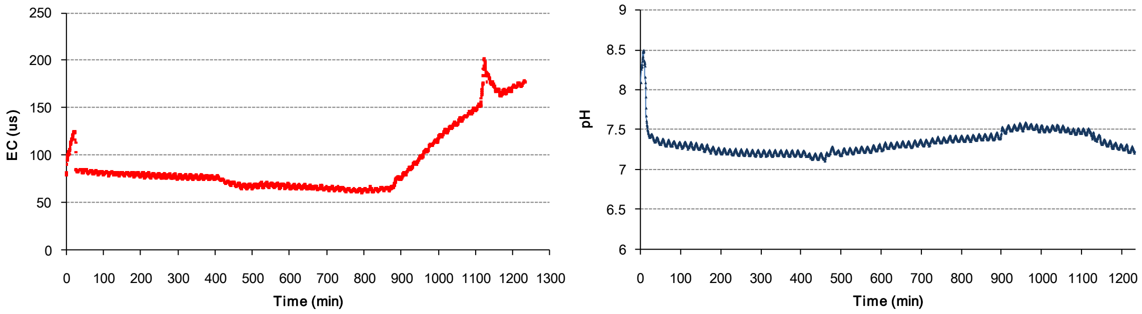
Fig. 4.13: Flow rate, pressure, *EC* and *pH* changes with time recorded in early Nov, 2012

The whole equipment test was split into 75 minutes free-flowing test and 1 hour recovery test with all the types of data recorded every minute by data logger. Considering the free-flowing test data collected manually, the above results show that the data of flow rate and pressure changes are problematic, while the *EC* and *pH* values may be fine. As there is stagnant water in the borehole before conducting the test, sampling results (for instance, *pH* and *EC*) prior to purging as well as post purging are different (Cook, 2003). The volume of water which should be purged must equate to two borehole volumes if the water sample is required from the aquifer.

Considering the quality of flow rate and pressure data collected in early November, 2012, the equipment was improved afterwards by adopting a different UFM and a better data logger with a built-in monitor. The third test was conducted in late November as soon as the test device was improved. The test was composed of 7 hrs constant drawdown test and 13 hrs recovery test. The static water head before releasing the water was 7.53 m. The tap was fully open during the test, with flow rate, pressure, *EC* and *pH* measured. However, due to technical problems, an approximate 30-minutes data gap took place during the free-flowing test. The data captured by the revised test device were presented in Fig. 4.14.



a) flow rate against time b) pressure against time



c) EC against time   d) pH against time

Fig. 4.14: Flow rate, pressure, EC and pH data captured during the test at borehole BH-1 in Rawsonville in late Nov, 2012

Flow data collected manually and by the device (Fig. 4.11 and Fig. 4.14a) were plotted in a semi-log plot shown in Fig. 4.15. It is clear that the data captured by the device shows a similar trend to data collected manually. The flow rate decreased slowly in the first 100 min, while it decreased sharply at a later stage. The *pH* values at an early stage, shown in Fig. 4.14d, prove the presence of unpurged water in the pipe, while the *pH* and *EC* data captured during the recovery test (Fig. 4.14c and d) indicate the possibly unstable groundwater quality.

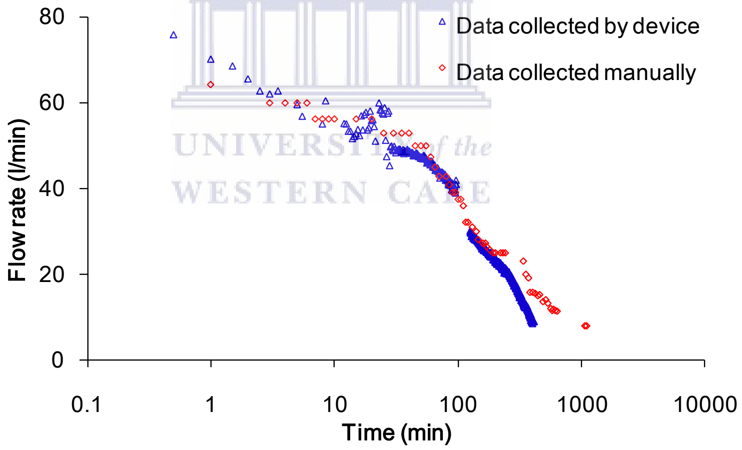


Fig. 4.15: Flow rate data collected manually and by the device, plotted at a semi-log scale

As discussed in Chapter 2, a classic method for determining hydraulic properties of artesian aquifers was developed by Jacob and Lohman (1952). The proposed equation is solved graphically on a semi-logarithmic grid by plotting values for the ratio of constant-drawdown to discharge (s_w/Q) on the linear scale against corresponding values of time (t) on the logarithmic scale, and then calculating T and S values using the slope for one log cycle of t based on the assumption that the artesian aquifer is homogeneous and isotropic. Theoretically, even though the aquifer may not be homogeneous or isotropic, the s_w/Q values calculated using data captured by the device and collected manually should show the same trend at semi-log scale, corresponding to each log cycle of time. The calculated s_w/Q values from the case study are plotted at a semi-log scale in Fig. 4.16. The shape is identical to the s_w/Q derived from data captured manually.

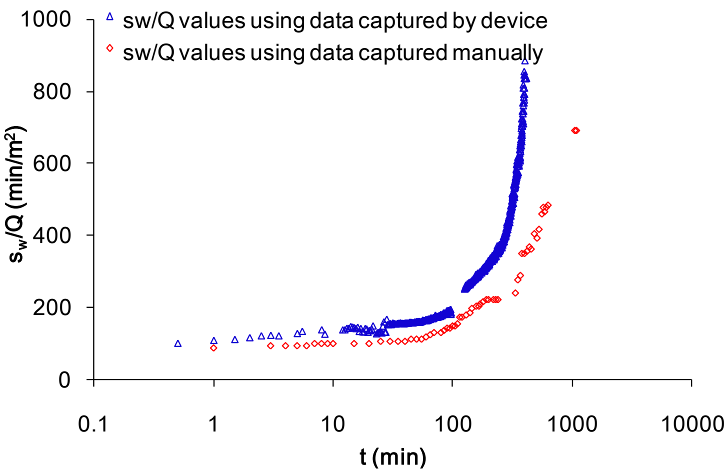


Fig. 4.16: s_w/Q at a semi-log scale using the data captured by the device and the data collected manually

It is noted that even though the two aquifer tests at Borehole BH-1 were conducted under different pressure head conditions, the results from both tests (Fig. 4.15 and Fig. 4.16) imply that the flow and pressure data captured by the device are accurate and reliable, and can aid considerably in determining aquifer properties (see s_w/Q values in Fig. 4.16, particularly). However, as the pressure in the aquifer rises very quickly at the beginning of the recovery test, taking pressure readings using a pressure gauge can be problematic; therefore no results were collected manually for the recovery test at Borehole BH-1.

4.6 Discussion and summary

The advantages of the device described include: (i) it is simple to use and portable; (ii) data captured is accurate and reliable; (iii) it can accommodate high flow rate (pressure head) as well as low flow rate (pressure head); and (iv) it is cost effective to purchase and use, in comparison with conventional methods of data collection for aquifer tests – no pump is needed, and it is less labour intensive. The shortcomings of the device which need to be solved in the future include: (i) requirement for a power supply; and (ii) sensitivity of the ultrasonic flowmeter to signal strength.

The problem of needing an external power supply can be solved by including a lithium-ion battery or solar panels in the device, and the sensitivity issue can be addressed through cautious adjustment of the location of the flowmeter transducers.

In conclusion, a hydraulic test device for free-flowing artesian boreholes was conceptualised and developed, and applied successfully in the TMG aquifers (Sun and Xu, 2014). Procedures of installation of the test device and data collection under different borehole conditions in the field are highlighted in particular. The test device, designed to measure the flow rate and pressure head simultaneously during the aquifer test, was demonstrated for the medium artesian condition. It is noted that the borehole must be sealed for days or weeks to build up enough pressure before conducting the aquifer test with the device. Water level or pressure head of all other boreholes nearby before as well as during the test need to be monitored. S_w/Q values collected manually and using the device were plotted on semi-log scale. Even though the two test were run under different conditions (different constant head), the results displays an identical trend, which indicates the flow rates captured by the device at a flowing artesian hole in Rawsonville were reliable and accurate compared with the data collected manually on the same borehole, and can be utilised to estimate the aquifer properties later on.

In addition to the flow and pressure data, *EC* and *pH* readings captured by the device may be used to indicate the possible changes of flow regime and groundwater quality. It is recommended that the measurements of the quality indicators be used to verify the testing conditions, for instance, identifying the purging process.

It is noticed that a number of boreholes in the TMG aquifers are artesian in nature. The device presented in this paper would be valuable for wide application to other flowing artesian boreholes in TMG. With due improvement of the test device, its wider application in similar conditions, such as the artesian holes in the Karoo, would be expected in future. The data captured by the device can be used to evaluate artesian aquifer properties using proper pumping test models such as the Jacob-Lohman method (Jacob and Lohman, 1952; Hantush and Jacob, 1955; Lohman, 1979), which will be discussed in later chapters.

Chapter 5
Software development for data interpretation

5.1 Introduction

After data collection of pumping test is completed, an appropriate approach needs to be selected to estimate the transmissivity (*T*) and storativity (*S*) of aquifer. Methods of pumping test data analysis were summarized in Chapter 2. The formulas and methods available to hydrologists are almost unlimited in number. Approaches for interpretation of test data collected from flowing artesian borehole are discussed in particular.

Due to the fact that most fault zones developed in the TMG sandstones and siltstones are evidenced to be lithified and act as aquitards (Newton et al., 2006), some of the assumptions of conventional straight-line method developed by Jacob and Lohman (1952) may not be fulfilled. Method based on Jacob-Lohman equation needs to be developed to accommodate different boundary conditions.

In this chapter, hydraulic testing at a flowing artesian borehole is conceptualized. A user-friendly program is developed based on the theories of artesian aquifer test summarized in Chapter 2. The program is separated into three components, which consist of the interfaces for analysing free-flowing test data, recovery test data, skin factor and effective radius. Analytical methods under different boundary conditions are highlighted in particular. The terminologies and procedures to use the program are outlined. Diagnostic plot analysis method using reciprocal rate and reciprocal rate derivative is reviewed and developed for free-flowing test data analysis, followed by a discussion of noise elimination. Advantages and disadvantages of diagnostic plot method are discussed as well.

5.2 Conceptualization of hydraulic testing

Unlike the constant-rate pumping test, flow rate rather than water-level data during free-flowing test period is used to assess the aquifer properties, while the water-level data is measured during recovery test. In terms of flow rate and hydraulic pressure changes at test borehole, the process of aquifer tests at flowing artesian borehole can be divided into three phases shown in Fig. 5.1.

- Adjusting period. Once a flow breakout begins, the rate of the discharge can reach maximum over a short time, while hydraulic head will drop to ground surface or the elevation of the borehole rim immediately. The duration can be less than 1 minute or several minutes (0 - t_1);

- Free-flowing test period. Hydraulic head is zero or slightly over zero above the ground surface, and flow rate decreases over time (t_1 - t_2);
- Recovery test period. When the valve is shut down, flow will become zero, and the pressure head of the aquifer will start to rise in the test borehole as well as observation hole (t_2 - t_3).

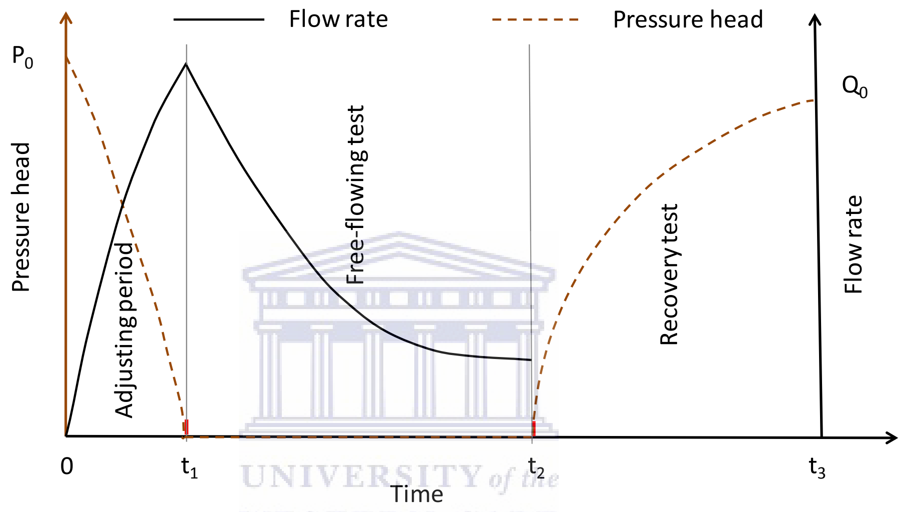


Fig. 5.1: Schematic aquifer test at flowing artesian borehole

To evaluate the *T* and *S* of an artesian aquifer, it is assumed that the duration of the adjusting period is negligible, and flow rate and hydraulic pressure data during the latter two periods are deemed to be more valuable.

5.3 Software interface for data interpretation

The measured data sets of pressure and flow rate to be taken during aquifer test must be correctly loaded onto a computer and analysed using proper method. It is proposed that interpreting software can be developed on spreadsheets platform as this would guarantee a user-friendly nature yet without losing accuracy. Alternatively, some commercial software package, such as AQTESOLV, may be used to analyse the test data.

Microsoft Excel as an application program provides sophisticated programming language-Visual Basic for Applications (VBA) that enables users to use some or all aspects of the program to manipulate, analyse and display data. Programming turns Excel into flexible tool.

There are several important advantages to Excel users with programming, including saving time, reducing error, and integrating other programs (such as the other Microsoft Office applications).

In particular, this program is based on Excel 2007 and Excel 2010, as most of users use these versions now. As far as the author is concerned, these two versions could accommodate more rows and columns than the previous ones, and are capable to handle huge amounts of data. Solver function in Excel needs be activated, and referenced in VBA afterwards before running the program.

The theories adopted and data required for the program developed for free-flowing test with constant head have been discussed in Chapter 2. The program developed includes three components, which consist of the interfaces for analysing free-flowing test data, recovery test data, skin factor and effective radius.

5.3.1 Interface for free-flowing test data analysis

Overflow or free-flowing test for artesian aquifers is a convenient method of estimating aquifer parameters. All that is necessary is that the borehole is allowed to flow freely and measurements are made. A program is developed to analyse the test data. The main interface of the program is shown in Fig. 5.2.

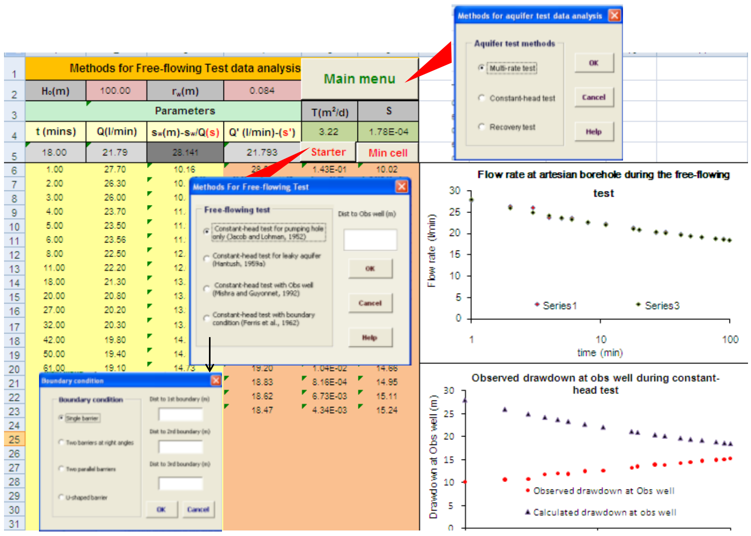


Fig. 5.2: The interface of program for hydraulic parameters estimation of artesian aquifers with free-flowing test data

- **Terms and notations area**:

The terms and notations in the program are delineated as follows:

H_0 – thickness of the aquifer in m

t_i – time since the beginning of free-flowing test in minute

r_{ew} – effective radius of artesian borehole (single-borehole pumping test) in m

r – distance from observation borehole to flowing artesian hole in m

r_i – distance between test borehole and a barrier boundary in m (under boundary condition)

T – transmissivity in m^2/d

S – storativity (dimensionless)

Q_i – observed flow rate of borehole at t_i in l/min (i >0)

Q'_i – calculated flow rate of borehole at t_i in l/min

s_w – constant drawdown in m

D'/K' – hydraulic resistance of the aquitard in d. The parameter is used for leaky confined aquifer only

- **Data entry**:

Yellow area contains the fields and grids for data entry (Fig. 5.2). Data that need to be entered in the program include t_i, H_0, r_w, s_w and Q_i.

- **Calculation area**:

The orange zone is calculation area; column 4 shown in Fig.5.2 represents the simulated flow rate.

- Starter **Starter** button opens a window from which relevant method could be selected according to the type of data. The program includes two components for analysing two different types of data from artesian borehole test, namely:
    - Free-flowing test; and
    - Recovery test
- Methods **Methods** button links to a window from which relevant method for analysing free-flowing test data can be chosen. The value of r_i needs to be input into cell if the test is carried out under boundary conditions in the study area.
- Min Cell **Min Cell** button is used to minimize the differences between the observed flow rates and simulated values by changing transmissivity and storativity values with Solver function in Excel.
- **Chart area**

Two charts shown in Fig. 5.2 are generated in the program. One chart is for single borehole aquifer test, while the other one is for aquifer test with observation borehole. The reason is that drawdown in observation borehole will be required for the latter situation.

Procedures

1. Download data from test device. Data including time, pressure, flow rate, *pH* and *EC* can be saved as .xls profile. The pressure value needs to be converted to pressure head in m later on.
2. Click Starter button to select "free-flowing test", and press enter to confirm. Data, including the effective radius of artesian borehole or the distance between artesian borehole and piezometer, time, constant-drawdown and flow rates of borehole, need to be entered the program. Initial transmissivity and storativity values need to be given arbitrarily into blank cells, for instance, 50 and 0.005 respectively.
3. Method selection. Choose appropriate method under a list of methods and click Enter to confirm. It may take a certain time to do the calculation. Four scenarios for free-flowing test are defined in the program, namely single borehole constant-drawdown test for confined aquifer, artesian borehole with observation borehole, single borehole constant-drawdown test for semi-confined (leaky) aquifer and single borehole test under different boundary conditions (a single barrier boundary, two barriers at right angles to each other, two parallel barriers and U-shaped barrier).
4. Simulation results. The charts will be generated automatically after simulation. "Min cell" button needs to be activated to adjust the transmissivity and storativity. The estimated T and S values will be estimated by minimizing the difference between observed values and calculated ones.

5.3.2 Interface for recovery test data analysis

It is always good practice to measure residual drawdowns during the recovery period. Recovery-test measurements allow the transmissivity of the aquifer to be calculated, thereby providing an independent check on the results of the free-flowing test. A program is developed to interpret residual drawdown data from recovery test. The interface of the program is shown in Fig. 5.3.

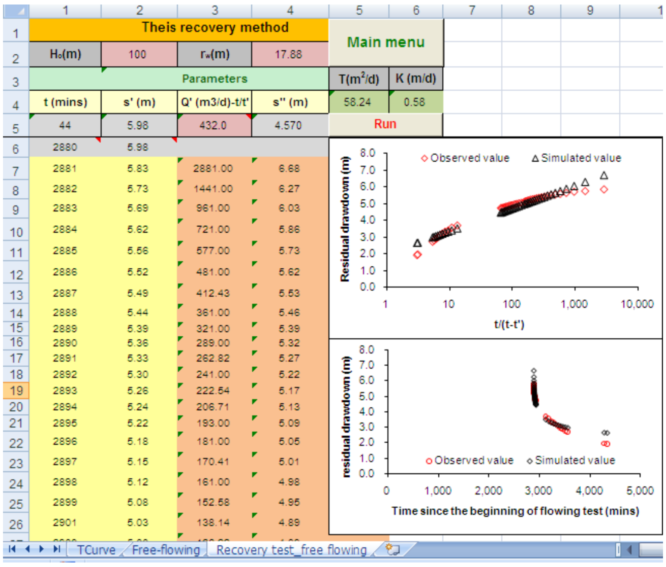


Fig. 5.3: The interface of program for hydraulic parameters estimation of artesian aquifers with recovery test data

- **Terms and notations area**:

Terms and notations adopted in the program are listed as follows:

r_w – effective radius of artesian borehole in m

t_i – time since the cessation of free-flowing test in minutes

Q'_i – flow rate of borehole at the end of free-flowing test in l/min

s'– observed residual drawdown measured in artesian borehole or piezometer at a distance r from the artesian borehole in m

s'' – calculated residual drawdown in m

- **Data entry**:

Yellow area contains the fields and grids for data entry (Fig. 5.3), which includes t_i, H_0, r_w, s'_w and Q'_i.

- **Calculation area**:

The orange zone is calculation area; column 4 stands for the simulated residual drawdown at artesian borehole or piezometer in m.

- **Chart area**
  - Observed residual drawdown and simulated values at semi-log scale; and
  - Observed residual drawdown and simulated values against time since the beginning of the test

- **Run** button links to apply Theis's recovery method using residual drawdown data from:

- Artesian borehole; or
- Observation borehole.

Procedures

1. Download data from test device. Data including time since the free-flowing test ceased, and hydraulic head in Pascal which needs to be converted to meter by dividing the value by 9.8, can be saved as xls profile.
2. Data input. Data includes effective radius of artesian borehole, time, flow rate at the end of free-flowing test and residual drawdown in artesian borehole or piezometer.
3. Simulation results. The chart will be generated automatically after the simulation is done. It is known that only *T* value can be determined from recovery test.

5.3.3 Interface for skin factor and effective radius

As discussed in Chapter 2, skin factor and effective radius have to be considered for single borehole aquifer test. A program is developed to address this issue based on the theory developed by Matthews and Russell (1967). The interface is displayed in Fig. 5.4.

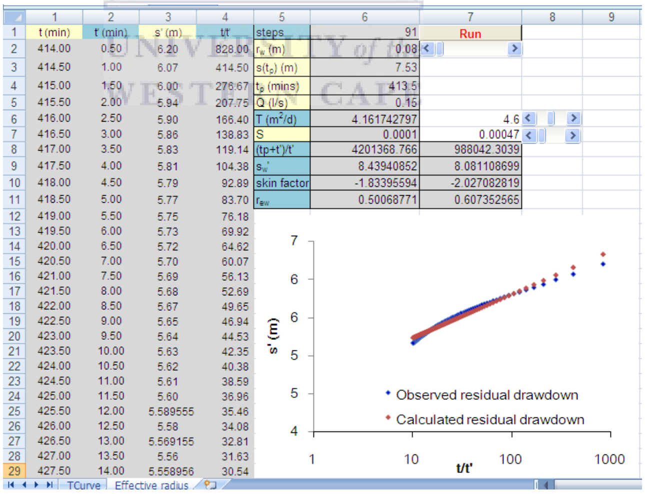


Fig. 5.4: The interface of program for evaluation of skin factor and effective radius of artesian borehole using recovery test data

- **Terms and notations area**:

r_w – radius of borehole screen in m

r_{ew} – effective radius of artesian borehole in m

T – transmissivity in m^2/d

S – initial storativity that needs to be input into the program (dimensionless)

Q – flow rate of test borehole at the end of free-flowing test in l/s

$s(t_p)$ – constant-drawdown in m

t – time since the beginning of free-flowing test in minutes

t_p – time of the cessation of free-flowing test in minutes

t' – time since the cessation of free-flowing test in minutes

- **Data entry**:

  Yellow area contains the fields and grids for data entry (see Fig. 5.4).

- **Calculation area**:

  The light blue zone is calculation area.

- **Chart area**

  The observed residual drawdowns of test borehole and calculated values will be displayed in the chart.

Procedures

1. Data input. Residual drawdown, radius of borehole screen, constant-drawdown and initial *S* values need to be imported into the program.
2. The chart will be generated automatically, with observed and calculated residual drawdowns displayed in Fig. 5.4. Skin factor and effective radius will be determined with *T* value of skin.

5.3.4 Discussion

Fully or partially-penetrating borehole

The program developed is targeted for aquifer test in fully penetrating borehole. The theories were discussed in Chapter 2. In reality, some aquifers are so thick that it may not be justified to install a fully penetrating borehole. Instead, the groundwater has to be pumped by partially-penetrating borehole. As the partial penetrating could induce vertical flow components in the vicinity of the borehole, the general assumption of borehole receiving water from horizontal flow may not be valid, and it leads to higher flow velocity in the immediate vicinity of the borehole than it would be otherwise, causing an extra head loss. The effects decrease with the distance away from the pumping borehole; it is negligible if measured at a distance that is 1.5 to 2 times greater than saturated thickness of aquifer, depending on the amount of penetration.

The methods applied for partially penetrating effects are listed in Table 5.1. For confined and leaky aquifers under steady-state conditions, Huisaman developed methods with which the observed drawdown could be corrected for partial penetration. For confined aquifer under unsteady-state conditions, the Hantush modification of the Theis method or of Jacob method can be utilized. For leaky confined aquifers under unsteady-state conditions, drawdown can be corrected with the Weeks method, which is based on Walton (1962) and Hantush curve-fitting methods for horizontal flow.

In practise, many uncertain parameters involved for application of methods for aquifer test data analysis in partially-penetrating borehole are very difficult to be determined; thereof these methods are not integrated in the program for now. However, it can be done in near future.

Table 5.1: Classification of methods applied for partially penetrating borehole in artesian aquifer

Method	Application	Original source
Huisman method	• Steady state	Anonymous, 1964
Huisman method	• Steady state • Time of pumping relatively short	Hantush (1961a, 1961b)
Hantush modification of Theis method	• Unsteady state • Time of pumping relatively short	Hantush (1961a, 1961b)
Hantush modification of Jacob method	• Unsteady state • Time of pumping relatively long	Hantush (1961b)
Weeks', modification of Walton and Hantush curve fitting method	• Leaky • Steady state flow	Weeks (1969)

5.4 Diagnostic plot analysis

5.4.1 Diagnostic method

Since the idea of using the logarithmic derivative of drawdown in the interpretation of constant-rate tests was developed early on in the history of hydrogeology (Chow, 1952), the technique has become a standard in petroleum engineering, especially over the last 20 years (Bourdet et al., 1989; Ehligh-Economides et al., 1994b); it is used routinely only in some specific or highly technical projects in hydrogeology. For instance, drawdown derivative analysis (ds/d(lnt)) may help improve understanding of aquifer tests and provide a description of different hydrogeological formations during constant-rate and its following recovery tests (Djebbar and Kumar, 1980; Horne, 1995; Samani et al., 2006). The concept and its application have been well elaborated in numerous related articles (Gringarten et al., 1974; Spane and Wurstner, 1993; Renard, 2005; Renard et al., 2009; Xiao and Xu, 2014).

