REPUBLIC OF ZAMBIA		FEDERAL REPUBLIC OF GERMANY
Ministry of Energy and Water Development	COOPERATION REPUBLIC OF ZAMBIA FEDERAL REPUBLIC OF GERMANY	Federal Institute for Geosciences and Natural Resources
ONE ZAMBIA ONE NATION		BGR

Development of a Groundwater Information & Management Program for the Lusaka Groundwater Systems

TECHNICAL NOTE NO. 8

RESULTS OF DRILLING AND TEST PUMPING AT SELECTED SITES IN KAFUE AND CHIBOMBO DISTRICTS

Roland Bäumle, Jim Anscombe, Chisanga Siwale & Andrea Nick

Lusaka, June 2012

Development of a Groundwater Information & Management Program for the Lusaka Groundwater Systems

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Commissioned by:	Federal Ministry for Economic Cooperation and Development (BMZ: Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung)
Project Numbers:	BMZ PN 2008.2125.6 (Phase II) BGR 05-2344-01
Implementing Agencies:	Ministry of Energy and Water Development, Department of Water Affairs, Lusaka Federal Institute for Geosciences and Natural Resources (BGR: Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover)
Pages:	121
Place and date of issuance:	Lusaka, June 2012

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Apr. 2009	Museteka L. & R. Bäumle	*Groundwater Chemistry of Springs and Water Supply Wells in Lusaka - Results of the sampling campaigns conducted in 2008*	Report No. 1
Oct. 2009	R. Bäumle. & S. Kang'omba	*Development of a Groundwater Information & Management Program for the Lusaka Groundwater System: Desk Study and Proposed Work Program Report*	Report No. 2
March 2010	Hahne K. & B. Shamboko-Mbale	*Karstification, Tectonics and Land Use in the Lusaka region*	Report No. 3
Oct. 2010	Mayerhofer C., Shamboko-Mbale B. & R.C. Mweene	*Survey on Commercial Farming and Major Industries: Land Use, Groundwater Abstraction & Potential Pollution Sources-*	Report No. 4
Aug. 2012	Hennings V.	*Assessment of annual percolation rates in the Lusaka region*	Report No. 5
Feb. 2008	Bäumle, R. & J. Nkhoma	*Preliminary Assessment of the Hydrogeological Situation around Lusaka South Local Forest Reserve No. 26*	Technical Note No. 1
Nov. 2010	Tena, T. & A. Nick	*Capacity Building and Awareness Raising Strategy for Phase II (2010-2012)*	Technical Note No. 2
Nov. 2010	Nick A., Museteka L. & Kringel R.	*Hydrochemical Sampling of Groundwater in the Lusaka Urban Area (April/May 2010) and Preliminary Findings*	Technical Note No. 3
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Apr. 2011	Kringel R., Fronius A., Museteka L. & A. Nick	*Assessment of CVOC- and BTEX-contamination level in Lusaka ground-water in 2010 based on developing and testing a method to sample and analyse groundwater containing organic volatile substances after extended storage*	Technical Note No. 5
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2012, in prep.	Krekeler T & C. Siwale	*Discharge measurements and rating curves*	Technical Note No. 7

Summary

Authors: Jim Anscombe (ANSCO Ground Water Ltd.), Dr. Roland Bäumle (BGR), Andrea Nick (BGR), Chisanga Siwale (DWA)

Title: Results of drilling and test pumping at selected sites in Kafue and Chibombo districts

Keywords: Cheta formation, Chunga Formation, Lusaka Dolomite Aquifer, step drawdown test, constant rate test, recovery test, water quality analysis,

At three sites in Lusaka Province production boreholes and piezometers were drilled and test-pumped to improve the hydrogeological data basis. The report gives an overview of the borehole siting, the drilling works and test pumping, the pumping test and the water quality analysis.

Executive Summary

The analysis of existing pumping test data from boreholes in the Lusaka and Central Province (Bäumle 2010) showed a lack of information in areas covered by Cheta limestones and schists of the Cheta and Chunga formation. It was therefore decided to drill boreholes and observation wells at three selected areas and to carry out multi-well pumping tests.

The identification of the drilling sites and the hydrogeological monitoring of the drilling and test pumping were carried out by an external supervisory consultant.

Site selection

The three target areas under investigation to the southwest and northwest of Lusaka were selected with respect to the geological formation, mapped faults and lineament and/or sinkholes traces in satellite imageries. They are occupied by Lusaka Dolomite (Kasanova), crystalline limestone of the Cheta Formation (Katete) and quartzite, schists and psammites of the Cheta Formation (Makeni) (Part A: Figure1, Table 2).