Besides the application of the drawdown derivative from a constant-rate test, a method using reciprocal flow rate and its derivative from a constant bottom-hole pressure test is often adopted for reservoir (analogous to aquifer in hydrogeology) characterization purposes in the petroleum industry. The formation adjacent to a production well is usually hydraulically fractured to enhance its yield. Pressure at the production well is maintained as constant during the test, while flow data are captured for interpretation. Linear, bilinear, pseudo-radial, and pseudo-steady state flow regimes can be identified using semi-log or log-log plots of the reciprocal rate and reciprocal rate derivative (Nashawi and Malallah, 2006; Escobar et al., 2012; Nobakht and Clarkson, 2012). Parameters, such as fracture conductivity, reservoir permeability, drainage area (analogous to area of influence in hydrogeology), skin factor and reservoir shape factor, may be determined according to the flow regime. For instance, when the effect of the production well reaches the outer boundary of the reservoir, the reciprocal rate changes exponentially with time, and the reciprocal rate derivative starts to deviate from the pseudo-radial horizontal line. The drainage area and shape factor can be calculated (Nashawi and Malallah, 2006).

As many theories developed in petroleum engineering are compatible with theories of hydrogeology in well hydraulics (Renard, 2005), and a free-flowing test at a flowing artesian borehole in hydrogeology is analogous to the constant bottom-hole pressure test at a production well in the petroleum industry, the theory of reciprocal rate and the reciprocal rate derivative in the latter field can be adapted for aquifer characterization in hydrogeology field. However, a significant difference is that the free-flowing test is under artesian conditions. When an artesian borehole is flowing from an effectively infinite and isotropic aquifer, the flow toward the borehole is essentially purely radial, no borehole storage needs to be considered, which differs from the flow under the non-artesian situation at the early time (Chow, 1964), of which process is defined as purging.

In this section, the diagnostic plot analysis is reviewed and utilised to evaluate the artesian aquifer properties with reciprocal rate and reciprocal rate derivative data. The method can be used to help identify the flow regimes and discern the boundary conditions, which provide useful information to conceptualize the aquifer and facilitate an appropriate analytical method to evaluate the aquifer properties using reciprocal rate and the reciprocal rate derivative. Methods of noise elimination to smooth the raw rate and reciprocal rate derivative are discussed. Based on the results of reciprocal rate derivatives, conceptual models can be developed, and appropriate analytical method will be advised and adopted to evaluate the transmissivity (T) and storativity (S). The advantages and limitations of using the diagnostic plot method are discussed at the end of the section.

5.4.1.1 Basic equations

Diagnostic plot as an additional tool can be utilized to identify the groundwater flow regime (Renard and Mejias, 2009), which can verify the results derived from the methods above. The idea of using the logarithmic derivative in borehole-test interpretation is attributed to Chow (1952). He demonstrated that the transmissivity of an ideal confined aquifer is proportional to the ratio of the pumping rate by the logarithmic derivative of the drawdown at late time (after purging for non-artesian aquifer condition). The idea of using the log-derivative drawdown data within a unique plot had many advantages:

- The logarithmic derivative is highly sensitive to subtle variations in the shape of the drawdown curve. It allows detecting behaviours that are difficult to observe on the drawdown curve alone.
- The analysis of the diagnostic plot of a data set facilitates the selection of a conceptual model.
- For certain models, the values of the derivative can directly be used to estimate rapidly the parameters of the model.

The idea applying diagnostic plots on constant-rate pumping test can be adapted to the constant-head test. Recall the theory of constant head discussed in Chapter 2. The unsteady discharge of a free-flowing borehole under constant head test is expressed as (Jacob and Lohman, 1952):

$$Q = 2\pi T s_w G(\alpha) \tag{5-1}$$

$$\alpha = \frac{Tt}{r_{ew}^2 S}$$

Where s_w represents constant drawdown in the test borehole (difference between static head measured during shut-in of the borehole and the outflow opening of the borehole), Q is unsteady discharge from artesian borehole, T the transmissivity, r_{ew} effective radius of the artesian borehole, S the storativity, and $G(\alpha)$ Jacob-Lohman's free-flowing borehole discharge function for confined aquifer.

According to Jacob and Lohman (1952), the function $G(\alpha)$ can be approximated by $2/W(u_w)$ for all but extremely small values of t ($W(u_w)$ is named the Theis well function). If, in addition, $u_w < 0.01$, Equation 5-1 can be expressed as:

$$Q = \frac{4\pi T s_w}{\ln(2.25Tt / r_{ew}^2)} \text{ or } \frac{1}{Q} = \frac{1}{4\pi T s_w}\ln\left(\frac{2.25Tt}{r_{ew}^2}\right) \tag{5-2}$$

As discussed in Chapter 4, the whole flowing test process can be divided into two phases. Namely, the adjusting period and free-flowing test period. The reciprocal rate derivative for each period can be calculated as follows:

$$\frac{\partial(1/Q)}{\partial(\ln t)} = t\frac{\partial(1/Q)}{\partial(t)} = \frac{1}{4\pi T s_w} = m \tag{5-3}$$

If the asymptote of reciprocal rate derivative shows that it is a constant value (for instance, constant value *m*), the assumptions underlying the Jacob-Lohman method, i.e. a two-dimensional infinite-acting radial flow (IARF), are most probably valid. The straight-line method proposed by Jacob-Lohman can be utilized in this circumstance. It is highlighted that the constant derivative should be at least 1-1.5 log-cycles.

5.4.1.2 Reciprocal rate derivative with boundary conditions

Under different no-flow boundary conditions discussed above, reciprocal rate and reciprocal rate derivative can be calculated based on Equation 2-17 discussed in Chapter 2. The results are displayed in Table 5.2.

Table 5.2: Reciprocal rate and reciprocal rate derivative under different barrier boundary conditions

Boundary condition	Reciprocal rate (1/*Q*)	Reciprocal rate derivative (d(1/*Q*)/d(ln*t*))
One barrier boundary	$\dfrac{2\ln(\frac{2.25Tt}{r_w{}^2S}) - 2\ln(r_{r1})}{4\pi T s_w}$	2*m**
Two barrier boundaries at right angle	$\dfrac{4\ln(\frac{2.25Tt}{r_w{}^2S}) - -2\sum_{i=1}^{3}\ln(r_{ri})}{4\pi T s_w}$	4*m*
Two parallel barrier boundaries	$\dfrac{8\ln(\frac{2.25Tt}{r_w{}^2S}) - 2\sum_{i=1}^{7}\ln(r_{ri})}{4\pi T s_w}$	8*m*
U-shaped barrier boundary	$\dfrac{16\ln(\frac{2.25Tt}{r_w{}^2S}) - 2\sum_{i=1}^{15}\ln(r_{ri})}{4\pi T s_w}$	16*m*

* *m* is the reciprocal rate derivative during IARF

A significant increase of reciprocal rate derivative indicates the possibility of no-flow boundary and its effect on the flow rate. The assumption of IARF is not valid. Method of simplification applying the Jacob-Lohman method without considering boundary condition can be problematic in such case.

According to the results of reciprocal rate derivatives, theoretically the flowing test process can be divided into the following phases (Fig. 5.5).

- Adjusting period. Reciprocal rate derivative is negative.
- Infinite-acting radial flow. Reciprocal rate derivative becomes positive after the adjusting period, and stabilizes at a constant value. Groundwater flow towards the artesian borehole is radial flow.
- Transition. Flow at the artesian borehole will decrease significantly where there is a no-flow boundary. Alternatively, it may decrease slowly due to the leakage from the aquitard upwards. The reciprocal rate derivative deviates during the transition, and time of deviation depends on the distance from the test borehole to the boundary.
- Boundary-dominated flow. The reciprocal rate derivative becomes constant after transition under no-flow boundary as well as in leaky aquifer conditions. If the test is long enough, the flow regime would become pseudo-steady state flow, which is also called equilibrium in some papers in the literature (Logan, 1964; Misstear, 2001). Flow rate is constant under this condition. The Thiem equilibrium equation (Thiem, 1906) is applicable to estimate transmissivity with water level data at the observation borehole (Kruseman and De Ridder, 1991; Logan, 1964; Misstear, 2001).

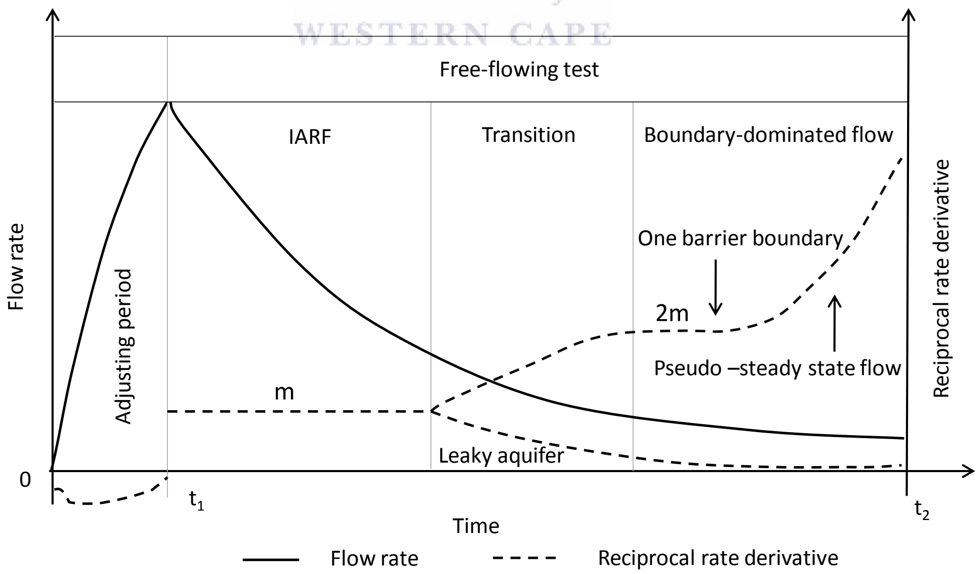


Fig. 5.5: Schematic result of the diagnostic plot analysis during free-flowing test

It is noted that it is difficult to identify flow regimes and boundary conditions with graph of flow rate itself. However, the reciprocal rate derivative would make it possible. For instance, under the no-flow boundary condition, the reciprocal rate derivative is constant during IARF, and it starts to deviate from the IARF line as soon as the effect of the test borehole reaches the no-flow boundary (Fig. 5.5).

5.4.2 Noise elimination

5.4.2.1 Noise elimination of raw rate data

Theoretically flow at test borehole should be decreasing during the test. However, in reality, it is often found that flow measurements tend to decrease with certain fluctuations. What's worse, in the situation where the number of data points is rather limited or the measurements are affected by measurement uncertainties, the calculated derivative can be extremely noisy, which may lead to the wrong interpretation. In order to minimize these artefacts, numerous techniques can be adapted to smooth the raw data prior to the computation of the derivative, or smooth the derivative (Bourdet et al., 1989; Spane and Wurstner, 1992; Horne, 1995; Veneruso and Spath, 2006). Based on the fact that the reciprocal rate derivative is very sensitive to subtle changes of flow, it is recommended that raw flow data be smoothed prior to calculating reciprocal rate derivative. The polynomial regression approach using the method of least squares is adopted to eliminate the noise data. For a given data set of reciprocal rate ($1/Q$) and time as natural logarithmic scale ($\ln(t)$), a polynomial regression of this kind and residual R can be expressed as:

$$y = a_0 + a_1 \ln t + a_2 (\ln t)^2 + a_3 (\ln t)^3 + \ldots + a_p (\ln t)^p \tag{5-4}$$

$$R_i = y_i - (a_0 + a_1 \ln t_i + a_2 (\ln t_i)^2 + a_3 (\ln t_i)^3 + \ldots + a_p (\ln t_i)^p) \tag{5-5}$$

Where y and y_i are reciprocal rate ($1/Q$), t and t_i the time, p the degree, R_i the residual, and a_i the coefficients, which can be determined during the calculation. In this regression method, the choice of degree and the evaluation of the fit's quality depend on judgements that are left up to the user. It is known about this method that an effort to squeeze more correlation out of the algorithm than the data can support will sometimes produce a function that, although it matches the data points, wanders wherever it pleases between those points. Therefore, a "good" (approaching 1.0) correlation coefficient is not enough to assure a well-behaved or meaningful function. Decision about a result's appropriateness is more a matter of judgment than mathematics. Caution should be exercised when one sets the degree of the regression. The smoothing should start from IARF period to avoid the noise at the beginning of the test. In addition, end effects take place when computing derivatives near the beginning or end of a set of flow data. One often finds in practice that derivatives calculated near the end of a data set are less reliable (Horne, 1995).

5.4.2.2 Noise elimination of reciprocal rate derivative data

Another method for eliminating noise can be done by smoothing the reciprocal rate derivative. When the measurements are frequent and accurate, the results by Equation 5-3 can provide good estimation of the log derivative values. The reciprocal rate derivative is calculated numerically from a discrete series of n $1/Q_i$ and time t_i values. There are several ways to compute the log derivative. The simplest way is the following:

$$\frac{\partial(1/Q)}{\partial(\ln t)} = \frac{{}^1\!/_{Q_i} - {}^1\!/_{Q_{i-1}}}{\ln(t_i) - \ln(t_{i-1})} \tag{5-6}$$

Alternatively, the slope can be calculated with the so-called Bourdet derivative method using the following simple three-point formula to compute $1/Q$ derivative:

$$\left(\frac{\partial(1/Q)}{\partial(\ln t)}\right)_i = \frac{(\Delta(1/Q_{i-1})/\Delta\ln(t_{i-1}))\Delta\ln(t_{i+1}) + (\Delta(1/Q_{i+1})/\Delta\ln(t_{i+1}))\Delta\ln(t_{i-1})}{\ln(t_{i+1}) - \ln(t_{i-1})} \tag{5-7}$$

In hydrogeology, robust and simple solutions involving resampling (Lagrange interpolation or Spline interpolation) the signal at a fixed number of time intervals regularly spaced in a logarithmic scale are usually done when the data are irregularly spaced in time. The derivative is then computed with Equation 5-6 on the resampled signal. 20-30 points are usually enough to get a general shape of the logarithmic derivative. Lagrange interpolation is adopted to get good estimation of general shape of the derivative. The flow rate of a point of interest is calculated with adjacent three points. The interpolation function is expressed as follows:

$$f(t_i) = f(t_1)\frac{(t_i - t_2)(t_i - t_3)}{(t_1 - t_2)(t_1 - t_3)} + f(t_2)\frac{(t_i - t_1)(t_i - t_3)}{(t_2 - t_1)(t_2 - t_3)} + f(t_3)\frac{(t_i - t_1)(t_i - t_2)}{(t_3 - t_1)(t_3 - t_2)} \tag{5-8}$$

Where i is the point of interest, t_1, t_2 and t_3 are the adjacent points before or after i point. $f(t_i)$ is flow rate at the point of interest.

5.4.3 Discussion

It is noted that there are some limitations when the diagnostic plot method using reciprocal rate derivative is applied with free-flowing test data.

- Variation of flow during the test could lead to artefacts in the shape of reciprocal rate derivative, especially when flow is changing rapidly at the beginning and end of the test; and
- The method is complicated and time-consuming to some extent.

The first problem can be solved by smoothing raw rate data prior to calculating the derivative. It is known that drawdown will increase during the constant-rate pumping test.

However, similar phenomena may not apply to a free-flowing test for an artesian borehole. It is observed that flow rate tends to decrease over the free-flowing test yet with fluctuations. Given the fact that the reciprocal rate derivative is very sensitive to rate variations, the reciprocal rate derivative with flow measurements can be extremely noisy, especially under the condition that the measurements are taken manually with short intervals. Accuracy of the measurements should be as high as possible. Smoothing raw rate before calculating the derivative can help avoid the noise problem. Care should be exercised to avoid overly smoothing the data. The diagnostic method requires a large number of calculations, which can be best handled by computer generated algorithms.

It is important to acknowledge that the difficulties and limitations are real. Due to the high sensitivity of flow rate and time values, the accuracy of the measurements should be as high as possible, thereof a proper test device for data capturing, for instance, the device discussed in Chapter 4, is recommended.

5.5 Data requirements

To enhance the *T* and *S* estimates of artesian aquifer in TMG both on a large scale and relatively small scale, besides knowledge of the hydrogeological information, monthly rainfall, natural pressure head in the study area should be monitored.

In case of the connection among an artesian borehole with some other boreholes, the water level at other boreholes should be tested occasionally as well to confirm no leakage among the aquifers. The following measurements need to be taken during the test:

- Radius of screen (to calculate the effective radius of borehole later on)
- Pressure head at flowing artesian borehole and observation hole (before, during and after the test)
- Flow rate at test borehole
- Water-level in other boreholes in the study area

The correlation between the rainfall throughout the year and water level fluctuations in flowing artesian borehole as well as other boreholes needs to be confirmed. It is recommended that the automatic pressure data logger set be put into test borehole to record pressure with certain interval. If the borehole location is close to coast, hydraulic pressure needs to be measured prior to test. Rainfall events need to be avoided prior to the test.

5.6 Summary

It is often possible to evaluate the aquifer properties with analytical methods by devising approximate methods of analysis based on idealized models of aquifer situations. Classic method developed for artesian aquifer by Jacob and Lohman (1952) and its variations were discussed. Due to the fact that the fractured rock aquifer in TMG is often delimited by one or more barrier boundaries, time-drawdown or time-flow data deviates more than once under influence of two or more image wells. Based on those analytical solutions, a program to analyse free-flowing test and recovery test data under different boundaries was developed. The terminologies and procedures to use the program were outlined.

The diagnostic plot method adopted to interpret flow data from free-flowing test at a flowing artesian borehole is developed. The approach could help identify the flow regimes and discern the boundary conditions, of which results further provide useful information to conceptualize the aquifer and facilitate an appropriate analytical method to evaluate the aquifer properties using reciprocal rate and reciprocal rate derivative.

Limitations of the diagnostic plot method using reciprocal rate derivative are discussed. It is acknowledged that the reciprocal rate derivative is more sensitive to rate variations than the reciprocal rate. Accuracy of the measurements should be as high as possible. In addition, methods to eliminate noise (method to eliminate rate noise and method to eliminate reciprocal rate derivative noise) were discussed. It is recommended that raw flow data be smoothed prior to calculating reciprocal rate derivative.

Chapter 6
Evaluation of artesian aquifer properties with case studies

6.1 Introduction

In this chapter, two case studies in TMG area, with locations shown in Fig. 6.1, were selected and documented to evaluate the artesian aquifer properties. Free-flowing test and recovery test were conducted at the first case study of Rawsonville, with data captured by the test device. A shut-in artesian borehole with observation hole in Oudtshoorn was chosen as second case study. A two-month free-flowing test and six-month recovery test was carried out during the dry season in 2009. Flow rate was measured manually during the flowing period; while the pressure head of two boreholes were captured with data logger.

All the measured data from both case studies were firstly interpreted with the conventional method. Diagnostic plot method as an additional tool was adopted to interpret the flow data from free-flowing test. Based on the results, conceptual models at local or intermediate scale were developed, and appropriate approaches were advised and adopted to evaluate the aquifer properties. The results were compared with those derived with conventional straight-line method.

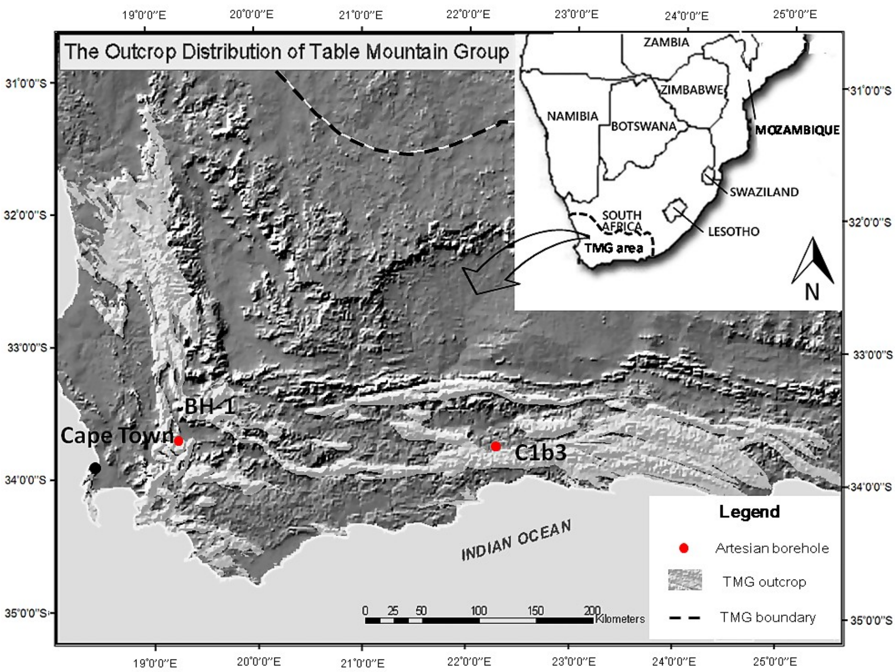


Fig. 6.1: The outcrop distribution of Table Mountain Group (TMG) and test artesian boreholes in TMG

6.2 Case study – Rawsonville

6.2.1 Site description

There are 5 boreholes that form a well network located in the main study area - Gevonden farm, 6 km west of Rawsonville, Western Cape. A perennial stream runs northwards with the water sourced from a catchment of about 80 km^2 in which the mountain height mostly reaches 2000 m but the elevation of the site is about 290 m. In the area, the majority of the TMG outcrop consists of Peninsula Formation. The bottom of Nardouw Formation and the Cedarberg Formation occur in the very north of the study area which is bounded by basement rocks in the west and southwest and faults (Brandvlei-Elkenhofdam megafault and Smiths Kraal fault) in the east and southeast (Fig. 6.2). The Waterkloof fault towards the northeast extends some 15 km cutting through the borehole site. Controlled by both this fault structure and the NE-trending TMG terranes, geomorphologic features of the area are mainly characterized by the steep bared rock slopes on the Peninsula outcrop, stepwise stream course on which there are three waterfalls with the altitudinal drops of 14 to 40 m, and a 6 m thick pluvial boulder soil covers the site area. Several springs on the stream are identified, but are not linked to one another in a regional flow system because the water head gradient may reach more than 1/20 just by rough estimation on the 1/50000 topography map. The phenomenon is also familiar in the other adjacent catchments where some more field surveys were initiated to have a better view of the boundary conditions of the study area. This suggests that the observed flow systems on the surface are very local which seem to be controlled by fractured blocks. On the other hand, this phenomenon obscures a detailed survey to the regional study.

At the Gevonden site, core drillings of boreholes BH-1 and BH-2 commenced in the mid of November 2005 by the drilling team from the Department of Water Affairs (DWA) and ended in December 2005. Two percussion boreholes (BH-3 and BH-4) were drilled in September 2006 and the BH-5 is an existing borehole. The details of physical properties of boreholes and surface water are listed and shown in Table 6.1 and Fig. 6.2, respectively. Among the five boreholes only borehole BH-1 is linked to artesian aquifer, and others are linked to unconfined aquifers.

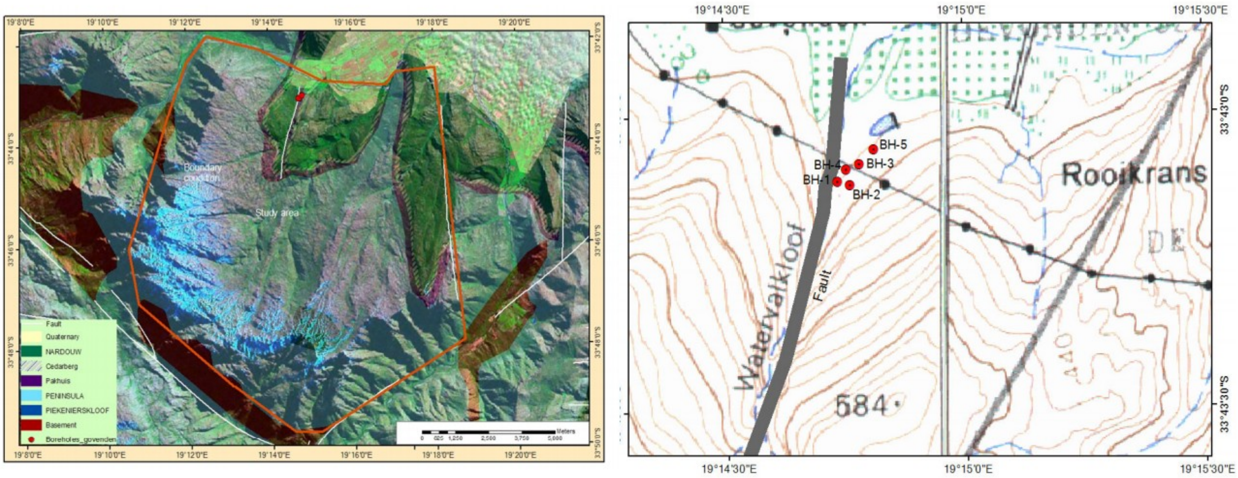


Fig. 6.2: Study area and boreholes of the Gevonden site in Rawsonville (Lin, 2007)

Table 6.1: Physical properties of borehole and surface water (Lin, 2007)

Item	BH1	BH2	BH3	BH4	BH5	Stream
Ground elevation (m)	273.6	273.06	274.1	274.5	276.9	
T (º)	20.15	19.25	18.5	18.9	20.05	14.50
Water depth (m)	0	1.8	3.05	2.59	5.57	
Water level (m)	273.6	271.26	271.05	271.91	271.33	
pH	6.8	5.5	5.8	5.6	5.2	4.41
EC (uS/m)	50-60	40-70	36-40	130-160	43-50	< 10
Formation	Nardouw	Peninsula	Peninsula	Regolith	Peninsula	Surface water

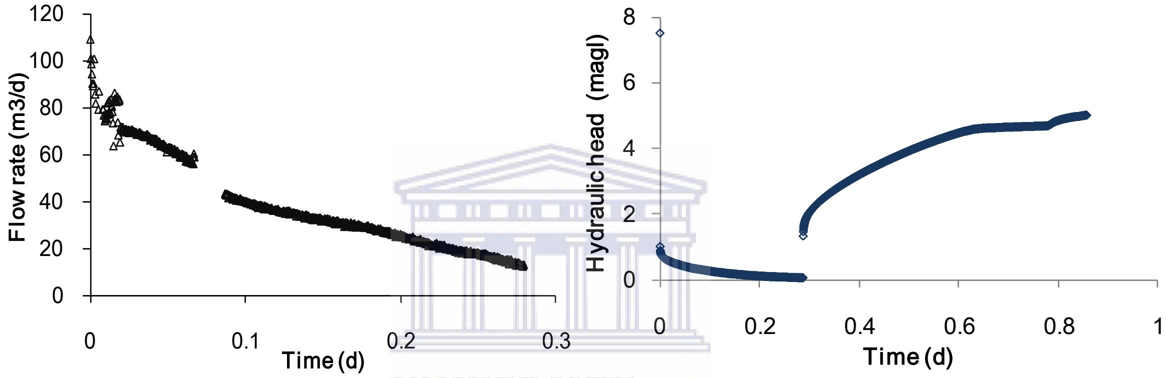
Note: the ground elevation was measured using a theodolite

Like the groundwater in other area of the TMG, groundwater observed in this site is from the fractured rocks with unknown flow path. This has been evidenced by the field observations through the identification of conductive zones during the core drilling and water level fluctuation during the percussion drilling. Moreover, field observations from the core logs and the site surveys show that the normal fault plays a key role in controlling the occurrence of groundwater. It is observed that the 80 m wide fault core, identified to be cemented cataclasites, acts as a groundwater barrier that separates the fractured rock aquifer into the eastern and western parts (Fig. 6.2). In the eastern wall (hanging wall) of the fault, groundwater only occurs with the static water level, but it appears as an artesian flow in the west one (foot wall). It is also observed that the conductive zones intercepted by the boreholes are not at the fault core but at its fracture zones of the fault.

In summary, the geology in the study area is complicated, and it must be conceptualized properly when analytical methods or numerical models are used. The connection among the aquifers and boundary conditions should be put into consideration in particular.

6.2.2 Data collection

Two hydraulic testings were successfully carried out in flowing artesian Borehole BH-1 in Rawsonville. The first test was conducted with data captured manually. The other one was carried out with data captured with the device. The details and data of the tests were discussed in sub-Chapter 4.5. Test data captured by the device is shown in Fig. 6.3, which is utilized for interpretation later on.



a) flow rate changes b) hydraulic head changes

Fig. 6.3: Free-flowing and recovery tests conducted at artesian borehole BH-1 in Rawsonville

6.2.3 Data analysis and results

6.2.3.1 Skin factor and effective radius

As it was discussed in Chapter 2, skin factor and effective radius need to be considered when dealing with single-borehole test. Unfortunately, it is very difficult to predict when the non-linear behaviour will take place, since it is determined by the areal dimension of the fracture/skin zone (Gringarten and Ramey, 1974). Theoretically the effective radius can be determined with the recovery test data, specifically with the early stage data; however, an initial storage coefficient of target aquifer needs to be given. Skin effect around artesian borehole will be taken into account in the two cases. To quantify the skin effect, it is simple to show that the additional drawdown s_d in the borehole due to a cylinder of radius r_s and having a transmissivity T_s is:

$$s_d = \frac{Q}{2\pi T}\sigma \tag{6-1}$$

With σ being the skin factor:

$$\sigma = (\frac{T - T_s}{T})\ln(\frac{r_s}{r_w}) \text{ or } \sigma = (\frac{k}{k_s} - 1)\ln(\frac{r_s}{r_w}) \quad (6\text{-}2)$$

σ is positive if the borehole is clogged ($T_s < T$ or $K_s < K$) and negative for the opposite case ($T_s > T$ or $K_s > K$). As with the Jacob-Lohman model, the late time data allows unique identification of the transmissivity of the aquifer from the slope of the straight line. In practice, the position of the line is both a function of storativity and of the skin effect. With skin factor value derived from recovery test data analysis, the effective radius of artesian borehole can be determined using the following equation (Matthews and Russell, 1967):

$$r_{ew} = r_w e^{-\sigma} \quad (6\text{-}3)$$

The previous researchers have proved that even with constant rate test on boreholes in fractured rock aquifers the non-linear behaviour will always be observed. The free-flowing test and recovery test data at a flowing artesian borehole indicate that a negative skin often occurs during the test, which implies that the permeability of skin zone adjacent to the wellbore is higher than the aquifer formation. According to the research done by Horne (Horne, 1995), the practical lower limit for negative skin factors is -5.

In a location in which the data from observation borehole are not available, the S value could still be estimated. An initial S value needs to be assumed according to the local geological formation. In the case of Rawsonville, the storativity of Peninsular Aquifer on the left side of cross-section is adopted to estimate the effective radius. A coefficient S ranging from 10^{-6} to 10^{-3} for fractured rock aquifer is recommended for TMG aquifers (Jia, 2007). For the Peninsula Aquifer in Rawsonville, according to the pumping tests done by UWC groundwater group, the S value ranging from 10^{-5} to 10^{-4}, is used to estimate the effective radius of Borehole BH-1 using the theory depicted in Chapter 2. The skin factor ranges from -2.98 to -1.83 through calculation, and the effective radius of borehole BH-1 is approximately 0.50 - 1.58 m. The simulation result of recovery test at early stage is shown in Fig. 6.4.

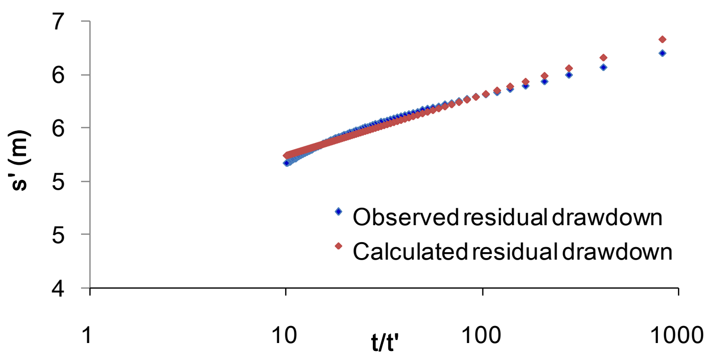
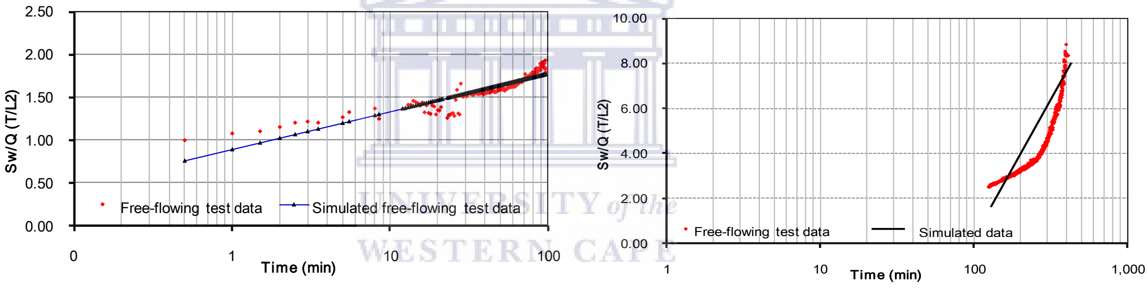


Fig. 6.4: Determination of skin factor and effective radius in Borehole BH-1 using recovery test data

6.2.3.2 Jacob-Lohman method

The aquifer test conducted at borehole BH-1 consists of about a 7 hrs free-flowing test with the constant drawdown s_w of 7.53 m. As shown in Fig. 4.16 in Sub-chapter 4.5, the semi-log s_w/Q curves of free-flowing test displays two main stages or slopes. The first stage is a slow decrease, after which it enters the second stage. During the later stage, the s_w/Q shows a rapid decrease where the slope steepens. Jacob-Lohman straight-line method is used to interpret the flow data. To clarify the impact of skin effect on flow, borehole radius of 0.07 m was used to evaluate aquifer properties. The simulation results are shown in Fig. 6.5 and Table 6.2. The estimated T and S values with early free-flowing test data is 15.43 m^2/d and 4.48×10^{-3}, respectively; while the T value is 2.95 m^2/d with erroneous S value derived with the free-flowing test data at later stage (>1). The T value ranging from 10 to 20 m^2/d is reasonable compared with the value derived from the pumping test at Peninsula Aquifer at the eastern part of fault core (Table 6.3).



a) free-flowing test data in early stage b) free-flowing test data in later stage

Fig. 6.5: Simulation results of free-flowing test data analysis using straight-line method in BH-1

Table 6.2: Estimated T and S values of the artesian aquifer in Rawsonville without considering skin effect

Method	Early stage		Late stage	
	T (m^2/d)	**S**	**T (m^2/d)**	**S**
Jacob-Lohman (1952,1979)	13.53	4.04×10^{-3}	2.95	9*
Swamee et al. (2000)	14.37	1.32×10^{-3}		-
Singh (2007)	18.40	8.07×10^{-3}		-
Average	15.43	4.48×10^{-3}		-

* Storativity value cannot exceed 1

Table 6.3: Hydraulic properties from pumping tests in Rawsonville (Jia, 2007)

Hydraulic properties (Peninsula)	Borehole BH-3 drawdown			Borehole BH-5 drawdown	
	Radial flow		Image borehole	Radial flow	Image borehole
	Withdraw	Recovery	Withdraw	Withdraw	Withdraw
T (m^2/d)	14.69	6.91	38.88	6.13	10.37
S^*			1×10^{-5} to 1×10^{-4}		

* Recommended storativity values for TMG confined aquifers (Jia, 2007)

The estimated S value from early free-flowing test data ranges from 1.32×10^{-3} to 8.07×10^{-3} (Table 6.2), which is bigger than storativity of Peninsula Aquifer shown in Table 6.3. With the effective radius input into the program, the transmissivity will not change, while the storativity ranges from 2.16×10^{-5} to 2.16×10^{-4} by analysing flowing test data at early stage (Table 6.4).

Table 6.4: Estimated S values of artesian aquifer in Rawsonville considering skin effect

Method	Effective radius (m)	Test data at early stage S
Jocab-Lohman (1952,1979)	0.50 - 1.58	1.03×10^{-4}-1.04×10^{-5}
Swamee et al. (2000)		3.39×10^{-4}-3.39×10^{-5}
Singh (2007)		2.07×10^{-4}-2.07×10^{-5}
Average		2.16×10^{-4}-2.16×10^{-5}

6.2.3.3 Theis's recovery method

The result of recovery test data analysis using Theis's recovery method displays the same characteristics of flow rate-time curve. On these two curves, two distinct slopes indicate the possibility of different flow regimes (Fig. 6.6). The estimated early-time T value is 4.2 m^2/d using Theis's recovery method; while the T value is 0.62 m^2/d derived with late-time data. The observed and simulated residual drawdowns in these stages are shown in Fig. 6.7. Unfortunately, the S value cannot be achieved by single borehole recovery test.

This type of behaviour is not restricted to fractured aquifer, it happened in Karoo aquifers with constant rate pumping test as well. A conclusion that all the boreholes taking place in fractured aquifers are located on large-scale fractures was drawn, such as faults or dykes (Vivier and van Tonder, 1997).

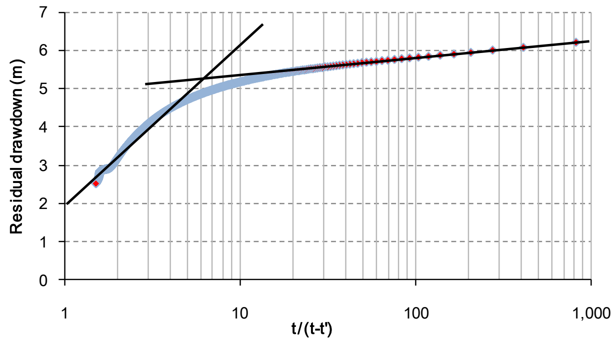
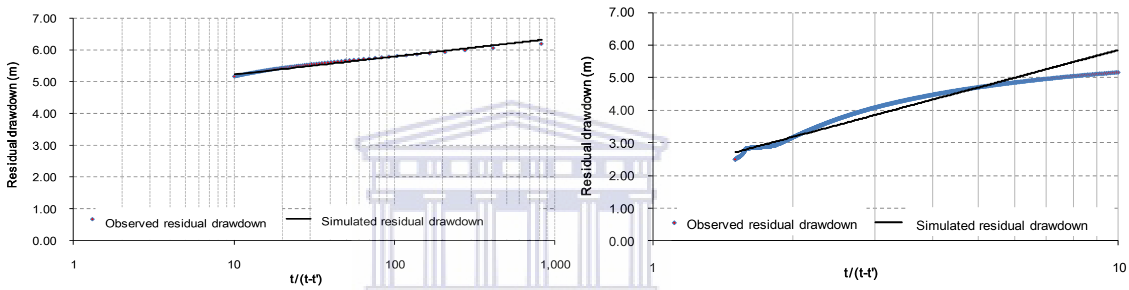


Fig. 6.6: 14-hour recovery test data after free-flowing test in borehole BH-1



a) recovery test data in early stage b) recovery test data in later stage

Fig. 6.7: Result of recovery test data analysis in borehole BH-1

Due to the complexity of fracture connectivity, probably formation losses as well as the unrealistic assumption of infinite aquifer, the conventional straight-line method failed to interpret the test data. Consequently the analysed results with late-stage data are less reliable for this case. Therefore, an additional method, for instance, the diagnostic plot analysis method can be carried out to re-evaluate the results using the straight-line method.

6.2.3.4 Derivative results

Since the reciprocal rate derivative is very sensitive to flow data, noise elimination is done with raw flow rate data. Raw rate, rate after noise elimination and reciprocal rate derivative at borehole BH-1 are shown in Fig. 6.8. The reciprocal rate derivatives with smoothing data at semi-log and log-log scales show that the IARF lasted about 0.01 d (2.4 hr), and the derivatives start to deviate after 0.01 d, which implies that assumptions of homogeneous, isotropic and/or infinite aquifer for the Jacob-Lohman method are only valid for the first stage (<0.01 d), during which the straight-line method is applicable to estimate T and S values. Boundary condition needs to be considered with later stage data (>0.01 d).

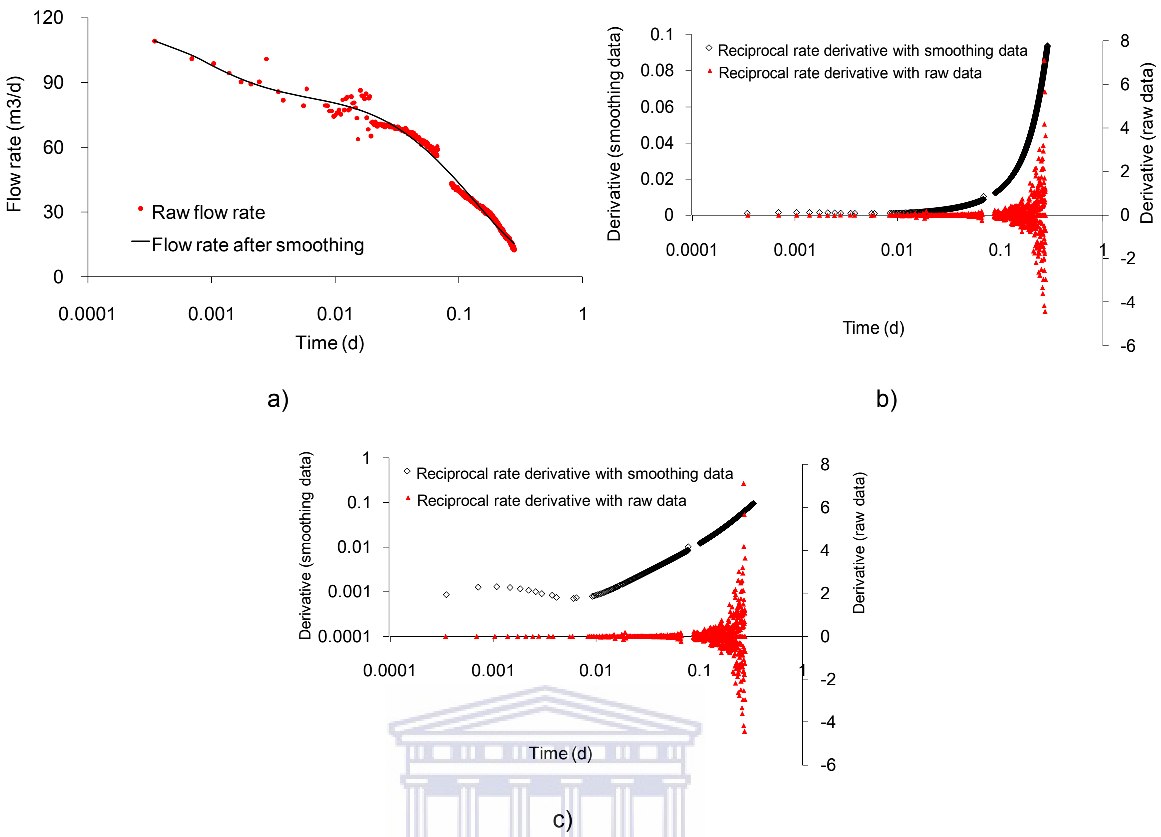


Fig. 6.8: Flow rate and reciprocal rate derivative at borehole BH 1 in Rawsonville
a) Raw rate and rate after noise elimination b) Reciprocal rate derivative at semi-log scale c) Reciprocal rate derivative at log-log scale

6.2.3.5 Conceptualization and simulation results

As it was discussed earlier, there are three independent flow systems underground in Rawsonville shown in Fig. 6.9. The Dip-slip faults divides two fractured rock aquifers on both sides of the impermeable fault, and another is the shallow unconfined aquifer flow through the boulder soil (borehole BH-4). According to the borehole logging done by Department of Water Affairs in the mid of November 2005 (boreholes BH-1 and BH-2), the aquifer flow system in the east wing is Peninsula Aquifer covered with alluvial deposition, while in the west wing of flow system, the Peninsula Aquifer is locally confined aquifer with Cedarberg aquitard lying on the top of it. The Nardouw Aquifer is situated above the impermeable layer. The recharge mainly in winter season takes place further up the mountain, which leads to the potentiometric surface of artesian aquifer rising up, while in dry season, the water head of artesian aquifer drops to ground level.

The results from both reciprocal rate derivative and previous pumping tests conducted at non-artesian boreholes prove that the 80 m wide fault core acts as a groundwater barrier, which had significant impact on the flow at artesian borehole. The sharp increase of the reciprocal rate derivative at later stage (Fig. 6.8) indicates a possibility that there are more than one no-flow boundaries in the artesian zone. Cross-section of the artesian aquifercan be developed based on the above information (Fig. 6.9).

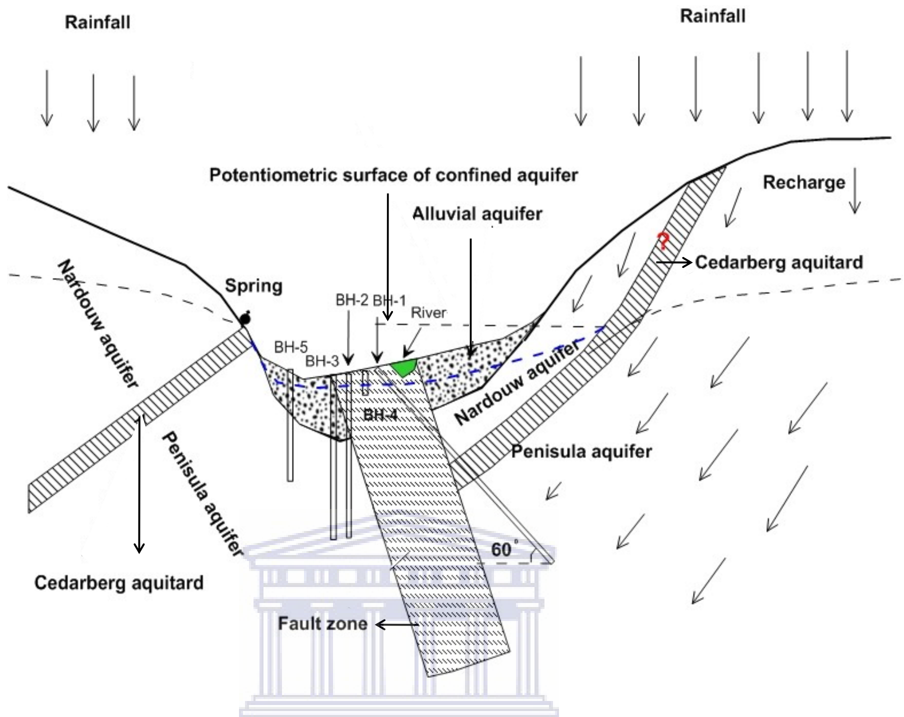


Fig. 6.9: Cross-section of the artesian basin in Rawsonville

For the no-flow boundary, two types of boundaries can be defined, namely physical no-flow boundary and non-physical no-flow boundary. Natural geologic features such as impermeable fault zones, impermeable bedrock, and significantly low-permeability deposits, are physical no-flow boundaries. A groundwater divide or an interface where two producing (or two injecting) boreholes are adjacent to one another may be also treated as a no-flow boundary, which is defined as a non-physical no-flow boundary. It is noted that the latter boundary does not physically bound the aquifer system. For the case of Rawsonville, it can be inferred that groundwater in the deep aquifer flows towards the fault zone. According to the local geomorphological condition, the groundwater divides coinciding with the western and southern TMG ridges can be considered as no-flow boundaries. Therefore, no groundwater from outside of the aquifer system came across the divides during the test. Image theories based on no-flow boundary described earlier can be adopted in the case. A simple conceptual model is developed based on the above assumptions (Fig. 6.10).

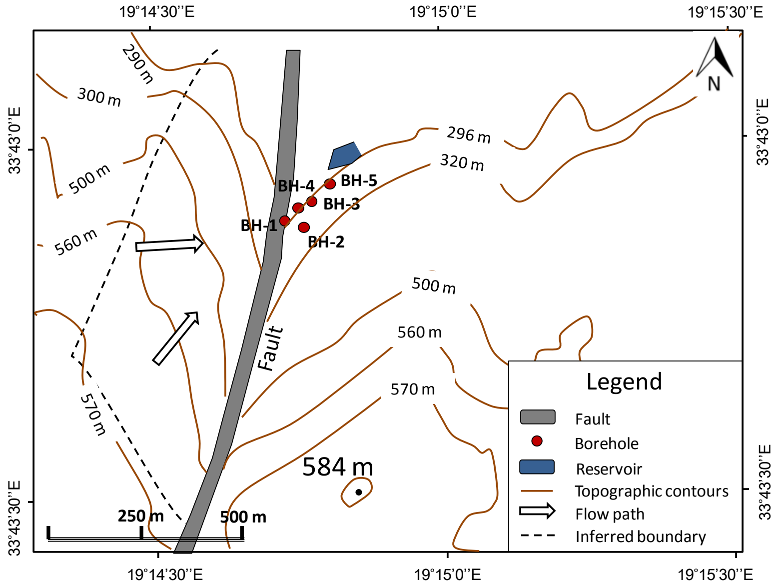


Fig. 6.10: Conceptual model of boundary conditions in Rawsonville

The curve-fitting method of discharge rate during the test can be developed under a U-shaped barrier condition (one physical no-flow boundary and two non-physical no-flow boundaries shown in Fig. 6.10). According to the study done by Stallman, under U-shaped barrier condition, the flow rate of test borehole drilled in confined aquifer at unsteady state can be expressed as:

$$Q = s_w 4\pi T / [W(u) + W(r_{r1}^2 u) + W(r_{r2}^2 u) + \ldots W(r_{r15}^2 u)] \tag{6-4}$$

With

$$u_i = \frac{r_i^2 S}{4Tt} = \frac{r_r^2 r_w S}{4Tt} = r_r^2 u$$

Where Q is the discharge rate from artesian borehole, r_w the radius of artesian borehole, r_i the distance between the test borehole and barrier, and their ratio $r_i/r_w = r_r$. The distance between the artesian borehole to fault is 21.2 m (It is noted that no fluctuation was monitored at BH 2 during the free-flowing test. Therefore, the distance between artesian borehole and fault core is assumed to be in the middle of two boreholes). The simulated results and estimated T and S values under different boundary conditions are shown and listed in Fig. 6.11 and Table 6.5, respectively.

The simulated results shown in Fig. 6.11 confirm the idea that there is probably more than one barrier boundary surrounding the artesian borehole, which caused discharge rate decreasing sharply at later stage. The simulated discharge rate under U-shaped barrier boundary condition fits better with observed values. The *T* value is calculated as 7.5-7.9 m^2/d, while the *S* value is approximately 2.0×10^{-4}-5.5×10^{-4}.

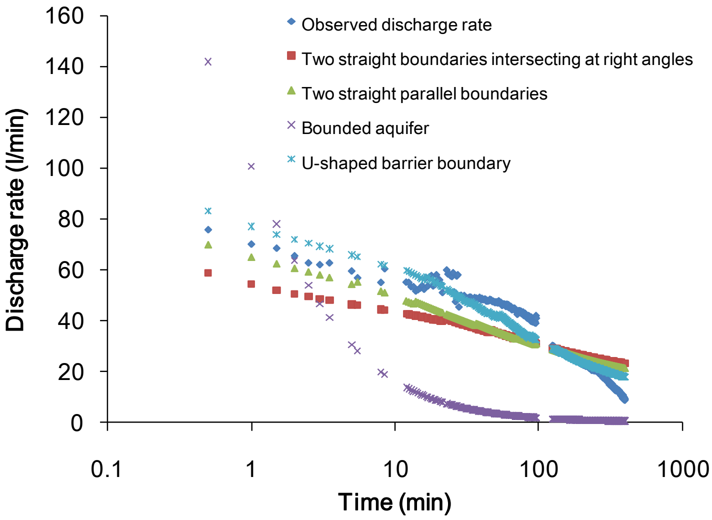


Fig. 6.11: Discharge rate simulation during free-flowing test at borehole BH-1 with scenarios of different boundary conditions

Table 6.5: Parameter estimation of the artesian aquifer in Rawsonville under different boundary conditions

Model name	Effective radius (m)	*T* (m^2/d)	*S* (-)
No barrier boundary-early stage data (Straight-line method)	0.50-1.58 m	18.2	1.9×10^{-4}-1.9×10^{-3}
No barrier boundary –later stage data (straight-line method)		1.7	>0.725
A single barrier boundary		3.5	2.0×10^{-4}-2.0×10^{-3}
Two straight boundaries intersecting at right angles		4.5-7.1	4.5×10^{-5}-1.8×10^{-4}
Two parallel boundaries		5.4-6.2	1.3×10^{-4}-6.0×10^{-4}
U-shaped boundary		7.5-7.9	2.0×10^{-4}-5.5×10^{-4}

6.3 Case study – Oudtshoorn

6.3.1 Site description

The second study site is located south of Oudtshoorn (artesian borehole C1b3 in Fig. 6.1), Western Cape Province of SA, with Peninsula Aquifer located at depths > 300 m below ground level, geopressured to -800 kilopascal (8 bar) hydraulic head. Two rain gauges (GZ33 RF and AL8 RF) were installed in the study area in early 2005. The monthly rainfall has been monitored with two rain gauges. The data were shown in Fig. 6.12 (Umvoto, 2009). It is noticed that most rainfall takes place during the rainy season from May to August. An artesian borehole C1b2 715 m-deep was drilled in 2005 as a monitoring borehole. Another artesian borehole C1b3 with depth of 608 m was drilled at 25 m distance in 2008 as a production borehole, which was piloted with a core borehole down to a low level (- 290 m) within the Goudini Aquitard, where it became marginally artesian and was then plugged and sealed. A few pumping tests proved that borehole C1b2 has connection with C1b3 (Riemann and Hartnady, 2013).

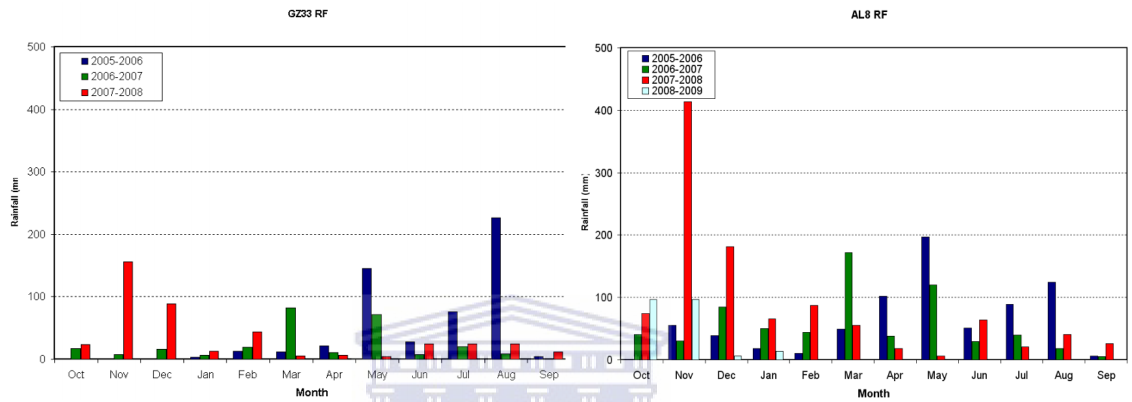


Fig. 6.12: Monthly rainfall data for GZ33RF and AL8RF over three hydrological years (2005-6, 2006-7, 2007-8. Umvoto, 2009)

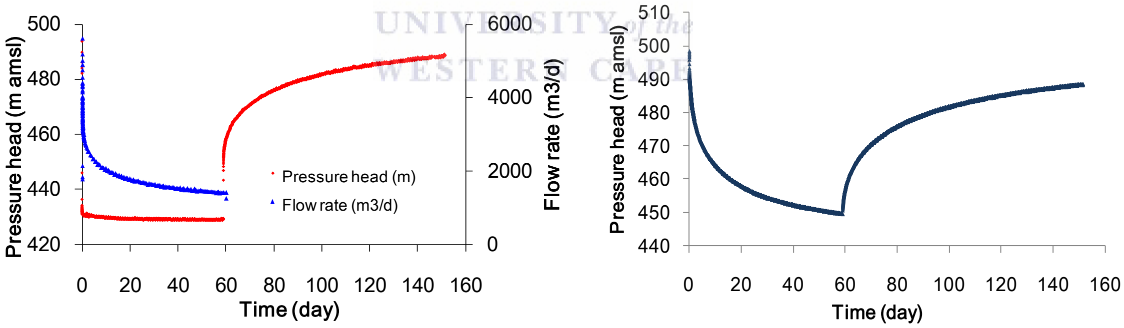
6.3.2 Data collection

A free-flowing test on borehole C1b3 in Oudtshoorn was carried out at 1 pm on 22 September, and finished at 1 pm on 21 November 2009, followed by a six-month recovery test. The construction details of artesian borehole C1b3 are listed in Table 6.6. The test involved allowing the groundwater to flow freely without pumping under the artesian conditions for 2 months, during which the tap on borehole C1b3 was fully opened, and the water was discharged into a furrow, which is 5 m above wellhead shown in Fig. 6.13. Flow rate and pressure head at C1b3 were measured, and the simultaneous hydraulic head at observation hole C1b2 drilled into the same aquifer system (25 m away from borehole C1b3) was monitored as well. Recharge zone is approximately 15 km away from the artesian site (Hartnady et al., 2013). The test data from two boreholes are presented in Fig. 6.14.

Table 6.6: Construction details of shut-in artesian borehole C1b3 in Oudtshoorn

Borehole ID	Depth (m)	Datum (mamsl)	Internal diameter (inch)	Artesian pressure (bar)	Borehole construction
C1b3	608	423.76	10	7.6	10-inch casing until 96 m 8-inch casing until 212 m 6.5-inch open hole until 608 m

Fig. 6.13: Artesian borehole C1b3 in Oudtshoorn and the free-flowing test conducted from late September till November, 2009 (Hartnady et al., 2013)



a) data from artesian borehole C1b3 b) data from observation borehole C1b2

Fig. 6.14: Flow rate and/or pressure head during the free-flowing test and recovery test

6.3.3 Data analysis and results

6.3.3.1 Skin factor and effective radius

For the Peninsula Aquifer in Oudtshoorn, the storativity value of 1.05×10^{-3} derived with the observation hole drilled in the same artesian aquifer (discussed in Section 6.3.3.6), is adopted to estimate the effective radius of borehole C1b3 using recovery test data at early stage (20 hours). The skin factor is -2.20, whilst the effective radius of borehole C1b3 is 0.74 m through calculation, which would be used to determine the *T* and *S* values with the program developed for single borehole aquifer test. The simulation result of recovery test at early stage is shown in Fig. 6.15.

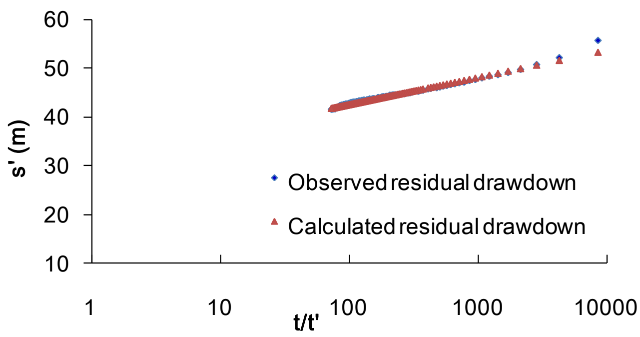


Fig. 6.15: Determination of skin factor and effective radius in borehole C1b3 using recovery test data

6.3.3.2 Jacob-Lohman method

Unsteady state

The s_w/Q-time (t) data are plotted in semi-log paper shown in Fig. 6.16. One could see that there are also two segments in the graph, which is similar with the data at the case study of Rawsonville. The higher slope at later stage implies the possibility of low transmissivity of aquifer, or reaching the no-flow boundary condition.

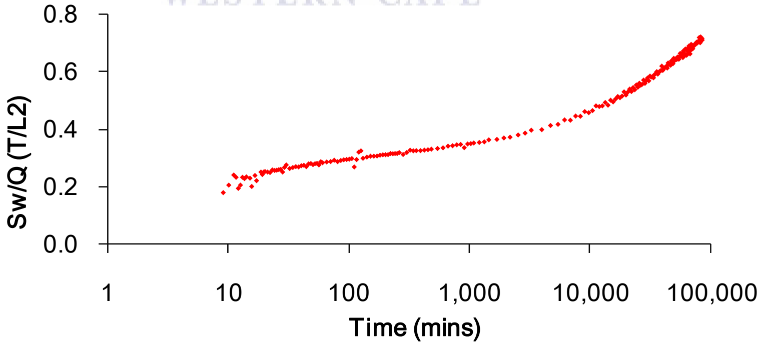
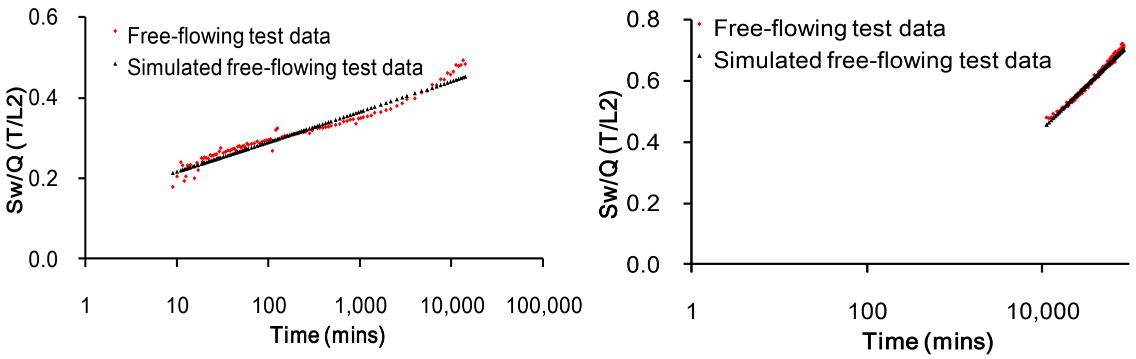


Fig. 6.16: Time-s_w/Q plot from free-flowing test at borehole C1b3

Jacob-Lohman straight-line method for single-borehole constant-head aquifer test was applied with two segments of the data. Two scenarios without considering skin effect and considering skin effect are simulated, with results shown Fig 6.17, Table 6.7 and Table 6.8. It is noticed that the S value is unrealistic when borehole radius of 0.08 m was chosen as effective radius. However, considering effective radius value of 0.74 m, one calculates rough value of transmissivity of 95 m^2/d with early stage data; while transmissivity is approximately 25 m^2/d with later stage data. The storativity is 4.71×10^{-3}.



a) simulation result with early stage data b) simulation result with later stage data

Fig. 6.17: Simulation results of free-flowing test data analysis using straight-line method in Oudtshoorn

Table 6.7: Estimated *T* and *S* values of the artesian aquifer in Oudtshoorn without considering skin effect

Method	**Early stage**		**Late stage**	
	T **(m^2/d)**	***S***	***T*** **(m^2/d)**	***S***
Jocab-Lohman (1952,1979)	83.18	2.97×10^{-1}	21.78	> 1
Swamee et al. (2000)	87.93	1.01×10^{-1}	23.03	> 1
Singh (2007)	113.91	5.59×10^{-1}	28.83	> 1
Average	95.01	3.19×10^{-1}	24.55	> 1

Table 6.8: Estimated *T* and *S* values of the artesian aquifer in Oudtshoorn considering skin effect

Method	**Early stage**		**Late stage**	
	T **(m^2/d)**	***S***	***T*** **(m^2/d)**	***S***
Jocab-Lohman (1952,1979)	83.18	2.25×10^{-3}	21.78	> 1
Swamee et al. (2000)	87.93	7.64×10^{-3}	23.03	> 1
Singh (2007)	113.91	4.23×10^{-3}	28.83	> 1
Average	95.01	4.71×10^{-3}	24.55	> 1

Steady state

In hydrogeology, usually, there is not a unique model allowing one to describe the behaviour observed in the field. The term steady state means that water level and discharge rate at the borehole do not change during a pumping test. The partial derivative of drawdown and discharge rate with respect to time is zero. For a constant-head pumping test situation the equations can be presented as follows:

$$\frac{\partial Q}{\partial t} = 0 \text{ and } \frac{\partial s}{\partial t} = 0 \qquad (6\text{-}8)$$

Where Q and s are the discharge rate and drawdown at the test borehole, respectively, and t is the time.

It is noted from Fig. 6.14a that the discharge rate from artesian borehole C1b3 at later stage became fairly stable (flow rate ranging from 16.1 to 17.0 l/s lasted for more than two weeks at the end of free-flowing test). It is assumed that the flow regime became steady state. Therefore, steady state equations can be applied under this situation. The method is based on the well-known Thiem steady state equation (1906) which can be written as:

$$T = (2.3Q/2\pi s)\log(r_e/r_w) \qquad (6\text{-}9)$$

Where T is the aquifer transmissivity, Q the borehole discharge rate, s the maximum drawdown, which is equal to s_w for constant drawdown test, r_e the radius of influence of the borehole, and r_w the borehole radius.

In the Thiem equation, the ratio r_e/r_w cannot be determined accurately unless several observation boreholes are available during the aquifer test. Although this ratio may vary considerably, the logarithmic term is relatively insensitive to such variations. Logan (1964) proposed a value of 3.32 as "typical" for this logarithmic ratio. Then the Thiem equation can be approximated with the following equation:

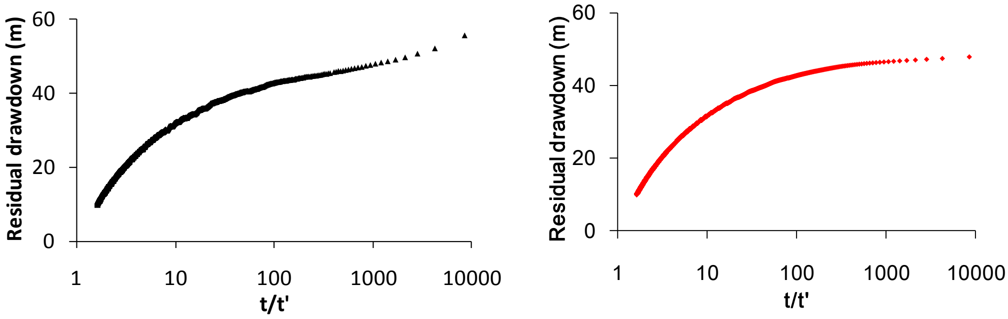
$$T = 1.22Q/s \qquad (6\text{-}10)$$

Strictly speaking, the Logan approximation given above only applies to confined aquifer conditions (Misstear, 2001), although another equation can be applied for the unconfined aquifer situation, which will not be mentioned here. Given the discharge rate ranging from 16.1 to 17.0 l/s with constant-drawdown of 69.4 m, the aquifer transmissivity is approximately 25 m^2/d, which is very close to transmissivity value of 24.55 m^2/d with late stage data.

6.3.3.3 Theis's recovery method

Recovery test is easy to perform and provides more reliable estimate of T. The most common and easiest way to interpret a recovery test is to use the Theis recovery method (Theis, 1935), which was discussed in Chapter 2.

In this section, Theis solution is adapted to estimate the transmissivity of the artesian aquifer in Oudtshoorn with recovery tests data from flowing borehole and observation borehole. The tests data are displayed in Fig. 6.18.



a) test borehole C1b3 b) observation hole C1b2

Fig. 6.18: Recovery test data from artesian borehole C1b3 and observation hole C1b2 in Oudtshoorn

The interpretation of a recovery test is performed by plotting residual drawdown against equivalent time on semi-logarithmic plot. An approximation to the recovery test data is:

$$s = \frac{2.303Q}{4\pi T}\log(\frac{t+t'}{t'}) = 0.183\frac{Q}{m}\log(t^{*}) \qquad (6\text{-}11)$$

Where s is the residual drawdown, Q the discharge rate at the end of free-flowing test, T the transmissivity, t the free-flowing time, and t' the elapsed time since the test free-flowing test stopped. The variable $t^{*} = (t+t')/t'$ is termed equivalent time, and m is the slope of straight line for the plotting data for the homogeneous aquifer.

Recovery test data can be utilized to determine the skin factor and effective radius. In hydrogeology, four types of recovery test plots can be categorized (Fig. 6.19). It is clearly visible that, the shapes of the curves at the Fig. 6.18 are similar with Fig. 6.19d, which is not straight line. It is incorrect to apply the Theis solution method directly. The non-straight line curves indicate the heterogeneity of transmissivity, which implies the impact from skin zone. Analytical method was adapted to estimate the transmissivity for the fourth type of curve in Fig. 6.19.

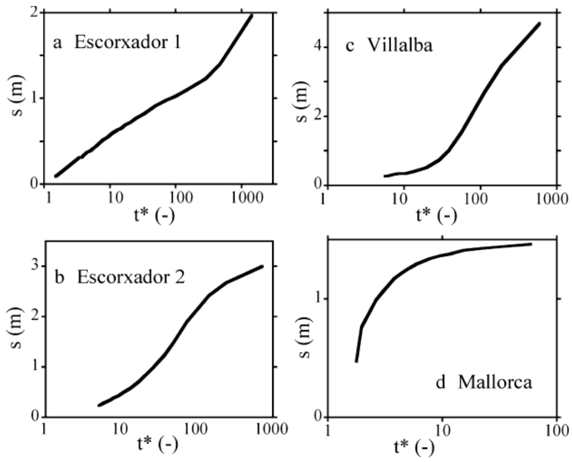
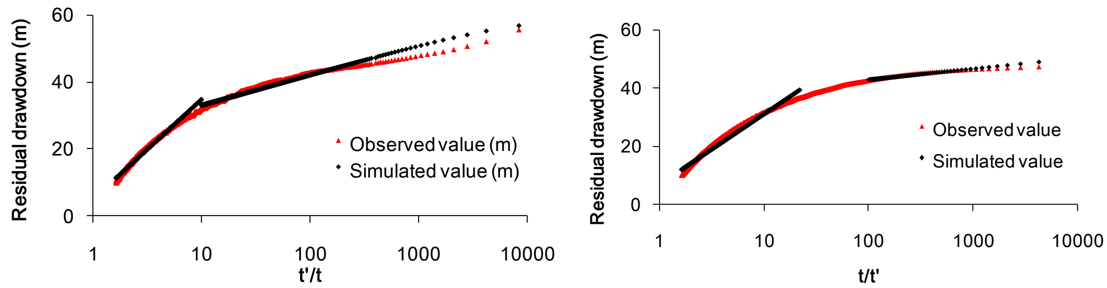


Fig. 6.19: Examples of field recovery tests performed within the city of Barcelona, Spain (Willmann et al., 2007)

Recovery test data of test borehole C1b3 at early stage (20 hrs) and late stage data (156 days) were plotted into the program developed for determination of skin factor and effective radius. The T values are 46.7 and 8.6 m^2/d, respectively using recovery test data from test borehole; while the T values are 68.5 and 10.5 m^2/d with data from observation hole. Due to the reason that the skin zone is fairly close to the observation hole (<17 m), and the heterogeneity and anisotropic entity of aquifer, it is expected that the T values from the test borehole data analysis differ from the observation hole. The observed and simulated values for both boreholes are displayed in Fig. 6.20.



a) from free-flowing borehole b) from observation borehole C1b2

Fig. 6.20: Recovery test data analysis from boreholes C1b3 and C1b2 in Oudtshoorn

The idea of a negative skin zone was proved in the vicinity of flowing borehole in Fig. 6.19d (Willmann et al., 2007). The recovery test data in Fig. 6.20a confirm the idea that a negative skin zone also exists around borehole C1b3. Together with the topography of the study area, a cross-section from north to south through borehole C1b3 can be drawn (Fig. 6.21). T_{loc} is the transmissivity of inner zone surrounding the borehole, which is defined as skin zone. T_{reg} is the transmissivity of outer zone, which represents the regional transmissivity.

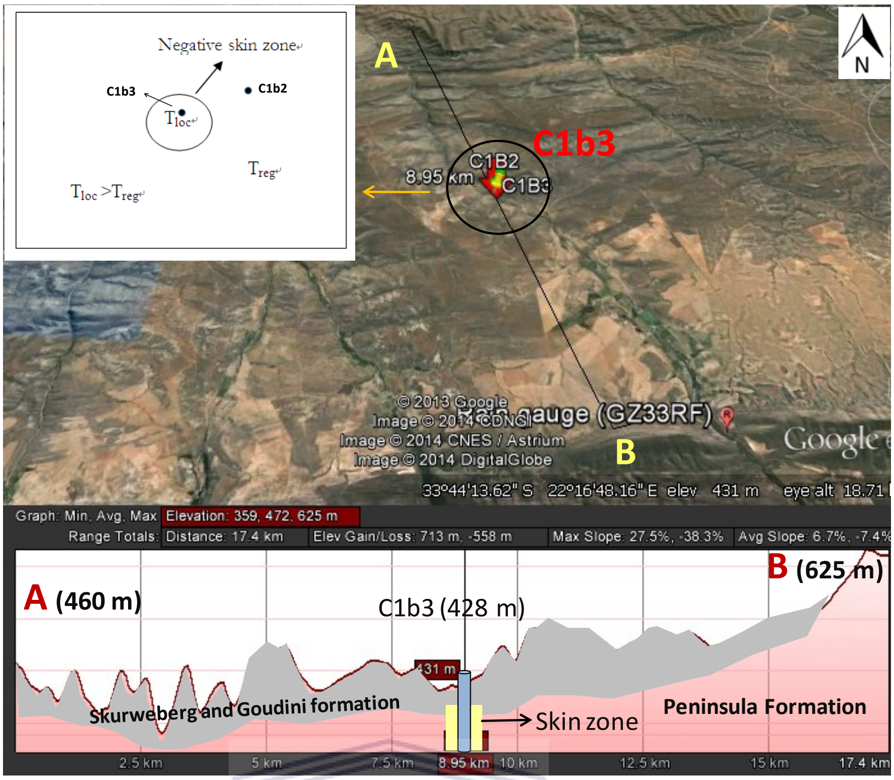


Fig. 6.21: Cross-section of the artesian basin through artesian borehole C1b3 in Oudtshoorn (Google Earth)

The interpretation consists of three steps. Dimensionless drawdown is firstly plotted against the logarithm of equivalent time (t^*). Then, two different slopes are defined at any given time. Slope k_1, which is defined as the tangent of the residual drawdown data, is its derivative with respect to $t^* = (t+t')/t'$ (Fig. 6.22). The slope is computed by using moving windows in order to avoid numerical artefacts. A second slope, k_2, is defined as that corresponding to the secant that joins any given point of the semi-log plot with the origin (s = 0, t^* = 1). Third, slopes are converted into normalized estimates of transmissivities $T^* = T/T_{loc}$ by means of the following equations:

$$T^*_{k1} = 0.183\frac{Q}{T_{loc}k_1} \text{ or } T_{k1} = 0.183\frac{Q}{k_1} \quad (6\text{-}12)$$

$$T^*_{k2} = 0.183\frac{Q}{T_{loc}k_2} \text{ or } T_{k2} = 0.183\frac{Q}{k_2} \quad (6\text{-}13)$$

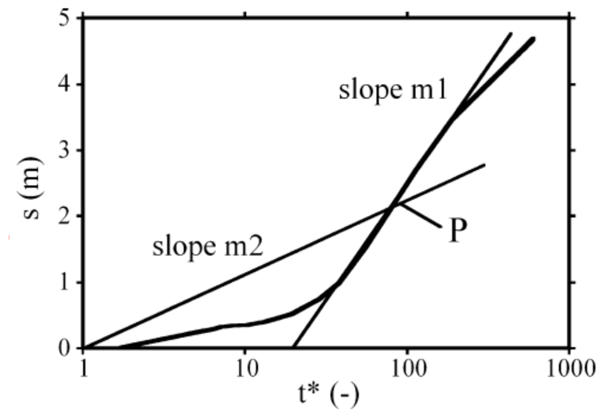
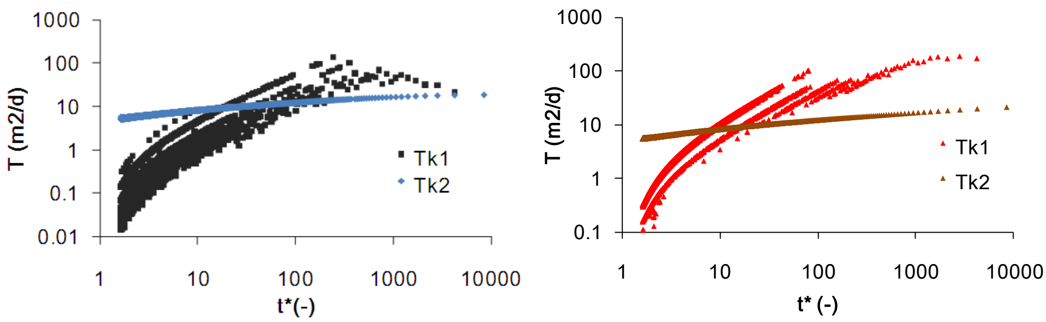


Fig. 6.22: Two different calculations of slope k in a heterogeneous aquifer. At any point P, the slope can be calculated as that of tangent (k_1) or as that of the secant, the line between the origin and P (k_2) (Willmann et al., 2007)

When the duration of recovery test is long enough, T_{k1} provides good estimate of T_{loc} with early time data and eventually tends to T_{reg}. T_{k2}, on the other hand, helps to identify departure from ideality, as it consistently lies between T_{loc} and T_{reg}. The advantage of using T_{k2} is that it converges to the large-scale value much faster than T_{k1}. Note that in the case of homogeneous aquifer, $T_{k1}^* = T_{k2}^* = 1$ should be obtained in the range of validity of the method (Willmann et al., 2007).

The T value of the artesian aquifer in Oudtshoorn can be derived with the recovery test data from test borehole and observation borehole with the above equations. The results are shown in Fig. 6.23.



a) recovery test data analysis at C1b2 b) recovery test data analysis at C1b3

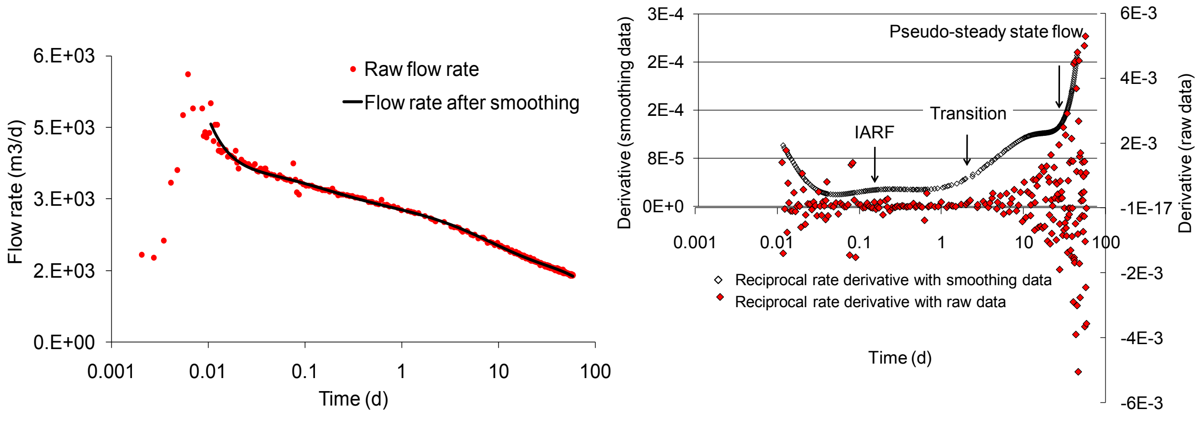
Fig. 6.23: Interpretation of recovery tests data using method developed by Willmann et al (2007).

As discussed above, Fig. 6.20a and b display clearly two different slopes. The corresponding estimated transmissivities (T_{k1}) in Fig. 6.23 suggest a decrease from T_{loc} to T_{reg}. The different T_{loc} indicates that skin effect plays important role during the test. The T_{loc} is approximately 40.7 m^2/d derived from test borehole and 100 m^2/d from recovery test data at observation hole (Fig. 6.23). Recovery in observation boreholes usually only renders an intermediate value of transmissivity as early time responses are delayed and late time responses are usually not resolved. Therefore, the method is recommended for pumping borehole.

Due to the frequent measurements and the fact that residual drawdowns become small for late time recovery (Fig. 6.20), the transmissivities for T_{k1} in Fig. 6.23 do not converge. The T_{k2} converges to 10 m^2/d, which can be regarded as transmissivity of aquifer at large-scale.

6.3.3.4 Derivative results

Raw rate, rate after eliminating the noise and reciprocal rate derivate at borehole C1b3 are shown in Fig. 6.24. It is noted that the noise of the reciprocal rate derivative plot with raw data becomes very pronounced after about 10 days, which provides little useful information for interpretation. However, the reciprocal rate derivative using smoothing data produces a clear signal of flow regimes. For instance, the fairly steady reciprocal rate derivative at early stage (0.03-3 d) indicates the IARF regime, which implies that the Jacob-Lohman method is applicable. Later, the reciprocal rate derivative starts to increase slowly, which represents the transition flow. The pseudo-steady state flow appears after four weeks approximately. The Thiem equilibrium equation may be used to estimate the T value with drawdown from the observation borehole (Thiem, 1906; Kruseman and De Ridder, 1991; Logan, 1964; Misstear, 2001).



a) Raw rate and rate after noise elimination b) Reciprocal rate derivative at semi-log scale

Fig. 6.24: Flow rate and reciprocal rate derivative at borehole C1b3 in Oudtshoorn

6.3.3.5 Conceptualization and simulation results

The consistent reciprocal rate derivative at early stage (0.03-3 d) indicates that the Peninsula Formation in Oudtshoorn area can be assumed as infinite, homogeneous and isotropic at local scale. Later, the deviation of reciprocal rate derivative implies the influence of the barrier boundary. The slope of reciprocal rate derivative during IARF, m, to boundary-dominated flow regime $4m$ implies the possibility of two straight-line boundaries at right angles. The geological map of the region shows that the artesian borehole C1b3 is surrounded by numerous synclines and anticlines (Fig. 6.25), with deep-seated groundwater flows towards the northwest. The Witkliprug Anticline with length of 20 km is located in the north of the wellfield. The slope of reciprocal rate derivative $4m$ at later stage implies that the anticline may be deformed by faulting in the deep formation below, which results in no-flow boundary. Given the above information, a conceptual model with a cross-section can be developed (seen Fig. 6.25).

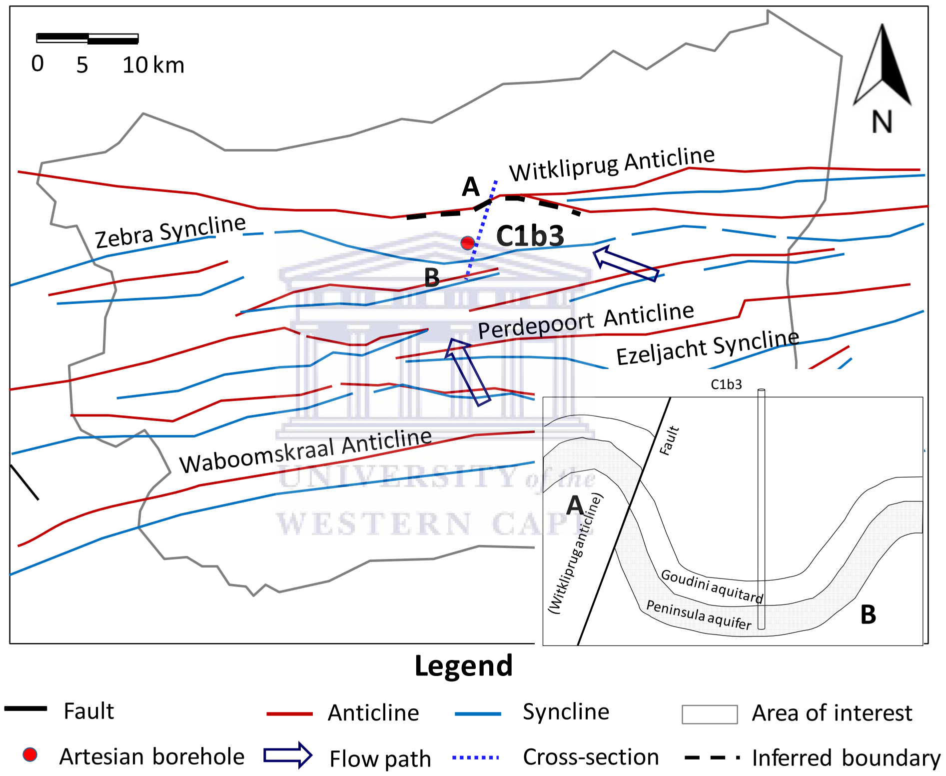


Fig. 6.25: Conceptual model of Oudtshoorn area with inferred boundary conditions (after Riemann and Blake, 2010)

The distance between artesian borehole C1b3 and the inferred no-flow boundary (coinciding with Witkliprug Anticline) is about 3 km. The same distance from artesian borehole to the east limb of the boundary is expected. With effective radius of 0.74 m derived from early recovery test data, two scenarios, namely, a single barrier boundary and two straight boundaries intersecting at right angles (a right angle was adopted for calculation purposes), are simulated based on the above conceptualization. The simulation results under different scenarios are shown in Fig. 6.26 and Table 6.9, respectively.

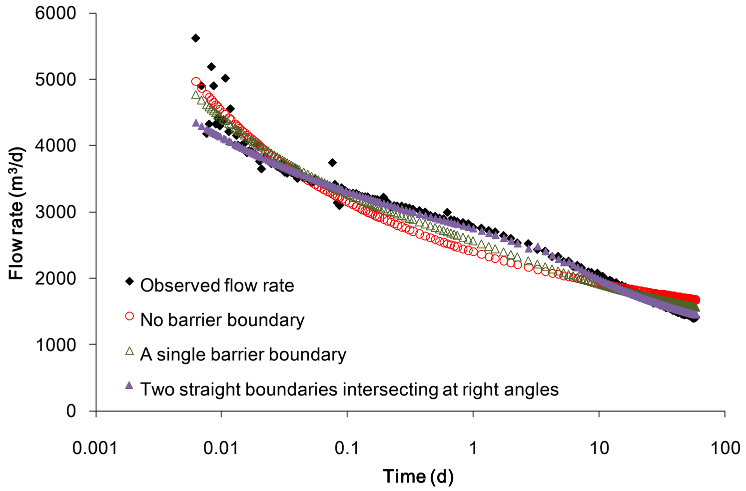


Fig. 6.26: Flow simulation during free-flowing test at borehole C1b3 in Oudtshoorn under different boundary conditions

Table 6.9: Parameter estimation of the artesian aquifer in Oudtshoorn under different boundary conditions

Model name	***T*** **(m^2/d)**	***S*** **(-)**
No boundary-early stage data (Straight-line method)	116.3	5.6×10^{-3}
No boundary-later stage data (Straight-line method)	32.2	-
A single barrier boundary	29.4	4.4×10^{-3}
Two straight boundaries intersecting at right angles	36.7	1.8×10^{-3}
Two parallel boundaries	-	-
U-shaped boundary	-	-

6.3.3.6 Data analysis with observation borehole data

During the 2 months free-flowing test at borehole C1b3, the hydraulic head at observation hole C1b2 was measured as well. As it was discussed in Chapter 2, the drawdown at the observation borehole, normalized by the flow rate at the test borehole, is the same for both constant-rate and constant-head conditions at the test borehole. The s/Q –time (t) data are plotted at semi-log scale displayed in Fig. 6.27. However, the relationship between the two factors is not linear. Discharge rate at test borehole and drawdown data from observation borehole are plotted in Fig. 6.28.

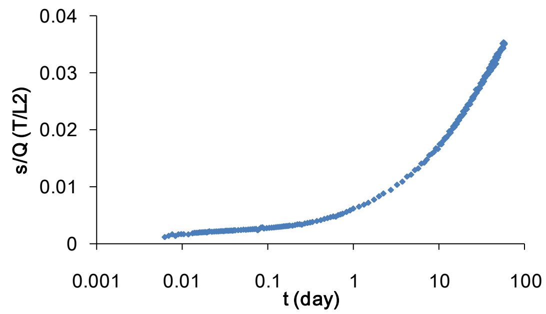


Fig. 6.27: s_w/Q – time at observation borehole C1b2 during the free-flowing test at borehole C1b3

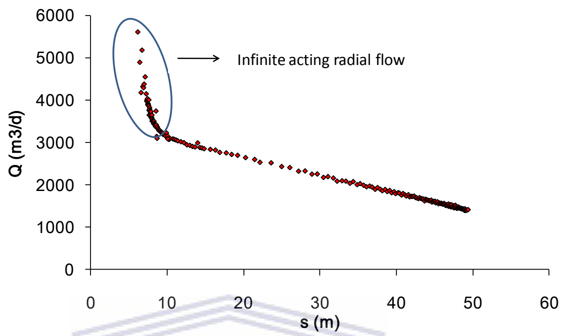


Fig. 6.28: The relationship between flow rate at borehole C1b3 and drawdown at observation borehole C1b2

As shown in Fig. 6.27 and 6.28, the flow from observation hole C1b2 to test borehole C1b3 can be assumed as infinite acting radial flow for about 6 hrs. During this time, s/Q and time can be plotted at semi-log scale, the transmissivity and storativity of aquifer with observation-hole response during a constant-head test can be determined with the following equations (Mishra and Guyonnet, 1992):

$$T = \frac{2.3}{4\pi k} \tag{6-14}$$

$$S = \frac{2.25 T t_0}{r^2} \tag{6-15}$$

Where k is the slope of s/Q against t at semi-log scale, t_0 the value intercepted with time (t) axis, and r the distance from the observation hole to the test borehole. The transmissivity is about 360.85 m^2/d, and storativity is 1.05×10^{-3} with simulated results and observed values shown in Fig. 6.29:

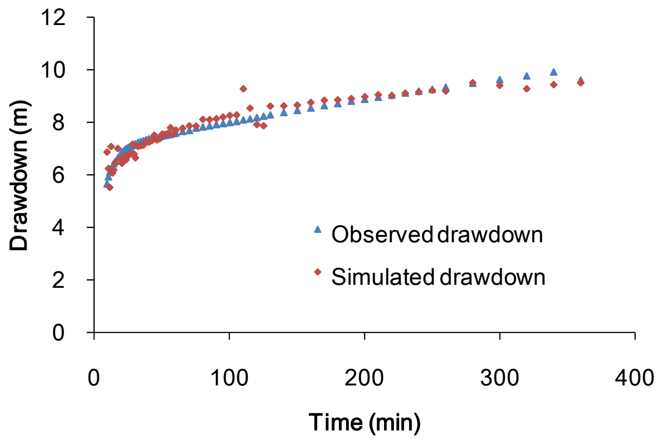


Fig. 6.29: Observed drawdown and simulated drawdown at early stage of free-flowing test at observation hole C1b2

After 6 hrs free-flowing test, the relationship between Q (m^3/d) and s (m) displayed in Fig. 6.28 indicates the linear flow towards observation hole C1b2. At any time t_i during the free-flowing test, under natural flow condition, Darcy's law can be applied to estimate the rough transmissivity of aquifer:

$$Q = -KAJ = K \cdot 2\pi rD \cdot \frac{dh}{dr} \qquad (6\text{-}16)$$

According to continuity equation, the flow rate from observation hole C1b2 towards test borehole C1b3 is continuous. Therefore, the above equation can be written as:

$$Q_i = \frac{s_i 2\pi T}{\ln(r/r_w)} \qquad (6\text{-}17)$$

$$T = \frac{\Delta Q_i}{\Delta s_i} \frac{\ln(r/r_w)}{2\pi} \qquad (6\text{-}18)$$

Where Q_i is the discharge rate from artesian borehole C1b3, s_i is the hydraulic head difference between test borehole and observation hole, r_w is the radius of test borehole screen (0.09 m), r is the distance between test borehole and observation hole (25 m). The above equation shows that the discharge rate has linear relationship with hydraulic head at observation hole. The simulated Q against h_0 results are plotted in Fig. 6.30. The transmissivity is approximately 37.9 m^2/d, which is close to the T value derived from free-flowing test data at later stage at test borehole (25 m^2/d).

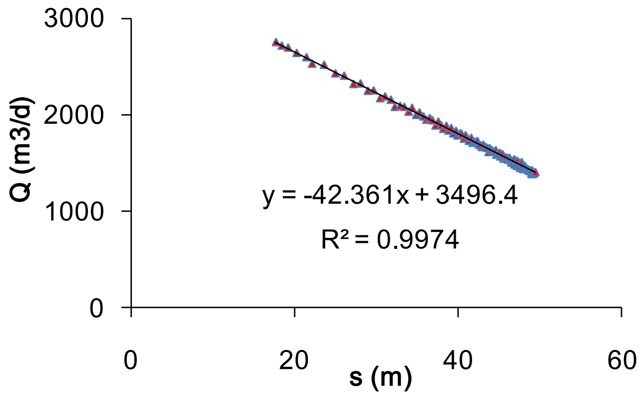


Fig. 6.30: Simulated results from observation hole at later stage

6.4 Discussion and summary

Flow and recovery test data from two aquifer tests conducted in TMG are analysed using the conventional method and diagnostic plot method in this Chapter. The results confirm the fact that the TMG aquifers are often bounded by impermeable faults or folds, which imply that assumptions of infinite aquifer required for the straight-line method cannot be fulfilled. The simulated flow results using diagnostic plot analysis method for flow rates under barrier boundary conditions fit better with observed values. Together with the geological information at local scale, conceptual models were developed. The *T* values derived under different boundary conditions for both cases are fairly consistent. The *S* estimates by the straight-line method using early stage data are fairly close to the results derived under boundary condition. However, the *S* estimate will be incorrect, when the straight-line method is applied with flow rate data at later stage.

The results of both cases indicate that there is a negative skin zone surrounding the test borehole, and the effective radius of test borehole is bigger than the actual borehole radius, which is often realized for a borehole drilled in a fractured-rock aquifer. Flow simulation under different boundary conditions shows better fitting with observed data than that under the no-flow boundary condition. It also indicates that the *T* and *S* estimates derived under different boundary conditions are smaller than the ones using the straight-line method with early stage data. The *T* value of the artesian aquifer in Rawsonville is calculated as 7.5 – 7.9 m^2/d, while the *S* value is approximately ranging from 2.0×10^{-4} to 5.5×10^{-4}. The *T* value of the artesian aquifer in Oudtshoorn is approximately 36.7 m^2/d, while the *S* value is 1.8×10^{-3}.

It is noted that the *T* and *S* estimates under different boundary conditions are all smaller than the results with the Jacob-Lohman method using early stage data. However, the *S* value is incorrect with flow data at later stage. Researchers have often encountered a similar situation when applying Jacob's method (Jacob, 1946) to late-time drawdown data at a pumping borehole or observation borehole during constant-rate pumping tests (Meier et al., 1998). With late time drawdown data, transmissivity estimates T using Jacob's method tend to be fairly constant, while the storativity estimates S display a great spatial variability. Similar observations have previously been reported by Schad and Teutsche (1994) and Herweijer and Young (1991) in studies in which the Theis method (1935) is used to analyse drawdown data from observation boreholes in heterogeneous alluvial aquifers. The reason can be attributed to the fact that methods developed for homogeneous media without boundary effects (for instance, Jacob-Lohman method) are being used for interpretation of tests performed in heterogeneous formations (Meier et al., 1998).

In summary, the diagnostic plot analysis method using reciprocal rate derivative to interpret flow data from free-flowing test, could help identify the flow regimes and discern the boundary conditions, which results provide useful information to conceptualize the aquifer and facilitate an appropriate analytical method to evaluate the aquifer properties. The simulation results can make the no-flow boundary more visible. It can be used as an additional tool to double check whether the interpretation by conventional straight-line method is valid or not. Difficulties and limitations of this approach have been discussed in the previous Chapter, which will not be discussed here.

It is known that flow mechanisms or behaviours can occur throughout the aquifer test period as the expanding drawdown encounters boundaries and heterogeneities. Usually, there is not a unique model allowing one to describe the behaviour observed in the field. It is noted that the heterogeneity of the artesian aquifer may have the same effect on flow rate for the free-flowing test, which needs to be addressed in future.

Chapter 7
Storage determination in artesian aquifer with case studies

7.1 Introduction

Evaluation of groundwater storage is significantly important for sustainable development and management of groundwater resources. The mechanism of groundwater storage, depending on the geometic and physical properties, and the recharge and discharge processes of the aquifer, is different in various aquifers, particularly in fractured rock aquifers of which the anisotropic properties are extremely difficult to determine. For the purpose of evaluating the groundwater storage capacity, quantification of the bulk groundwater resources is usually based on assumptions that the aquifer is homogeneous at large scale, and that an average specific storage or storativity value is applicable across all aquifers.

Quantification of groundwater storage capacity is the product of the size of the area, the saturated thickness and the storativity (S) of confined aquifer, which is the volume of water that the aquifer can release from storage per unit surface area per unit decline in hydraulic head normal to the surface (Kruseman and De Ridder, 1991). Storativity of confined aquifer (S), which equals the specific yield (S_y) or the effective porosity for unconfined aquifer, is often determined through aquifer tests. Accurate estimate of storativity is critical in water resources evaluation and further assisting aquifer management. An overestimated S value, for instance, may lead to water withdraw from an aquifer that exceeds its capacity. It is concluded that the storativity of the confined Peninsula Aquifer in TMG generally falls in a wide range from 10^{-5} to 10^{-2}.

Research on quantification of groundwater resources in South Africa started in 1970 (Enslin, 1970). Continuous studies were followed up afterwards (Baron et al., 1998; WSM, 2001). The methodology for assessment of groundwater resources has been revised from time to time. Procedures for groundwater resources assessment in South Africa have been described in various documents. The reports by Bredenkamp et al. (1995) and Xu et al. (2003) describe the methodologies and case studies at local and regional scales. In later 2003, the Department of Water Affairs (DWA) initiated a project aiming at the quantification of the groundwater resources on a national scale. In 2006, DWA published an official document for groundwater resources assessment at national level. The procedure of groundwater assessment at national level adopted in South Africa is considered as the most detailed information on the subject available in the public domain (Chatterjee and Ray, 2014).

In 2007, a comprehensive research on flow conceptualization and storage determination of TMG aquifers, sponsored by WRC, was launched for better understanding groundwater flow dynamics and potential utilization of TMG aquifer system in terms of aquifer media and spatial variation (Xu et al., 2009). A Geographic Information System (GIS) based methodology was developed to calculate the groundwater storage capacity for the whole TMG aquifer system (both confined and unconfined aquifers). It is noted that the storativity and the thickness of aquifer are often scale-dependent. For sustainable groundwater development, it is recommended that evaluation of groundwater storage capacity be done at a local or intermediate scale. For the deep Peninsula Aquifer in TMG which refers to artesian aquifer, inasmuch as the aquifer is often bounded by impermeable faults or folds, which are considered as no-flow barriers, it is suggested that storage estimate be done on catchment basis for groundwater development.

In this chapter, classification and methods for estimation of groundwater storage capacity in artesian aquifer in TMG are reviewed, followed by applications with case studies. Storativity values of artesian aquifers in TMG derived in the previous chapter will be used to calculate the groundwater storage capacity of artesian aquifer at a local scale. The storage estimates of artesian aquifer will provide valuable information for decision-makers to develop sustainable groundwater utilization programme.

7.2 Storage classification and estimation

Many types of classification of groundwater storage capacity have been developed in many countries based on their own knowledge and understanding. Four-storage classification was widely used in groundwater resources evaluation in Russia and China; namely, total storage or static storage capacity, mobile storage capacity, adjustable storage capacity and exploitable storage capacity (Jia, 2007). According to the geological settings of TMG aquifers, the conceptualization of artesian aquifer storage can be established (shown in Fig. 7.1).

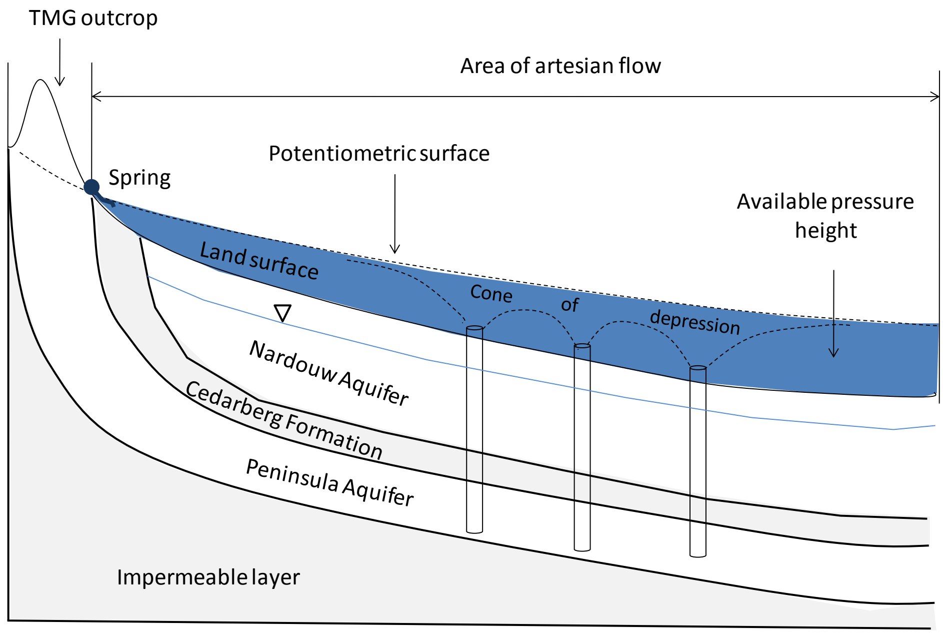


Fig. 7.1: Conceptualization of artesian aquifer storage in TMG aquifer system

7.2.1 Total storage capacity

The total storage capacity or the static storage of confined aquifer is defined as the total volume of groundwater in the aquifer, which is expressed as (Jia, 2007; Blake et al., 2010):

$$V = S \cdot A \cdot D \tag{7-1}$$

$$S = S_S \cdot D \tag{7-2}$$

Where V [m^3] is the total groundwater in storage, S [-] the storativity of confined aquifer, S_s [m^{-1}] specific storage of confined aquifer, A [m^2] the size of confined aquifer, and D [m] the thickness of confined aquifer. Since the groundwater level varies all the time, there is no absolutely static storage in reality. When groundwater level in the aquifer declines to the discharge datum plane, the movement of groundwater stops and the volume of water resources keeps unchanged, which can be considered as “static”.

It is highlighted that the outcrop areas of TMG aquifers are often considered as recharge zone (Xu et al., 2007). Fractures in shallow rock layers, together with fissures that are due to weathering near the surface, are the most important factors that promote both rainfall infiltration and groundwater recharge in the outcrop areas. These outcrops of the TMG form the main recharge areas of the aquifers as do the foothills and foot-slopes of the mountains where springs occur (Fig. 7.1). Deep-seated faults, conducive to preferential flow, that are linked to dense fracture intersections at shallow locations appear to facilitate recharge processes in the deep TMG aquifer system. Based on Equation 7-1, groundwater storage capacity in artesian aquifer in TMG aquifer system can be estimated with the following equation:

$$V_a = S_s \cdot D \cdot (A - A_{crop}) \cdot D \tag{7-3}$$

Where V_a [m^3] is total groundwater storage capacity in artesian aquifer, S_s [m^{-1}] specific storage of artesian aquifer, A [m^2] the size of study area, A_{crop} the area of TMG outcrop, and D [m] the thickness of artesian aquifer.

7.2.2 Active storage

The term "active storage" may be used to describe the amount of groundwater that can be readily developed and manipulated without dewatering the artesian aquifers (Feth et al., 1966). This water would be obtained by lowering water levels in the artesian aquifers and in the recharge area, where groundwater is under water table conditions.

The active groundwater storage includes the storage of available pressure height, which can be accessed without a pump, and the component of storage below ground surface without dewatering the aquifer, which can be utilized using a pump. The active storage of artesian aquifer is equal to total groundwater storage capacity.

7.2.3 Available pressurized storage

Given that water level of a strong artesian aquifer is above ground surface, the available pressurized storage can be defined as the volume of groundwater that can be utilized without using a pump (blue colour in Fig. 7.1). The volume of groundwater that can be released from the artesian aquifer under natural condition relies on the initial pressure in the artesian aquifer, the hydraulic properties (transmissivity and storativity) and size of the aquifer, the number and the discharge rates of flowing artesian boreholes, and the duration etc. Given that the pressure head in the artesian aquifer remains constant, the available pressurized storage of artesian aquifer can be calculated with the following equation:

$$V_p = S_s \cdot D \cdot (A - A_{crop}) \cdot h \tag{7-4}$$

Where V_p [m^3] is available pressurized storage of artesian aquifer, and h [m] artesian head of artesian aquifer above ground surface. If artesian head of aquifer in TMG aquifers declines under free-flowing condition (Δh [m]), the maximum volume of groundwater (V_0 [m^3]) that can be released from the artesian aquifer can be expressed as the following equation:

$$V_0 = S_s \cdot D \cdot (A - A_{crop}) \cdot \Delta h \tag{7-5}$$

7.2.4 Other classifications

7.2.4.1 Adjustable storage capacity

The adjustable storage is defined as the groundwater volume between the highest and lowest water level during a hydrological year. For an artesian aquifer, the value can be calculated with the following equation:

$$V_a = S \cdot A \cdot (h_{\max} - h_{\min}) \qquad (7\text{-}6)$$

Where V_a [m^3] is the adjustable storage, S [-] storativity for confined aquifer, A the size of the aquifer, and h_{max} [m] and h_{min} [m] is the highest and lowest water level during a hydrogeological year, respectively.

Another similar type of storage is named as dynamic storage, which is defined as the storage between the average groundwater evaluation and base of the natural dynamic groundwater elevation.

7.2.4.2 Exploitable storage

Exploitable storage is defined as the volume of groundwater that can be abstracted from the aquifer under certain conditions. The amount depends on the feasibility of exploitation of groundwater resources and the exploitation technique. The concept of exploitable storage under a nature condition does not apply to the exploitable storage in a condition when the relationship between recharge and discharge is changeable during the progress of exploitation.

7.2.5 Procedures of estimation of groundwater storage capacity

An approach to quantifying groundwater storage on a national scale was discussed in an official report by DWA (2006). A map of the whole country was divided into small grids (1km×1km), with information of thickness of aquifer, which were based on the water-strike frequency curves obtained from the NGDB in the early 1990's (Vegter, 1995). However, the approach adopted by Vegter in obtaining drilling depths is not clearly described in his report. To estimate groundwater storage capacity of artesian aquifer at a local or regional scale, one can follow the following steps based on the procedures drafted by DWA (2006).

1. Delineate the area to be studied. Information of geological settings, aquifer types, number of Quaternary Catchments that fall into the study area, and size of each Quaternary Catchment is required.

2. Establish the size and thickness of artesian aquifer in each Quaternary Catchment. Inasmuch as the outcrop of TMG aquifers is considered as recharge zone (unconfined aquifer), most part of the Peninsula Aquifer in non-outcrop of TMG aquifers can be considered as artesian aquifer. The thickness of artesian aquifer can be obtained by drawing the cross-sections in the study area, which may be completed using the drilling information of series of boreholes penetrating into the artesian aquifer. In some occasions, such values can also be found in previous reports.
3. Establish the storativity (S) or specific storage (S_s) of artesian aquifer within each Quaternary Catchment. The S value can be estimated through the aquifer test conducted at flowing artesian borehole, and the S_s value can be calculated with Equation 7-2. Alternatively, S_s value may also be estimated under certain conditions; for instance, scenarios with different temperatures and aquifer materials, which determine the compressibilities of material and water, can be simulated to estimate the S_s value. In most occasions, the number of artesian boreholes in the study area is rather limited, specific storage (S_s) of artesian aquifer may have to be considered as constant in such case.
4. The groundwater storage capacity and available pressurized storage of artesian aquifer in each Quaternary Catchment can be calculated with the equations discussed above (Equations 7-3 and 7-4). Total groundwater storage capacity within study area can be obtained as the sum of storage capacities in all the Quaternary catchments.

7.3 Application with case studies

It is widely acknowledged that the thickness and spatial distribution of the TMG rocks varies with locations. It is therefore essential to determine the thickness of artesian aquifer for groundwater storage capacity evaluation. In practice, cross-section construction is often adopted to estimate the thickness of aquifer (Jia, 2007).

The purpose of constructing cross section is to visualize, analyse and measure the variation in depth, thickness and altitude of the different formations of the TMG over the Cape Fold Belt. Regionally the key rocks that control the TMG aquifer system are the Peninsula and Cedarberg Formations and the overlying Nardouw Subgroup.

Generally the TMG is strongly compartmentalized by faults or fault zones created in the Palaeozoic and reconstructed during the Mesozoic tectonics. Two major faults (Worcester and Kango faults) control the TMG distribution to a large extent. Nine geological profiles were selected across the structures to encompass the variation in lithology and thickness of the

TMG (shown in Fig. 7.2). The cross sections were done manually by capturing and reading the coordinates and elevation of the intersection points of cross section lines and geological formations. Point data of elevations (top elevation and bottom elevation) of each typical layer at each location were collected. Typical layers only involve the two main aquifers (Nardouw Aquifer and Peninsula Aquifer), the Cedarberg Aquitard, and the TMG basement. Later, isobaths and isopachs of each layer in TMG can be generated with ArcGIS (Jia, 2007). Such maps would provide valuable information for groundwater storage capacity estimation at regional and local scales.

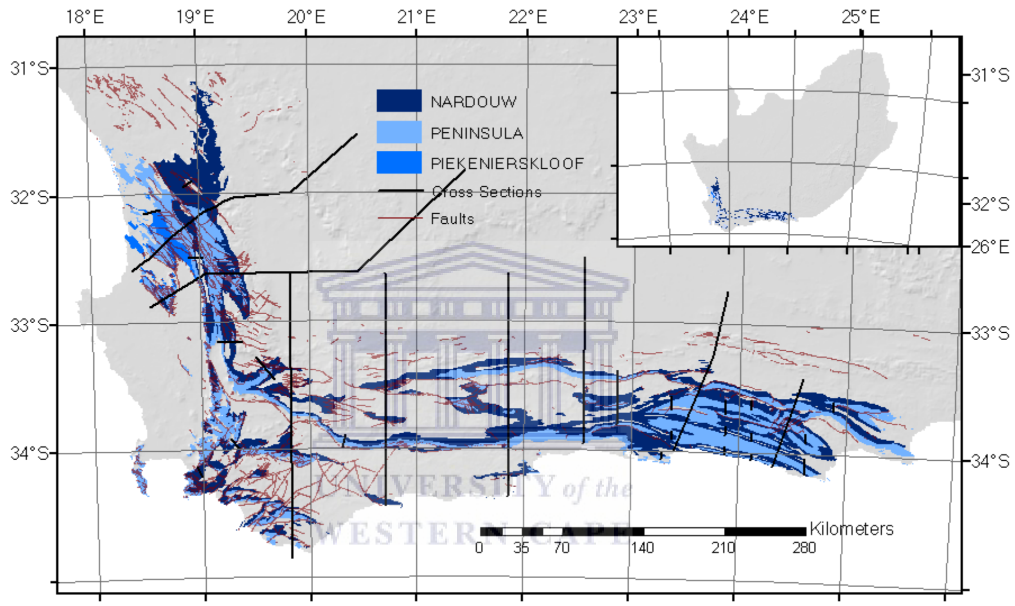


Fig. 7.2: Location of nine cross sections in the TMG area (Jia, 2007)

7.3.1 Case study-Rawsonville

7.3.1.1 Site information

The study area of Rawsonville has been discussed in the earlier chapter. The artesian aquifer (Peninsula Aquifer) in Rawsonville area, with thickness of 361.75 m, is located in quaternary catchment H10J in Bree Primary Catchment, which is under Breede Water Management Area (WMA). There are six other flowing artesian boreholes in the whole Breede WMA.

The oldest rocks in the study area are the meta-sediments of the Malmesbury Group which are exposed mainly by fault controlled valleys (Fig. 7.3). Granite plutons of the Cape Granite Suite have intruded into the Malmesbury Group and small outcrops are evident throughout the area. The Cape Supergroup occupies most of the map area and was deposited in a trough depositional setting (Tankard et al., 1982). The Supergroup constitutes the largely arenaceous Table Mountain Group which unconformably overlies the Malmesbury and Cape Granite rocks, and underlies the Bokkeveld Group (composed predominantly of argillaceous beds) and the uppermost Witteberg Group (consisting of alternating shales and sandstones). The geology of Breede WMA is shown in Fig. 7.3.

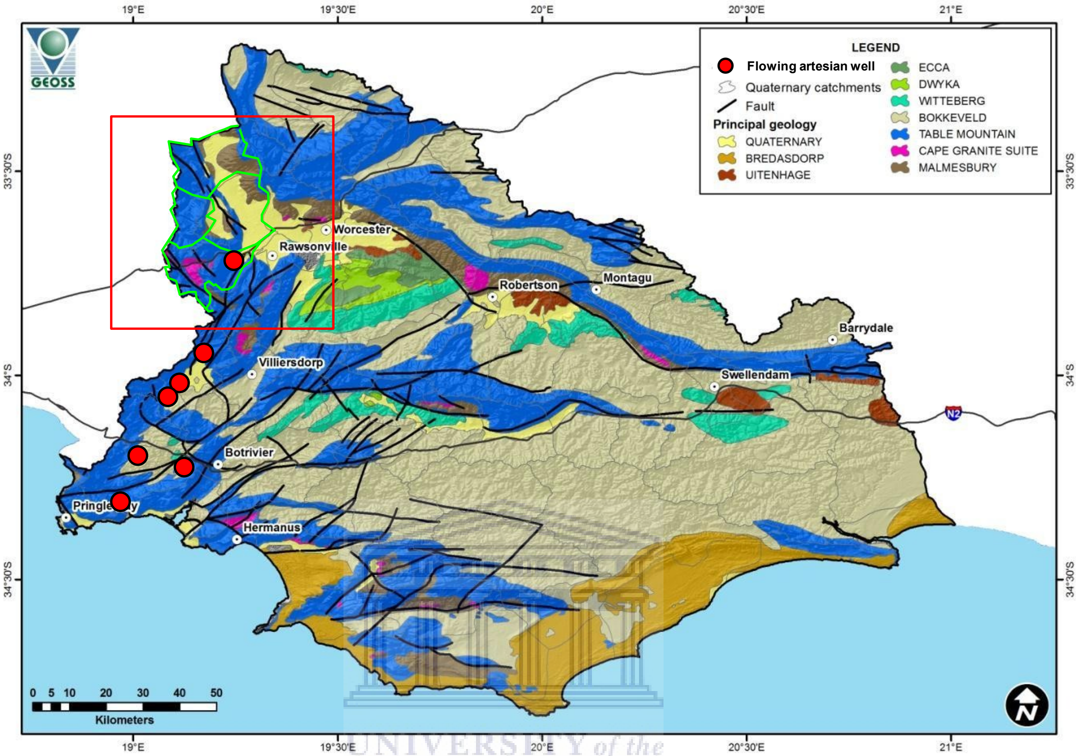


Fig. 7.3: Geological setting of study area in Rawsonville (after DWA, 2011)

7.3.1.2 Aquifer types and distributions

In terms of geological formation, there are about three types of aquifers in Rawsonville (Fig. 7.4); namely, fractured aquifers, intergranular aquifers, and fractured and intergranular aquifers.

The fractured aquifers are by far the most important within the study area. Of the fractured aquifers, the TMG aquifer is the most important, while rocks of the Malmesbury, Witteberg and Karoo Supergroup can yield water under fractured conditions. Most boreholes in the area are drilled into the TMG aquifers.

The intergranular aquifers consist of unconsolidated to semi-consolidated coastal and alluvial deposits in which the granular interstices and pore spaces contain groundwater.

Fractured and intergranular aquifers are commonly related to weathered coarse-medium grained granites of the Cape Granite Suite where the groundwater is contained in the intergranular interstices in the saturated zone or in the jointed and occasionally fractured bedrock (DWAF, 2003b).

Fractured and intergranular aquifers are limited in extent. They are present to the northwest in the TMG structurally controlled valleys where alluvium along the rivers overlies the fractured and high yielding TMG. A significant high yielding aquifer of this type is found in this area.

There are a number of large scale faults within this WMA which relate to the large folding within the TMG. It has been suggested that the north-south trending faults in the area are more closed (compressional), while the east-west trending faults are open (tensional faults) (DWAF, 2003b). It is possible that the fault does not conduct water along its entire length as Smart (1998) speculated that faulting in incompetent sedimentary rocks (shales) results in the formation of a low permeability rock flour which decreases permeability or results in a closed fault. The fault occurring in Rawsonville area falls into such category.

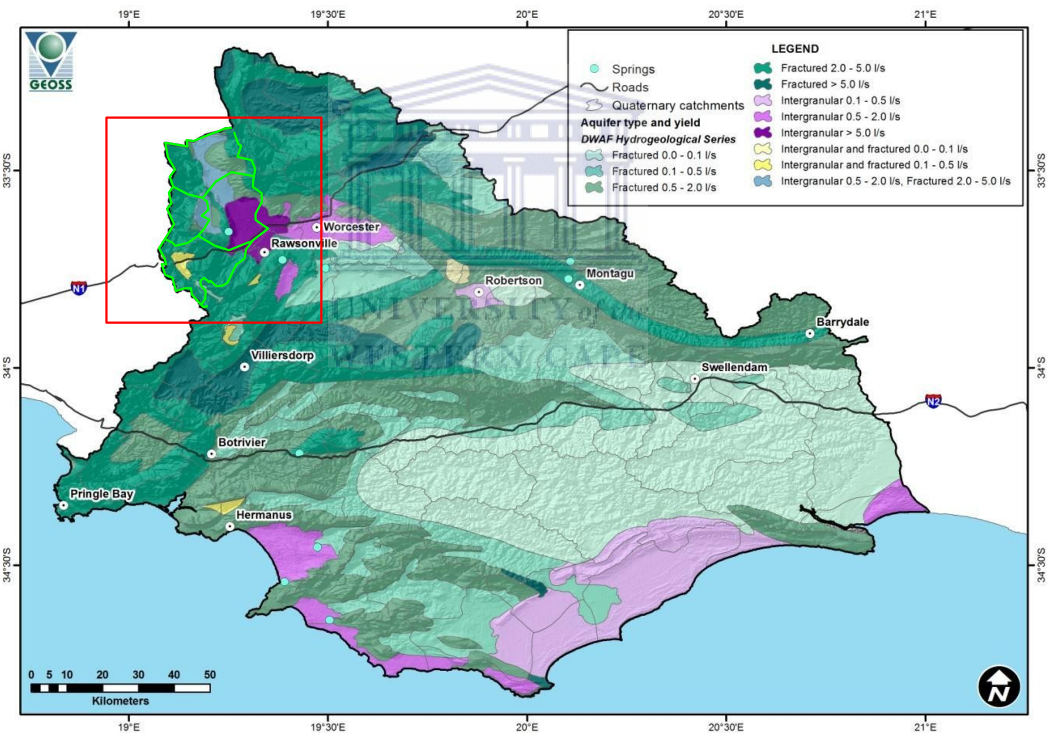


Fig. 7.4: Aquifer types and distributions in Rawsonville (after DWA, 2011)

7.3.1.3 Total groundwater storage capacity in artesian aquifer

The intergranular aquifers in Rawsonville area are surrounded by fractured aquifers (Fig. 7.4), most of which is the outcrop of TMG. The outcrop of TMG is considered as recharge area for the TMG aquifer system. Springs are often found at the lower altitude of outcrop. Given that non-outcrop area of TMG and intergranular aquifers in Rawsonville area are artesian aquifers, together with the information of specific storage, area and the thickness of artesian aquifer

(Peninsula Aquifer) listed in Table 7.1, the groundwater storage capacity at local scale can be estimated (Equation 7-2). The results are listed in Table 7.1.

Table 7.1: Total groundwater storage capacity of the artesian aquifer in Rawsonville area

Quaternary	Outcrop area (km^2)	Quaternary area (km^2)	Area_ Percentage (%)	S_s (m^{-1})	Thickness _Peninsula (m)	Volume_ Peninsula (10^6m^3)	GW-Storage (10^6m^3)
H10E	81.61	84.81	96.23		282.25	903.20	0.14
H10F	125.48	247.85	50.63		291.14	35626.80	5.73
H10G	136.91	270.39	50.63	5.53×10^{-7}	363.71	48548.01	9.76
H10J	175.77	213.76	82.23		361.75	13742.88	2.75
Total	519.8	816.8	63.6			98820.9	18.4

7.3.1.4 Available pressurized storage

If the pressure of shut-in artesian borehole is great enough to expel the water from the aquifer to the surface, groundwater stored in the artesian aquifer can be accessed without pumping facilities. Such storage can be defined as available pressurized storage. It is noted that the value can be changeable as a result of fluctuation of water level in the aquifer.

The original pressure head of shut-in artesian borehole in Rawsonville was 7.53 m, which is used to estimate the available pressurized storage of artesian aquifer in the area. Given that the pressure head of artesian aquifer in the study area is constant, available pressurized storage can be calculated with Equation 7-4. The results of storage yield and available pressurized storage of the artesian aquifer in Rawsonville area are shown in Table 7.2.

Table 7.2: Storage yield and available pressurized storage of the artesian aquifer in Rawsonville area

Quaternary	Outcrop area (km^2)	Quaternary area (km^2)	Area_ Percentage (%)	S_s (m^{-1})	Thickness_ Peninsula (m)	GW-Storage (10^6m^3)	Volume per head decline of (10^6m^3)		
							1 m	5 m	7.53 m
H10E	81.61	84.81	96.23		282.25	0.14	0.000499	0.0025	0.00376
H10F	125.48	247.85	50.63		291.14	5.73	0.0197	0.0985	0.148
H10G	136.91	270.39	50.63	5.53×10^{-7}	363.71	9.76	0.0268	0.134	0.202
H10J	175.77	213.76	82.23		361.75	2.75	0.0076	0.038	0.0572
Total	519.8	816.8	63.6			18.4	0.0546	0.273	0.411

7.3.2 Case study-Oudtshoorn

7.3.2.1 Site information

The flowing artesian boreholes in Oudtshoorn area are located in three quaternary catchments, and the artesian aquifer falls into Gouritz WMA within Western Cape Province. The Gouritz WMA is the largest WMA in the Western Cape with a total surface area of 53,139 km^2.

The geological setting of the whole Gouritz WMA is complex due to the wide range of Groups, sub-groups and formations (Fig. 7.5). The rock types in the study area are mainly part of Bokkeveld, Quaternary, Uitenhage and Table Mountain Group. These rock types are part of the southern portion of the Cape Fold Belt.

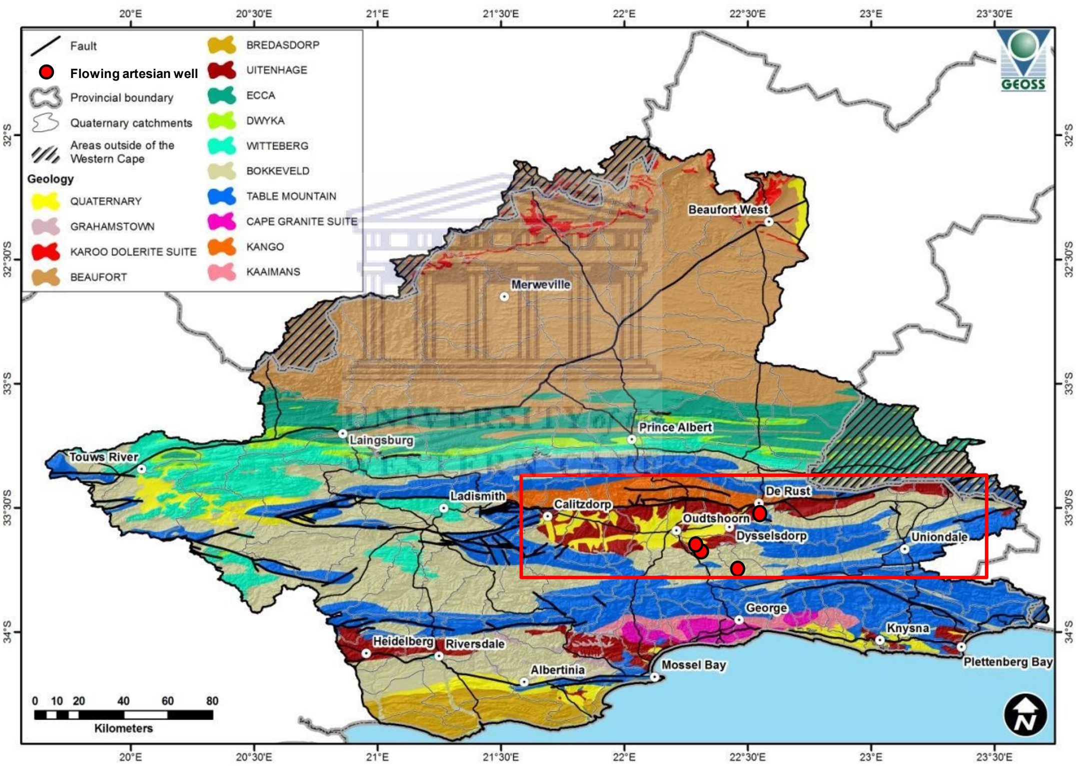


Fig. 7.5: Geological settings of study area in Oudtshoorn (after DWA, 2011)

7.3.2.2 Aquifer types and distribution

Fractured aquifers predominate (94%) in the whole Gouritz WMA (Fig. 7.6). The artesian aquifer (Peninsula Aquifer) in Oudtshoorn area is surrounded by outcrop of TMG (blue in Fig. 7.5), which is considered as recharge zone. The Peninsula Formation is the topographically dominant unit, building most of the high mountain ranges, which has the maximum precipitation and recharge potential and the greatest subsurface volume of permeable fractured rock.

The permeability of the rock is an important factor for the aquifer to store water, while the occurrence of fractures or fault zones are necessary to transmit the stored water in a sufficient amount to the borehole or discharge zone.

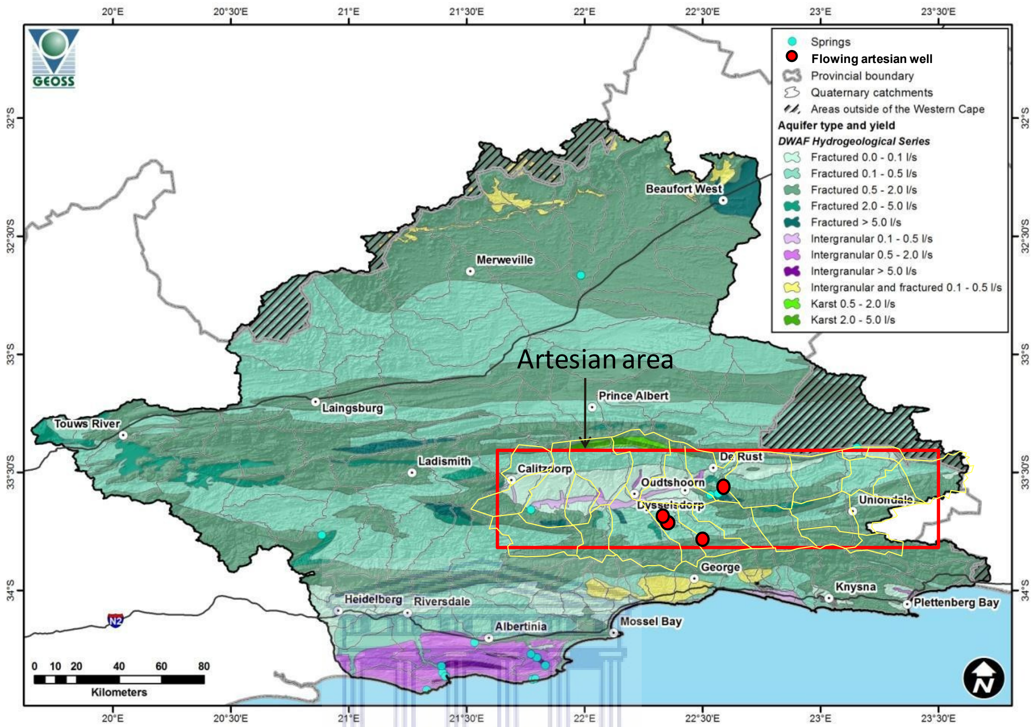


Fig. 7.6: Aquifer types and springs in Oudtshoorn area (after DWA, 2011)

7.3.2.3 Total groundwater storage capacity in artesian aquifer

The depths to artesian aquifers and the thickness vary widely according to the aquifer being sought in drilling, the geologic structure, the location, and the surface altitude. There are about 28 quaternary catchments in the study area of Oudtshoorn (within the red line in Fig. 7.6). The information of each quaternary catchment in the area is listed in Table 7.3. Given that the storativity of artesian aquifer is 1.8×10^{-3} as discussed in the previous chapter, groundwater storage capacity of the artesian aquifer in Oudtshoorn area can be estimated (shown in Table 7.3).

Table 7.3: Total groundwater storage capacity of the artesian aquifer in Oudtshoorn area

Quaternary	Outcrop area (km^2)	Quaternary area (km^2)	Area_Percentage (%)	S_s (m^{-1})	Thickness_Peninsula (m)	Volume_Peninsula (10^6m^3)	GW-Storage (10^6m^3)
J25D	53.85	210.24	25.61		950.57	148659.64	233.24
J25E	159.51	286.34	55.71		1788.80	226873.50	669.85
J31A	311.14	447.04	69.60		1993.70	270943.83	891.60
J31B	112.65	200.56	56.17		1649.75	145029.52	394.92
J31C	103.3	167.97	61.50		2232.62	144383.54	532.06
J31D	31.07	303.65	10.23		1959.62	534153.22	1727.70
J32E	63.8	971.15	6.57		2281.87	2070454.74	7798.08
J33A	173.77	449.46	38.66		2117.43	583754.28	2040.19
J33B	220.15	590.72	37.27		1994.65	739157.45	2433.52
J33C	98.83	427.93	23.09		1413.29	465113.74	1084.98
J33D	93.3	258.86	36.04		1806.05	299009.64	891.35
J33E	115.94	328.67	35.28		1371.41	291740.05	660.38
J33F	47.69	365.62	13.04		1044.42	332052.45	572.42
J34A	220.05	252.19	87.26	1.7×10^{-6}	1490.92	47918.17	117.92
J34B	211.37	341.55	61.89		1711.90	222855.14	629.70
J34C	243.29	318.90	76.29		1853.04	140108.35	428.53
J34D	179.09	354.20	50.56		1744.18	305423.36	879.27
J34E	120.72	257.98	46.79		1486.79	204076.80	500.81
J34F	85.65	319.96	26.77		1243.55	291376.20	598.06
J35A	96.55	427.35	22.59		672.15	222347.22	246.68
J35B	237.24	651.13	36.44		1090.54	451363.60	812.45
J35C	181.8	264.48	68.74		1343.06	111044.20	246.16
J35D	46.64	506.95	9.20		751.23	345798.68	428.77
J35E	29.52	215.16	13.72		1362.20	252878.81	568.57
J35F	146.41	500.04	29.28		1357.43	480027.97	1075.51
J40A	237.58	453.31	52.41		1672.66	360842.94	996.22
K60A	161.46	161.46	100.00		1734.34	0.00	0.00
K60B	143.2	143.20	100.00		1642.36	0.00	0.00
Total	3925.6	10176.1	38.6			9687387.1	27458.9

7.3.2.4 Available pressurized storage

The free-flowing test conducted at artesian borehole C1b3 in Oudtshoorn was discussed in the previous chapter. During the two-month free-flowing test, the constant drawdown was 69.4 m above the borehole rim, which is 5 m above the ground surface. Therefore, the original pressure head of artesian aquifer before releasing the groundwater from borehole was 74.4 m above ground surface, which was used to estimate the available pressurized storage of the artesian aquifer in Oudtshoorn area. The results of storage yield and available pressurized storage of the artesian aquifer in Oudtshoorn area are shown in Table 7.4.

Table 7.4: Storage yield and available pressurized storage of the artesian aquifer in Oudtshoorn area

Quaternary	**Outcrop area (km^2)**	**Quaternary area (km^2)**	**Area_Percentage (%)**	**S_s (m^{-1})**	**Thickness_Peninsula (m)**	**GW-Storage (10^6m^3)**	**Volume per head decline of (10^6m^3)**		
							1 m	**20 m**	**74.4 m**
J25D	53.85	210.24	25.61		950.57	233.24	0.25	4.91	18.26
J25E	159.51	286.34	55.71		1788.80	669.85	0.37	7.49	27.86
J31A	311.14	447.04	69.60		1993.70	891.60	0.45	8.94	33.27
J31B	112.65	200.56	56.17		1649.75	394.92	0.24	4.79	17.81
J31C	103.3	167.97	61.50		2232.62	532.06	0.24	4.77	17.73
J31D	31.07	303.65	10.23		1959.62	1727.70	0.88	17.63	65.59
J32E	63.8	971.15	6.57		2281.87	7798.08	3.42	68.35	254.26
J33A	173.77	449.46	38.66		2117.43	2040.19	0.96	19.27	71.69
J33B	220.15	590.72	37.27		1994.65	2433.52	1.22	24.40	90.77
J33C	98.83	427.93	23.09		1413.29	1084.98	0.77	15.35	57.12
J33D	93.3	258.86	36.04		1806.05	891.35	0.49	9.87	36.72
J33E	115.94	328.67	35.28		1371.41	660.38	0.48	9.63	35.83
J33F	47.69	365.62	13.04		1044.42	572.42	0.55	10.96	40.78
J34A	220.05	252.19	87.26		1490.92	117.92	0.08	1.58	5.88
J34B	211.37	341.55	61.89	1.7×10^{-6}	1711.90	629.70	0.37	7.36	27.37
J34C	243.29	318.90	76.29		1853.04	428.53	0.23	4.63	17.21
J34D	179.09	354.20	50.56		1744.18	879.27	0.50	10.08	37.51
J34E	120.72	257.98	46.79		1486.79	500.81	0.34	6.74	25.06
J34F	85.65	319.96	26.77		1243.55	598.06	0.48	9.62	35.78
J35A	96.55	427.35	22.59		672.15	246.68	0.37	7.34	27.30
J35B	237.24	651.13	36.44		1090.54	812.45	0.75	14.90	55.43
J35C	181.8	264.48	68.74		1343.06	246.16	0.18	3.67	13.64
J35D	46.64	506.95	9.20		751.23	428.77	0.57	11.42	42.46
J35E	29.52	215.16	13.72		1362.20	568.57	0.42	8.35	31.05
J35F	146.41	500.04	29.28		1357.43	1075.51	0.79	15.85	58.95
J40A	237.58	453.31	52.41		1672.66	996.22	0.60	11.91	44.31
K60A	161.46	161.46	100.00		1734.34	0.00	0.00	0.00	0.00
K60B	143.2	143.20	100.00		1642.36	0.00	0.00	0.00	0.00
Total	3925.6	10176.1	38.6			27458.9	16.0	319.8	1189.6

7.4 Discussion

The method adapted for estimation of total groundwater storage capacity in artesian aquifer was based on an assumption that the hydraulic property of artesian aquifer is consistent, with known thickness of artesian aquifer. In practice, the transmissivity (*T*) and storativity (*S*) of artesian aquifer at regional scale often vary with locations. To estimate groundwater storage capacity at regional scale, more aquifer tests at the sites in which there are flowing artesian boreholes need to be carried out to refine the *S* values.

It is known that the pressure head of artesian aquifer varies temporally and spatially. The artesian pressure decreased gradually between the outcrops of TMG aquifers (recharge zone) to the artesian site. To evaluate available pressurized storage in artesian aquifer, the pressure head of artesian aquifer which is above ground surface is assumed to be constant.

Groundwater level behaviour at artesian aquifer is quite different from unconfined aquifer. Groundwater levels in artesian aquifers are very sensitive to changes in storage. Storage of artesian aquifer is much lower because it is not drained during pumping, and any water released from storage is obtained primarily by compression of the aquifer and expansion of the water when pumped. The drawdown of artesian aquifer is relatively large compared to an unconfined aquifer when groundwater is abstracted from the aquifer.

Inasmuch as *S* of artesian aquifer is usually very small (0.01 or much smaller) compared with specific yield (S_y) of unconfined aquifer, when the same amount of water is released from an artesian aquifer, the drawdown will be much more than in the unconfined aquifer.

In practice not all the storage (both total groundwater storage capacity and available pressurized storage) can be accessed. Natural discharge of flowing artesian borehole at different artesian sites can be significantly different. The wide range in flow rates is the result of many factors, including the thickness and permeability of the aquifer, construction of the well, the valve-gear, amount of shut-in artesian head, which in turn is dependent in part upon the length of time the borehole was shut-in and upon the relative heads in several aquifers that supply some boreholes. In a location in which there are many free-flowing artesian boreholes flowing at the same time, discharge will decrease significantly.

7.5 Summary

So far, quantification of groundwater storage capacity in TMG aquifers was completed at large scale. Storativity values adopted in the method were generalized from the various studies, including three scenarios, i.e. low, medium and high storativity value. Few studies of evaluation of groundwater storage capacity in artesian aquifer were conducted in locations where the pressure head is above ground surface. An assessment on this resource is very necessary for future utilization and management.

Groundwater storage capacity in artesian aquifer is evaluated at local scale based on the assumptions that the outcrops of TMG are considered as recharge zone and the Peninsula Aquifer (non-outcrop of TMG) below the Cedarberg Formation and Nardouw Aquifer as artesian aquifer. Specific storage of artesian aquifer at local scale is assumed as a constant value, which was derived from the aquifer test conducted on flowing artesian boreholes. Thickness of artesian aquifer generated using GIS for the whole TMG area by Jia (2007), was used for groundwater storage capacity of artesian aquifer.

The total groundwater storage capacity of artesian aquifer is 1.84×10^7 m^3 in Rawsonville, with available pressurized storage of the artesian aquifer in Rawsonville estimated as 4.11×10^5 m^3, which is only 2.08% of its total groundwater storage capacity. The total groundwater storage capacity of the artesian aquifer in Oudtshoorn area is estimated as 2.45×10^{10} m^3, with available pressurized storage approximately 1.19×10^9 m^3, which is 4.86% of its total groundwater storage capacity. These values may be conservative figures because as artesian pressure declines, the hydraulic gradient through the confining beds between the artesian aquifer and the overlying unconfined aquifer (Nardouw Aquifer) in places may be reversed. Thus, the artesian aquifer may receive additional recharge from the beds directly above.

Chapter 8
Guideline for hydraulic testing in artesian aquifer

8.1 Introduction

Analysing and evaluating pumping test data is as much an art as a science (Kruseman and De Ridder, 1991). It is a science because it is based on the theoretical models that the geologist or engineer must understand and on thorough investigations that one must conduct into the geological formations in the area of the test. It is acknowledged that different types of aquifers can exhibit similar drawdown behaviours, which demand interpretational skills on the part of the geologist or engineer. Basic concepts and terms of pumping test have been well elaborated in numerous publications. Some of the articles focus on the analysis and evaluation of pumping test data from a variety of aquifer types or aquifer systems, and from tests conducted under particular technical conditions (Lohman, 1979; Kruseman and Ridder, 1990). These publications provide guidance for conducting the pumping test at field site, development of a conceptual model and selection of an analytical test method for determination of hydraulic properties. However, no specific guideline or procedures for determining the hydraulic properties of strong artesian aquifer in TMG are made available.

In this chapter, a guideline is documented, which offers a set of instructions to evaluate hydraulic properties of strong artesian aquifer. Field procedures for conducting an aquifer test on a borehole drilled into the aquifer that is flowing, that is, the head of the borehole remains above the top of the borehole casing, are described. Method for data collection (discharge rate and pressure head) using the developed hydraulic test device during the test period was highlighted.

8.2 Apparatus setup

A hydraulic test device was developed to capture the aquifer test data at flowing artesian boreholes (Sun and Xu, 2014). Besides the device developed for this study, various types of equipment could also be used to measure the flow rate of artesian borehole and pressure during the recovery phase. The apparatus shall be placed on the artesian borehole discharge line such that the borehole can be shut in to prevent flow prior to conducting this field procedure and so that the apparatus will not constrict flow from the borehole when it is allowed to flow.

The procedures for installing the apparatus have been depicted in section 4.3. Parameters, including the pipe material, diameter, ranges and units etc., need to be entered into the test unit before conducting the test.

8.3 Procedures of hydraulic testing

8.3.1 Pre-test procedures

- Make a field reconnaissance of the site before conducting the test to collect as much detail as possible on the depth, continuity, extent and preliminary estimates of the hydrologic properties of the aquifers and confining beds. The information of other existing boreholes or conveying structures that might interfere with the test needs to be described as well. Turn off nearby boreholes and monitor the water levels before the test. Alternately, it may be necessary to pump some nearby boreholes to find out whether the artesian aquifer is connected to the same aquifers. In order to set up the range of flow rate for the device, it is necessary to do a short free-flowing test in artesian borehole to find out the ranges of flow rate. The artesian borehole should be equipped with a pipeline or conveyance structure adequate to transmit water away from the test site, so that the structure will not influence the flow of water from the artesian borehole.

- Measure the hydraulic pressure in the shut-in artesian borehole and all the other observation boreholes (if any) to determine the trend of water levels before the commencement of the test.
- Test the artesian borehole by allowing the borehole to flow and then stop the flow. Based on the recovery response, make a preliminary estimate of the hydraulic properties of the aquifer and estimate the initial flow rate from the artesian borehole expected during the aquifer test.
- Observation boreholes or piezometers need to be tested prior to the aquifer test to ensure that they are hydraulically connected to the aquifer. Accomplish this by withdrawing the water from artesian borehole and measure water-level or pressure response in other boreholes. The resultant response should be rapid enough to ensure that the water level in the observation borehole or piezometer will reflect the water level in the aquifer during the test. A conceptual model is necessary to be built up for better understanding the flow dynamics of aquifer.

8.3.2 Test procedures

The pre-test results and the conceptual model of the site will provide valuable information to determine the duration of the test. The duration may vary from a couple of hours to several days. The flow from the artesian borehole needs to be stopped completely prior to conducting the test for a period at least as long as the anticipated duration of the flowing portion of the test.

The constant drawdown needs to be achieved and maintained stable as soon as possible. Therefore, the pressure head above ground level is priority to accommodate measuring the flow rate accurately by apparatus if the flow rate is not too high. In such case, laborious work of adjusting the tap or valve can be avoided to maintain the constant head.

The discharge rate needs to be measured frequently during the early phase of discharge. The interval between may be increased as test continues. After the free-flowing test stops, the hydraulic pressure needs to be measured during the recovery test. According to the standard proposed by American Society for Testing and Materials (ASTM), suggested frequency of discharge rate and pressure measurements is listed in Table 8.1.

Table 8.1: Example of measurements frequency for artesian aquifer test (ASTM: D5786-95)

Frequency (1 measurement every)	**Elapsed time**
30 s	3 min
1 min	3 to 15 min
5 min	15 to 60 min
10 min	60 to 120 min
20 min	2 to 3 hrs
1 hr	3 to 15 hrs
5 hrs	15 to 60 hrs

8.3.3 Post-test procedures

- Tabulate the water level or hydraulic pressure, including the pre-test flowing, free-flowing and post-flowing levels. For observation borehole or piezometer, record the date, clock time, time since flowing started or stopped, and the measurement point.
- Tabulate the rate of discharge of the artesian borehole, the date, clock time, time since flowing started or stopped and the method of measurement.

- Prepare the description of each borehole, describing the measuring point, its elevation and the method of obtaining the elevation and the distance of the measuring point above the mean land surface.
- Prepare a plot of the rate of discharge versus time (semi-log paper) since discharge began, and plot the rate of the discharge pressure versus time. Plot the hydraulic pressure changes versus *t*/*t*' (semi-log paper) since the free-flowing test ceases. The data can be interpreted by appropriate methods using semi-log paper. Alternatively, it can be interpreted with the software described in Chapter 5.

8.4 Drafting report

Drafting a report containing field data, a description of the field site, plots of water level and discharge rate with time and the preliminary analysis of data, is necessary. It should start with an introduction stating the purpose of the test, the site information, weather, date and time the artesian borehole was shut in, date and time of free-flowing test and recovery test.

Prepare a map of the site showing all borehole locations, the distances among boreholes and the locations of all geologic boundaries or surface-water bodies which might affect the test. The locations of boreholes and boundaries that affect the aquifer tests need to be known with sufficient accuracy to provide a valid analysis. For most analyses, this means that the locations must provide data points within the plotting accuracy on the semi-log or log-log graph paper used for analysis. Radial distances from the artesian borehole to the observation boreholes usually need to be known with an accuracy of ± 0.5%. For prolonged large scale testing, it may be sufficient to locate boreholes from maps or aerial photographs. However, for the small scale tests, borehole locations should be surveyed using land surveying methods.

Data analysis needs to be done using appropriate methods following the data collection and conceptual model development. Conclusion can be drawn with the results. The tabulated field data collected during the test should be attached as appendixes at the end of the report.

8.5 Summary

When pressure in artesian aquifer is above ground surface, boreholes drilled into the aquifer will flow naturally without the need for pumping. Flowing aquifer test at flowing artesian borehole is preferred over conventional pumping test with pumping. Data collection, conceptual model development and appropriate analytical model selection for flowing artesian boreholes differ from the conventional constant-rate test. A guideline was developed to address this issue.

The procedure to conduct an aquifer test at a flowing artesian borehole was outlined. A pre-test of flowing artesian borehole can be conducted to find out whether the artesian aquifer is connected to the other aquifers (monitoring the boreholes drilled into underneath and upper aquifers). The ranges of discharge rate can also be determined to set up apparatus through pre-test.

During the free-flowing test period, discharge rate and pressure readings need to be as accurate as possible. A hydraulic test device to capture such data was recommended. Data interpretation and report drafting on evaluation of hydraulic properties of artesian aquifer need be completed from the data analysis.

Chapter 9
Conclusions and recommendations

9.1 Summary

There are approximately 37 flowing artesian boreholes in the whole TMG area. All these boreholes are mainly located in 5 out of the 15 hydrogeological units. In the past few years, there were limited studies on characterising artesian aquifers in TMG in which the pressure head is above ground surface. Previous studies focused on hydraulic pressure monitoring, conceptual model development and/or aquifer test data collection manually. No comprehensive methodology was developed to test and evaluate the artesian aquifer in TMG. In this study, hydraulic testing and evaluation of artesian aquifers in TMG aquifers are developed and demonstrated with two case studies, followed by storage determination in artesian aquifer using the *S* value derived from aquifer test analysis. All these values can be considered at local and intermediate scales.

A guideline was documented, which offers a set of instructions to evaluate hydraulic properties of strong artesian aquifer. The guideline could also be used as a reference for flowing artesian tests in similar conditions, e.g. to flowing artesian boreholes in the Karoo.

Hydraulic test device for data collection

In this study, an ultrasonic flow meter and pressure transmitter are jointly used as a hydraulic test device, which was applied at a flowing artesian borehole to capture flow rate and hydraulic pressure during free-flowing and recovery tests. Sufficient preparations are necessary to enhance the accuracy of the captured data. The preparations for applying the device on other flowing artesian holes include selection of a right size of straight pipe linking to it and related parameter inputs to the ultrasonic flow meter and data logger. Final check needs to be done before conducting the test. The sampling interval can be set for any durations such as 30 seconds, 1 minute, 2 minutes, 5 minutes or 10 minutes.

The hydraulic test device for free-flowing artesian boreholes was conceptualised and developed, and applied at the flowing artesian boreholes in the TMG aquifers. The test device, designed to measure the flow rate and pressure head simultaneously during the aquifer test, was demonstrated for medium artesian conditions. The flow rates captured by the device at the flowing artesian hole in Rawsonville were reliable and accurate compared with the data collected manually on the same borehole. The data were utilised to evaluate the aquifer properties.

Hydraulic properties of artesian aquifers in TMG

So far, a wealth of estimates of hydraulic properties of TMG aquifers is available at a lot of sites except for the artesian where the hydraulic heads are above local ground level. There are at least 37 flowing artesian holes in TMG area, which are located in Bokkeveldberg, Worcester-Grabouw, Oudtshoorn-Georage and Uitenhage groundwater subareas.

Based on the analytical methods, a program was developed in Excel spreadsheets using VBA to analyse the free-flowing and recovery tests data. Free-flowing and recovery tests data from a single borehole in Rawsonville and test borehole with an observation hole in Oudtshoorn were analysed and interpreted with the developed program.

In addition, diagnostic plot method using reciprocal rate derivative to interpret flow rate data from free-flowing test at a flowing artesian borehole was reviewed. The approach could help identify the flow regimes and discern the boundary conditions, which results provide useful information to conceptualize the aquifer and facilitate an appropriate analytical method to evaluate the aquifer properties using reciprocal rate and reciprocal rate derivative. Since the reciprocal rate derivative is more sensitive to rate variations than the reciprocal rate, it is necessary to eliminate noise. Methods to eliminate rate noise and reciprocal rate derivative noise were discussed. It is recommended that raw flow data be smoothed prior to calculating reciprocal rate derivative.

The aquifer tests data from Rawsonville and Oudtshoorn were analysed using the program and the diagnostic plot method. The results from these two case studies indicate that a negative skin zones exists surrounding the test boreholes. Skin factors ranging from -3 to -2 with effective radius ranging from 0.5 to 1.58 m were determined for artesian borehole BH-1 in Rawsonville; while the skin factor and effective radius of artesian borehole in Oudtshoorn are approximately -2.2 and 0.74 m, respectively.

The results from both cases further indicate that the aquifers are somehow bounded by no-flow conditions, especially in the case of Rawsonville where the recorded data supports this hypothesis. Generally the transmissivities of artesian aquifer in TMG ranges from 0.6 to 46.7 m^2/d based on calculations with recovery test data. Using the values of effective radius, the T value of the artesian aquifer in Rawsonville is estimated as 7.5 – 23 m^2/d, while the S value approximately 2.0×10^{-4} to 5.5×10^{-4}. The T value of the artesian aquifer in Oudtshoorn is approximately 36.6 m^2/d, with S value of 1.16×10^{-3}.

Diagnostic flow plots as an additional tool is illustrated to verify the results from analytical method in two case studies. Both results not only imply the existence of negative skin zone in the vicinity of the test boreholes, but also highlight the fact that the TMG aquifers are often bounded by impermeable faults at local or intermediate scale.

Storage determination in artesian aquifers in TMG

Groundwater storage capacity in artesian aquifer was evaluated at local scale based on the assumptions that the outcrops of TMG are considered as recharge zone and the Peninsula Aquifer (non-outcrop of TMG) below the Cedarberg Formation and Nardouw Aquifer as artesian aquifer. Specific storage of artesian aquifer (S_s) at local scale is assumed as a constant value, which was derived from the aquifer test conducted on the flowing artesian borehole. Thickness of artesian aquifer generated using GIS for the whole TMG area by Jia (2007), was used for groundwater storage capacity of the artesian aquifer.

The total groundwater storage capacity of the artesian aquifer in Rawsonville is 1.84×10^{7} m^3, with available pressurized storage of artesian aquifer estimated as 4.11×10^{5} m^3, which is only 2.08% of its total groundwater storage capacity. The total groundwater storage capacity of the artesian aquifer in Oudtshoorn area is estimated as 2.45×10^{10} m^3, with available pressurized storage approximately 1.19×10^{9} m^3, which is 4.86% of its total groundwater storage capacity. These values may be conservative because as artesian pressure declines, the hydraulic gradient through the confining layer between the artesian aquifers and the overlying unconfined aquifers (Nardouw Aquifer) in places may be reversed. Thus, the artesian aquifers may receive additional recharge from the layers directly above.

Guideline for hydraulic testing in artesian aquifer

A guideline was documented, which offers a set of instructions to evaluate hydraulic properties of strong artesian aquifers. Field procedures for conducting an aquifer test on a borehole drilled into the aquifer that is flowing are described. Procedure for data collection (discharge rate and pressure head) using the hydraulic test device during the test period was highlighted. The guideline can guide the practitioners to evaluate artesian aquifers through conducting aquifer tests at flowing artesian boreholes.

9.2 Recommendations

Based on this study, a number of topics for future and further research on artesian aquifers in TMG aquifers are suggested:

1. For the developed hydraulic test device, two probes to measure pH and EC were added to the device to capture additional water quality data, which would help better understanding the flow dynamics in the deep aquifer. Probes of temperature and other parameters may also be jointly used to improve the test device in future.

   The test device can be improved to be user-friendly. For instance, the external battery issue, it can be solved by including a lithium-ion battery or solar panels to the device, and the sensitivity of ultrasonic flow meter can be addressed through cautious adjustment of the location of the flowmeter transducers.
2. Transmissivity and storativity values of artesian aquifers in TMG were derived from aquifer tests conducted at limited flowing artesian boreholes. No comprehensive evaluation of hydraulic properties, especially storativity, of artesian TMG aquifers is made available at mega-scale. With hydraulic test device readily available, a number of aquifer tests can be carried out in other overflow artesian boreholes in TMG in future. Therefore it will be feasible to determine the hydraulic properties (transmissivity and storativity) of artesian aquifers at other sites.
3. Besides capturing test data in flowing artesian boreholes drilled in TMG, wider application of hydraulic test device in similar conditions like artesian holes in Karoo can also be realized in future.
4. Quantification of groundwater storage capacity in artesian aquifer in TMG was completed only at local or intermediate scales. The method adapted for storage determination in artesian aquifer was based on an assumption that the hydraulic property of artesian aquifer is consistent. In reality, the T and S values of artesian aquifer at regional scale often vary with locations. To increase the confidence level required for sustainable utilization, determination of groundwater resources in artesian aquifers in TMG should be carried out at mega-scale in the near future.
5. Numerical modelling is recommended, and should be very carefully used in evaluating groundwater problems in the fractured rock aquifers, because it is in most cases very difficult to determine the boundary conditions and the anisotropic features of a fractured aquifer body, water body (stream, lake, and so on), structural and lithologic boundaries.

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Appendix A Information of artesian boreholes in TMG aquifer system

Artesian	Primary catchment	Quaternary catchment	Lat	Long	BH depth or Ele* (m)	Ref
BH1	Bree	H10J	-33.7185	19.2462	270	Lin, 2007
D9		H60B	-34.0246	19.1103	340*	GEOSS, 2010
P1		H60B	-33.9526	19.1744	110/357*	
C3		H60A	-34.0569	19.0847	335*	
P5		G60B	-33.9510	19.1736	366*	
LT3	Berg	G10A	-33.8638	19.0452	104	
LPE1		G10D	-33.5285	19.0401	-	
A5		G40D	-34.2109	19.0036	288*	
BH4		G40D	-34.3263	18.9649	47/70*	
A4		G40D	-34.2309	19.1185	292*	
A11		G40A	-34.1508	18.9258	470*	
A1		G40A	-34.1558	18.9465	406*	
W7K1		G10B	-33.8229	19.0463	282*	
G40145		G30G	-32.1444	18.5208	> 800/120*	Lin, 2007
C1B3	Gouritz	J35B	-33.7344	22.2793	605/423*	UMVOTO, 2005
C1B2		J36B	-33.7341	22.2792	421	
GZ00335		J34F	-33.8038	22.4353	462	
GZ000339		J33E	-33.5870	22.5302	51	
71G	Swartkops	M10C	-33.7764	25.3306	202	Bush, 1985
72G		M11C	-33.7708	25.3233	200	
75G		M12C	-33.7708	25.3556	164	
20G		M13C	-33.8014	25.3403	157	
21G		M14C	-33.7889	25.3644	167	
1G		M15C	-33.7331	25.3083	258	
BK3	Olifants	E10E	-32.5514	19.0631	-	GEOSS, 2003
BK4		E10E	-32.5594	19.0594	-	
BK5		E10E	-32.5617	19.0558	-	
460/08		E10E	-32.5686	19.0274	-	
3219CA55		E10F	-32.5545	19.0169	-	
3219CA101		E10E	-32.6518	19.1359	-	
3219CA80		E10E	-32.5861	19.0784	-	
3219CA85		E10E	-32.6661	19.1078	-	
G40142		E10F	-32.3952	18.9592	801	
3219CC1000		E10D	-32.8614	19.1053	-	
3218DB5		E10F	-32.5686	18.9672	35	
3219CD1237		E21G	-32.8951	19.3565	35	
G40150		E10E	-32.5631	19.0556	350	

- Data is missing

Appendix B Free-flowing test conducted in borehole BH-1 in Rawsonville in TMG with data collected manually

Site: Rawsonville BH-1

Date: 18/03/2012

Weather: Sunny

Static WL: 94 kPa WL Kept as constant: 40 kPa Constant drawdown: 54 kPa (5.51 m)

Test started at: 13:40

Time (Min)	Actual time	yield(l/s)	Time filling the 15 L bucket (s)
1	13:41	1.071	14
3	13:43	1.000	15
4	13:44	1.000	15
5	13:45	1.000	15
6	13:46	1.000	15
7	13:47	0.938	16
8	13:48	0.938	16
9	13:49	0.938	16
10	13:50	0.938	16
15	13:55	0.938	16
20	14:00	0.938	16
25	14:05	0.882	17
30	14:10	0.882	17
35	14:15	0.882	17
40	14:20	0.882	17
45	14:25	0.833	18
50	14:30	0.833	18
55	14:35	0.833	18
60	14:40	0.789	19
65	14:45	0.750	20
70	14:50	0.714	21
80	15:00	0.714	21
85	15:05	0.682	22
90	15:10	0.652	23
95	15:15	0.652	23
100	15:20	0.625	24
105	15:25	0.625	24
110	15:30	0.600	25
115	15:35	0.536	28
120	15:40	0.536	28
130	15:50	0.517	29
140	16:00	0.500	30
145	16:05	0.469	32
158	16:18	0.455	33
166	16:26	0.455	33

170	16:30	0.441	34
180	16:40	0.429	35
192	16:52	0.417	36
200	17:00	0.417	36
220	17:20	0.417	36
230	17:30	0.417	36
240	17:40	0.417	36
336	19:16	0.385	39
352	19:32	0.333	45
370	19:50	0.319	47
380	20:00	0.263	57
400	20:20	0.263	57
420	20:40	0.259	58
440	21:00	0.250	60
455	21:15	0.254	59
484	21:44	0.227	66
510	22:10	0.234	64
530	22:30	0.221	68
560	23:00	0.200	75
575	23:15	0.192	78
590	23:30	0.197	76
610	23:50	0.192	78
630	00:10	0.190	79
1055	07:25	0.133	113
1090	08:00	0.133	113

Appendix C Free-flowing and recovery tests conducted in borehole BH-1 in Rawsonville in TMG with data captured by the hydraulic test device

Site: Rawsonville BH-1

Date: 12/11/2012

Weather: Sunny

Static WL: 73.8 kPa Constant drawdown: 73.8 kPa (7.53 m)

Test started at: 13:40

Date and time	Time (mins)	flow rate (l/min)	Date and time	Time (mins)	Pressure (kPa)
2012/11/12 16:12	0.5	75.8	2012/11/12 23:06	414	13
2012/11/12 16:13	1	70.1	2012/11/12 23:06	414.5	14.3
2012/11/12 16:13	1.5	68.5	2012/11/12 23:07	415	15
2012/11/12 16:14	2	65.5	2012/11/12 23:07	415.5	15.6
2012/11/12 16:14	2.5	62.7	2012/11/12 23:08	416	16
2012/11/12 16:15	3	62	2012/11/12 23:08	416.5	16.3
2012/11/12 16:15	3.5	62.7	2012/11/12 23:09	417	16.6
2012/11/12 16:16	4		2012/11/12 23:09	417.5	16.8
2012/11/12 16:16	4.5		2012/11/12 23:10	418	17
2012/11/12 16:17	5	59.5	2012/11/12 23:10	418.5	17.2
2012/11/12 16:17	5.5	56.8	2012/11/12 23:11	419	17.4
2012/11/12 16:18	6		2012/11/12 23:11	419.5	17.6
2012/11/12 16:18	6.5		2012/11/12 23:12	420	17.7
2012/11/12 16:19	7		2012/11/12 23:12	420.5	17.9
2012/11/12 16:19	7.5		2012/11/12 23:13	421	18
2012/11/12 16:20	8	55	2012/11/12 23:13	421.5	18.1
2012/11/12 16:20	8.5	60.4	2012/11/12 23:14	422	18.2
2012/11/12 16:21	9		2012/11/12 23:14	422.5	18.4
2012/11/12 16:21	9.5		2012/11/12 23:15	423	18.5
2012/11/12 16:22	10		2012/11/12 23:15	423.5	18.6
2012/11/12 16:22	10.5		2012/11/12 23:16	424	18.7
2012/11/12 16:23	11		2012/11/12 23:16	424.5	18.8
2012/11/12 16:23	11.5		2012/11/12 23:17	425	18.9
2012/11/12 16:24	12	55.1	2012/11/12 23:17	425.5	19
2012/11/12 16:24	12.5	55	2012/11/12 23:18	426	19.1
2012/11/12 16:25	13	53.3	2012/11/12 23:18	426.5	19.2
2012/11/12 16:25	13.5	53.3	2012/11/12 23:19	427	19.3
2012/11/12 16:26	14	51.6	2012/11/12 23:19	427.5	19.3
2012/11/12 16:26	14.5	52.1	2012/11/12 23:20	428	19.5
2012/11/12 16:27	15	52.7	2012/11/12 23:20	428.5	19.5
2012/11/12 16:27	15.5	53.7	2012/11/12 23:21	429	19.6
2012/11/12 16:28	16	52.3	2012/11/12 23:21	429.5	19.7
2012/11/12 16:28	16.5	56.9	2012/11/12 23:22	430	19.8

2012/11/12 16:29	17	53.6	2012/11/12 23:22	430.5	19.8
2012/11/12 16:29	17.5	57.2	2012/11/12 23:23	431	19.9
2012/11/12 16:30	18	57.7	2012/11/12 23:23	431.5	20
2012/11/12 16:30	18.5	53.6	2012/11/12 23:24	432	20.1
2012/11/12 16:31	19	54.1	2012/11/12 23:24	432.5	20.1
2012/11/12 16:31	19.5	58	2012/11/12 23:25	433	20.2
2012/11/12 16:32	20	55.8	2012/11/12 23:25	433.5	20.3
2012/11/12 16:32	20.5	56	2012/11/12 23:26	434	20.3
2012/11/12 16:33	21	54.4	2012/11/12 23:26	434.5	20.4
2012/11/12 16:33	21.5	51	2012/11/12 23:27	435	20.5
2012/11/12 16:34	22		2012/11/12 23:27	435.5	20.5
2012/11/12 16:34	22.5		2012/11/12 23:28	436	20.6
2012/11/12 16:35	23	59.9	2012/11/12 23:28	436.5	20.7
2012/11/12 16:35	23.5	58.3	2012/11/12 23:29	437	20.7
2012/11/12 16:36	24	58.2	2012/11/12 23:29	437.5	20.8
2012/11/12 16:36	24.5	57.6	2012/11/12 23:30	438	20.8
2012/11/12 16:37	25	57.3	2012/11/12 23:30	438.5	20.9
2012/11/12 16:37	25.5	58.8	2012/11/12 23:31	439	21
2012/11/12 16:38	26	51.2	2012/11/12 23:31	439.5	21
2012/11/12 16:38	26.5	47.4	2012/11/12 23:32	440	21.1
2012/11/12 16:39	27	57.5	2012/11/12 23:32	440.5	21.2
2012/11/12 16:39	27.5	58	2012/11/12 23:33	441	21.2
2012/11/12 16:40	28	45.3	2012/11/12 23:33	441.5	21.3
2012/11/12 16:40	28.5	49.7	2012/11/12 23:34	442	21.3
2012/11/12 16:41	29	49.9	2012/11/12 23:34	442.5	21.4
2012/11/12 16:41	29.5	49.1	2012/11/12 23:35	443	21.5
2012/11/12 16:42	30	48.8	2012/11/12 23:35	443.5	21.5
2012/11/12 16:42	30.5	49.8	2012/11/12 23:36	444	21.6
2012/11/12 16:43	31	49.1	2012/11/12 23:36	444.5	21.6
2012/11/12 16:43	31.5	48.3	2012/11/12 23:37	445	21.7
2012/11/12 16:44	32	48.8	2012/11/12 23:37	445.5	21.7
2012/11/12 16:44	32.5	48.8	2012/11/12 23:38	446	21.8
2012/11/12 16:45	33	49.1	2012/11/12 23:38	446.5	21.9
2012/11/12 16:45	33.5	49.2	2012/11/12 23:39	447	21.9
2012/11/12 16:46	34	49.1	2012/11/12 23:39	447.5	22
2012/11/12 16:46	34.5	48.7	2012/11/12 23:40	448	22
2012/11/12 16:47	35	48.5	2012/11/12 23:40	448.5	22.1
2012/11/12 16:47	35.5	48.4	2012/11/12 23:41	449	22.1
2012/11/12 16:48	36	49	2012/11/12 23:41	449.5	22.2
2012/11/12 16:48	36.5	48.1	2012/11/12 23:42	450	22.2
2012/11/12 16:49	37	48.8	2012/11/12 23:42	450.5	22.3
2012/11/12 16:49	37.5	48.6	2012/11/12 23:43	451	22.3
2012/11/12 16:50	38	48.5	2012/11/12 23:43	451.5	22.4
2012/11/12 16:50	38.5	48.6	2012/11/12 23:44	452	22.4
2012/11/12 16:51	39	49.1	2012/11/12 23:44	452.5	22.5

2012/11/12 16:51	39.5	48.7
2012/11/12 16:52	40	48.2
2012/11/12 16:52	40.5	48.7
2012/11/12 16:53	41	48.2
2012/11/12 16:53	41.5	48.2
2012/11/12 16:54	42	48.3
2012/11/12 16:54	42.5	48.4
2012/11/12 16:55	43	48.3
2012/11/12 16:55	43.5	47.6
2012/11/12 16:56	44	47.9
2012/11/12 16:56	44.5	47.6
2012/11/12 16:57	45	47.8
2012/11/12 16:57	45.5	47.8
2012/11/12 16:58	46	48.3
2012/11/12 16:58	46.5	48
2012/11/12 16:59	47	48.1
2012/11/12 16:59	47.5	47.7
2012/11/12 17:00	48	47.4
2012/11/12 17:00	48.5	47.6
2012/11/12 17:01	49	47.4
2012/11/12 17:01	49.5	47.3
2012/11/12 17:02	50	47
2012/11/12 17:02	50.5	47.3
2012/11/12 17:03	51	47.1
2012/11/12 17:03	51.5	47.3
2012/11/12 17:04	52	46.9
2012/11/12 17:04	52.5	46.9
2012/11/12 17:05	53	47.7
2012/11/12 17:05	53.5	47.5
2012/11/12 17:06	54	47.2
2012/11/12 17:06	54.5	47
2012/11/12 17:07	55	47.1
2012/11/12 17:07	55.5	46.8
2012/11/12 17:08	56	45.9
2012/11/12 17:08	56.5	46.4
2012/11/12 17:09	57	46.2
2012/11/12 17:09	57.5	46.5
2012/11/12 17:10	58	46.2
2012/11/12 17:10	58.5	46.4
2012/11/12 17:11	59	46.2
2012/11/12 17:11	59.5	45.5
2012/11/12 17:12	60	46.2
2012/11/12 17:12	60.5	46.4
2012/11/12 17:13	61	45.5
2012/11/12 17:13	61.5	45.9

2012/11/12 23:45	453	22.5
2012/11/12 23:45	453.5	22.6
2012/11/12 23:46	454	22.7
2012/11/12 23:46	454.5	22.7
2012/11/12 23:47	455	22.7
2012/11/12 23:47	455.5	22.8
2012/11/12 23:48	456	22.8
2012/11/12 23:48	456.5	22.9
2012/11/12 23:49	457	23
2012/11/12 23:49	457.5	23
2012/11/12 23:50	458	23
2012/11/12 23:50	458.5	23.1
2012/11/12 23:51	459	23.1
2012/11/12 23:51	459.5	23.2
2012/11/12 23:52	460	23.2
2012/11/12 23:52	460.5	23.3
2012/11/12 23:53	461	23.3
2012/11/12 23:53	461.5	23.4
2012/11/12 23:54	462	23.4
2012/11/12 23:54	462.5	23.5
2012/11/12 23:55	463	23.5
2012/11/12 23:55	463.5	23.6
2012/11/12 23:56	464	23.6
2012/11/12 23:56	464.5	23.6
2012/11/12 23:57	465	23.7
2012/11/12 23:57	465.5	23.7
2012/11/12 23:58	466	23.8
2012/11/12 23:58	466.5	23.8
2012/11/12 23:59	467	23.9
2012/11/12 23:59	467.5	23.9
2012/11/13 00:00	468	23.9
2012/11/13 00:00	468.5	24
2012/11/13 00:01	469	24
2012/11/13 00:01	469.5	24.1
2012/11/13 00:02	470	24.1
2012/11/13 00:02	470.5	24.2
2012/11/13 00:03	471	24.2
2012/11/13 00:03	471.5	24.3
2012/11/13 00:04	472	24.3
2012/11/13 00:04	472.5	24.3
2012/11/13 00:05	473	24.4
2012/11/13 00:05	473.5	24.4
2012/11/13 00:06	474	24.5
2012/11/13 00:06	474.5	24.5
2012/11/13 00:07	475	24.5

2012/11/12 17:14	62	46.2	2012/11/13 00:07	475.5	24.6
2012/11/12 17:14	62.5	45	2012/11/13 00:08	476	24.6
2012/11/12 17:15	63	45.3	2012/11/13 00:08	476.5	24.7
2012/11/12 17:15	63.5	45.2	2012/11/13 00:09	477	24.7
2012/11/12 17:16	64	44.9	2012/11/13 00:09	477.5	24.8
2012/11/12 17:16	64.5	45.5	2012/11/13 00:10	478	24.8
2012/11/12 17:17	65	45.1	2012/11/13 00:10	478.5	24.8
2012/11/12 17:17	65.5	44.2	2012/11/13 00:11	479	24.9
2012/11/12 17:18	66	44.7	2012/11/13 00:11	479.5	24.9
2012/11/12 17:18	66.5	44.4	2012/11/13 00:12	480	25
2012/11/12 17:19	67	44.3	2012/11/13 00:12	480.5	25
2012/11/12 17:19	67.5	44.8	2012/11/13 00:13	481	25.1
2012/11/12 17:20	68	44.7	2012/11/13 00:13	481.5	25.1
2012/11/12 17:20	68.5	44.8	2012/11/13 00:14	482	25.1
2012/11/12 17:21	69	44	2012/11/13 00:14	482.5	25.2
2012/11/12 17:21	69.5	44.1	2012/11/13 00:15	483	25.2
2012/11/12 17:22	70	44.2	2012/11/13 00:15	483.5	25.2
2012/11/12 17:22	70.5	43.8	2012/11/13 00:16	484	25.3
2012/11/12 17:23	71	43.6	2012/11/13 00:16	484.5	25.3
2012/11/12 17:23	71.5	42.4	2012/11/13 00:17	485	25.4
2012/11/12 17:24	72	43.6	2012/11/13 00:17	485.5	25.4
2012/11/12 17:24	72.5	43.6	2012/11/13 00:18	486	25.4
2012/11/12 17:25	73	43.8	2012/11/13 00:18	486.5	25.5
2012/11/12 17:25	73.5	43.8	2012/11/13 00:19	487	25.5
2012/11/12 17:26	74	43.1	2012/11/13 00:19	487.5	25.6
2012/11/12 17:26	74.5	43.8	2012/11/13 00:20	488	25.6
2012/11/12 17:27	75	43.1	2012/11/13 00:20	488.5	25.6
2012/11/12 17:27	75.5	43.2	2012/11/13 00:21	489	25.7
2012/11/12 17:28	76	43.6	2012/11/13 00:21	489.5	25.7
2012/11/12 17:28	76.5	42.7	2012/11/13 00:22	490	25.7
2012/11/12 17:29	77	42.8	2012/11/13 00:22	490.5	25.8
2012/11/12 17:29	77.5	43	2012/11/13 00:23	491	25.8
2012/11/12 17:30	78	42.4	2012/11/13 00:23	491.5	25.9
2012/11/12 17:30	78.5	43.3	2012/11/13 00:24	492	25.9
2012/11/12 17:31	79	42.8	2012/11/13 00:24	492.5	26
2012/11/12 17:31	79.5	41.9	2012/11/13 00:25	493	26
2012/11/12 17:32	80	42.4	2012/11/13 00:25	493.5	26
2012/11/12 17:32	80.5	42.1	2012/11/13 00:26	494	26.1
2012/11/12 17:33	81	42.8	2012/11/13 00:26	494.5	26.1
2012/11/12 17:33	81.5	42.2	2012/11/13 00:27	495	26.1
2012/11/12 17:34	82	42.2	2012/11/13 00:27	495.5	26.2
2012/11/12 17:34	82.5	41.8	2012/11/13 00:28	496	26.2
2012/11/12 17:35	83	42	2012/11/13 00:28	496.5	26.2
2012/11/12 17:35	83.5	41	2012/11/13 00:29	497	26.3
2012/11/12 17:36	84	41.5	2012/11/13 00:29	497.5	26.3

2012/11/12 17:36	84.5	40.8	2012/11/13 00:30	498	26.4
2012/11/12 17:37	85	41.2	2012/11/13 00:30	498.5	26.4
2012/11/12 17:37	85.5	41.9	2012/11/13 00:31	499	26.4
2012/11/12 17:38	86	41.3	2012/11/13 00:31	499.5	26.5
2012/11/12 17:38	86.5	41.7	2012/11/13 00:32	500	26.5
2012/11/12 17:39	87	41.6	2012/11/13 00:32	500.5	26.5
2012/11/12 17:39	87.5	41.4	2012/11/13 00:33	501	26.6
2012/11/12 17:40	88	40.7	2012/11/13 00:33	501.5	26.6
2012/11/12 17:40	88.5	41.1	2012/11/13 00:34	502	26.6
2012/11/12 17:41	89	39.7	2012/11/13 00:34	502.5	26.7
2012/11/12 17:41	89.5	41.3	2012/11/13 00:35	503	26.7
2012/11/12 17:42	90	39.6	2012/11/13 00:35	503.5	26.8
2012/11/12 17:42	90.5	40.4	2012/11/13 00:36	504	26.8
2012/11/12 17:43	91	40.1	2012/11/13 00:36	504.5	26.8
2012/11/12 17:43	91.5	39.4	2012/11/13 00:37	505	26.9
2012/11/12 17:44	92	40.4	2012/11/13 00:37	505.5	26.9
2012/11/12 17:44	92.5	39.4	2012/11/13 00:38	506	26.9
2012/11/12 17:45	93	39.4	2012/11/13 00:38	506.5	27
2012/11/12 17:45	93.5	39.9	2012/11/13 00:39	507	27
2012/11/12 17:46	94	40.4	2012/11/13 00:39	507.5	27
2012/11/12 17:46	94.5	39.1	2012/11/13 00:40	508	27.1
2012/11/12 17:47	95	39.5	2012/11/13 00:40	508.5	27.1
2012/11/12 17:47	95.5	41	2012/11/13 00:41	509	27.1
2012/11/12 17:48	96	38.9	2012/11/13 00:41	509.5	27.2
2012/11/12 17:48	96.5	41.9	2012/11/13 00:42	510	27.2
2012/11/12 17:49	97	40.9	2012/11/13 00:42	510.5	27.3
2012/11/12 17:49	97.5		2012/11/13 00:43	511	27.3
2012/11/12 17:50	98		2012/11/13 00:43	511.5	27.3
2012/11/12 17:50	98.5		2012/11/13 00:44	512	27.4
2012/11/12 17:51	99		2012/11/13 00:44	512.5	27.4
2012/11/12 17:51	99.5		2012/11/13 00:45	513	27.4
2012/11/12 17:52	100		2012/11/13 00:45	513.5	27.5
2012/11/12 17:52	100.5		2012/11/13 00:46	514	27.5
2012/11/12 17:53	101		2012/11/13 00:46	514.5	27.5
2012/11/12 17:53	101.5		2012/11/13 00:47	515	27.5
2012/11/12 17:54	102		2012/11/13 00:47	515.5	27.6
2012/11/12 17:54	102.5		2012/11/13 00:48	516	27.6
2012/11/12 17:55	103		2012/11/13 00:48	516.5	27.7
2012/11/12 17:55	103.5		2012/11/13 00:49	517	27.7
2012/11/12 17:56	104		2012/11/13 00:49	517.5	27.7
2012/11/12 17:56	104.5		2012/11/13 00:50	518	27.8
2012/11/12 17:57	105		2012/11/13 00:50	518.5	27.8
2012/11/12 17:57	105.5		2012/11/13 00:51	519	27.8
2012/11/12 17:58	106		2012/11/13 00:51	519.5	27.9
2012/11/12 17:58	106.5		2012/11/13 00:52	520	27.9

2012/11/12 17:59	107		2012/11/13 00:52	520.5	27.9
2012/11/12 17:59	107.5		2012/11/13 00:53	521	28
2012/11/12 18:00	108		2012/11/13 00:53	521.5	28
2012/11/12 18:00	108.5		2012/11/13 00:54	522	28
2012/11/12 18:01	109		2012/11/13 00:54	522.5	28.1
2012/11/12 18:01	109.5		2012/11/13 00:55	523	28.1
2012/11/12 18:02	110		2012/11/13 00:55	523.5	28.1
2012/11/12 18:02	110.5		2012/11/13 00:56	524	28.2
2012/11/12 18:03	111		2012/11/13 00:56	524.5	28.2
2012/11/12 18:03	111.5		2012/11/13 00:57	525	28.2
2012/11/12 18:04	112		2012/11/13 00:57	525.5	28.3
2012/11/12 18:04	112.5		2012/11/13 00:58	526	28.3
2012/11/12 18:05	113		2012/11/13 00:58	526.5	28.3
2012/11/12 18:05	113.5		2012/11/13 00:59	527	28.3
2012/11/12 18:06	114		2012/11/13 00:59	527.5	28.4
2012/11/12 18:06	114.5		2012/11/13 01:00	528	28.4
2012/11/12 18:07	115		2012/11/13 01:00	528.5	28.5
2012/11/12 18:07	115.5		2012/11/13 01:01	529	28.5
2012/11/12 18:08	116		2012/11/13 01:01	529.5	28.5
2012/11/12 18:08	116.5		2012/11/13 01:02	530	28.6
2012/11/12 18:09	117		2012/11/13 01:02	530.5	28.6
2012/11/12 18:09	117.5		2012/11/13 01:03	531	28.6
2012/11/12 18:10	118		2012/11/13 01:03	531.5	28.6
2012/11/12 18:10	118.5		2012/11/13 01:04	532	28.7
2012/11/12 18:11	119		2012/11/13 01:04	532.5	28.7
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2012/11/12 18:12	120		2012/11/13 01:05	533.5	28.8
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2012/11/12 22:19	367	11.8	2012/11/13 05:12	780.5	41
2012/11/12 22:19	367.5	12.2	2012/11/13 05:13	781	41
2012/11/12 22:20	368	11.5	2012/11/13 05:13	781.5	41
2012/11/12 22:20	368.5	11.7	2012/11/13 05:14	782	41
2012/11/12 22:21	369	11.9	2012/11/13 05:14	782.5	41
2012/11/12 22:21	369.5	11.6	2012/11/13 05:15	783	41.1
2012/11/12 22:22	370	11.4	2012/11/13 05:15	783.5	41.1
2012/11/12 22:22	370.5	11.3	2012/11/13 05:16	784	41.1
2012/11/12 22:23	371	11.5	2012/11/13 05:16	784.5	41.1
2012/11/12 22:23	371.5	11.6	2012/11/13 05:17	785	41.1
2012/11/12 22:24	372	11.4	2012/11/13 05:17	785.5	41.2
2012/11/12 22:24	372.5	11.1	2012/11/13 05:18	786	41.2
2012/11/12 22:25	373	11.4	2012/11/13 05:18	786.5	41.2
2012/11/12 22:25	373.5	11.4	2012/11/13 05:19	787	41.2
2012/11/12 22:26	374	11.3	2012/11/13 05:19	787.5	41.2
2012/11/12 22:26	374.5	10.8	2012/11/13 05:20	788	41.3
2012/11/12 22:27	375	11.6	2012/11/13 05:20	788.5	41.3
2012/11/12 22:27	375.5	11.3	2012/11/13 05:21	789	41.3
2012/11/12 22:28	376	10.7	2012/11/13 05:21	789.5	41.3
2012/11/12 22:28	376.5	10.6	2012/11/13 05:22	790	41.3

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2012/11/12 22:29	377.5	11.2
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2012/11/12 22:30	378.5	11.1
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2012/11/12 22:33	381.5	10.7
2012/11/12 22:34	382	10.1
2012/11/12 22:34	382.5	10.7
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2012/11/12 22:35	383.5	10.5
2012/11/12 22:36	384	10.4
2012/11/12 22:36	384.5	10.2
2012/11/12 22:37	385	9.8
2012/11/12 22:37	385.5	10.1
2012/11/12 22:38	386	10.5
2012/11/12 22:38	386.5	10.2
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2012/11/12 22:39	387.5	10.5
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2012/11/12 22:40	388.5	9.3
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2012/11/12 22:42	390.5	10.6
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2012/11/12 22:44	392.5	9.5
2012/11/12 22:45	393	9.6
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2012/11/12 22:46	394	9.5
2012/11/12 22:46	394.5	9.8
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2012/11/12 22:49	397	9.7
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2012/11/13 05:30	798.5	41.7
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2012/11/12 22:57	405	9
2012/11/12 22:57	405.5	9
2012/11/12 22:58	406	9
2012/11/12 22:58	406.5	9
2012/11/12 22:59	407	9
2012/11/12 22:59	407.5	9
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2012/11/12 23:00	408.5	9
2012/11/12 23:01	409	9
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2012/11/12 23:02	410	9
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2012/11/12 23:04	412.5	9
2012/11/12 23:05	413	9

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2012/11/13 05:45	813.5	42.2
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2012/11/13 05:46	814.5	42.2
2012/11/13 05:47	815	42.3
2012/11/13 05:47	815.5	42.3
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2012/11/13 05:49	817	42.3
2012/11/13 05:49	817.5	42.3
2012/11/13 05:50	818	42.4
2012/11/13 05:50	818.5	42.4
2012/11/13 05:51	819	42.4
2012/11/13 05:51	819.5	42.4
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2012/11/13 05:53	821.5	42.5
2012/11/13 05:54	822	42.5
2012/11/13 05:54	822.5	42.5
2012/11/13 05:55	823	42.5
2012/11/13 05:55	823.5	42.5
2012/11/13 05:56	824	42.6
2012/11/13 05:56	824.5	42.6
2012/11/13 05:57	825	42.6
2012/11/13 05:57	825.5	42.6
2012/11/13 05:58	826	42.7
2012/11/13 05:58	826.5	42.7