Field investigations included a hydrogeological reconnaissance survey and geophysical techniques. Suitable points for the test borehole and piezometers within the target areas have been determined applying geophysical techniques, i.e. EM profiling with a Max-Min unit in HLEM, Vertical Resistivity Soundings (VES) and Resistivity Profiling.

Drilling works

In all three target areas two air-lift drilling rigs were applied simultaneously. All boreholes were piloted at 6” (150mm) diameter. Within each target area the borehole with the best yield was selected for test pumping and subsequently reamed out at 305mm so that it could accommodate 200/185mm blue, flush-threaded PVC pipe casing with open area of 8%. Main boreholes were stabilized by pouring sieved rounded quartz gravel into the annulus outside the PVC casing and screen.

The boreholes not selected for test pumping were converted into piezometers by installing 3” (75mm) PVC pipe casing (3 piezometers at the Katete and Makeni sites and 2 piezometers at Kasanova, respectively). To ensure a responsive water column within the piezometers two to three 6-meter lengths of installed PVC casing were rough slotted on site using a hacksaw (about 100 slots per borehole).

The depths of the pumped wells are between 50 and 90 m. Their yield estimated by air-lift at the time of the well construction are 12 l/s in case of Cheta schists and limestones and more than 20/s in karstified Lusaka Dolomite. For summary statistics please refer to Part B, tables 3 to 5.

Test Pumping

The test pumping programme at the three test sites were performed between March 18 and April 11, 2012. The tests at each site comprised a step-drawdown test of five steps of 100 minutes each and a 48-hours constant rate test followed by a recovery period that was monitored over a period of 24 hours. Drawn water levels were measured at the pumped well and two to three observation wells. The mode of pumping was with an electric submersible pump (ESP) powered by a 380V output generator.

Discharge measurements were (at least) taken every 30 minutes. For analysis purposes the discharge was averaged over periods with similar pump rates. The analysis was performed using data recorded by the digital probes. Manual readings were used for data verification only.

From drilling records, high yielding boreholes (≥12 L/s) were reported at all three investigation sites. The highest expected yields with presumably over 20 L/s (!) were attributed to borehole P1-4 at Katete within the Cheta Limestone Formation and P2-2 at Kasanova within cavernous rock of the Lusaka Dolomite Formation. During test pumping, however, discharge at comparable rates could only be achieved at Makeni (14 L/s from P1-3) whereas pumped yields at Katete and Kasanova remained well below expectations. The low yields are explained by high well losses. It is assumed that hydraulic active fracture or cavernous zones could not be appropriately connected to the well.

In summary all boreholes and piezometers except one at the Kasanova site1 (subdued response) proved responsive with good data provided.

Test pumping analysis

The test pumping analysis provided valuable additional information on the hydraulic characteristics of the Lusaka Dolomite and Cheta formations in the Lusaka region. The results are summarised as followed:

	P-1 Katete	**P-2 Kasanova**	**P-3 Makeni**
Geology:	Interlayered/adjacent micaceous schist and crystalline limestone	Fractured and/or karstic dolomitic limestone	Interlayered calcareous mica schist, crystalline limestone and quartzitic psammite
Formation:	Cheta	Lusaka Dolomite	Cheta
Highest yield [1)]	> 20 L/s at P1-4	> 20 L/s at P2-2	15 L/s at P2-2
Step Test Results:	B = 28.5 min/m^2 C = 309 min^2/m^5 T = 147 m^2/d	B = 5.05 min/m^2 C = 44.15 min^2/m^5 T = 558 m^2/d	B = 6.09 min/m^2 C = 13.86 min^2/m^5 T = 228 m^2/d
Aquifer Test Results:	Q = 2.7 L/s q = 0.27 L/s/m (23 m^2/d) 80 m^2/d < T < 88 m^2/d 0.0010 < S < 0.0057	Q = 3.27 L/s q = 1.02 L/s/m (88 m^2/d) Cavernous section: T = 1,174 m^2/d S = 0.029 Fractured section T = 600 m^2/d S = 0.0028	Q = 14.1 L/s q = 0.67 L/s/m (58 m^2/d) Limestone section: 262 m^2/d < T < 280 m^2/d S = 0.018 Schist section: 430 m^2/d < T < 455 m^2/d 3.7 10^{-5} < S < 0.00031

The geological setup at all three investigated sites is extremely heterogeneous with respect to lithology (schist/limestone) and degree of fracturing and karstification. As a consequence, groundwater flow conditions were equally complex.

Transmissivity: Values for transmissivity of the aquifers tested are to be considered "moderate to high" or "high". The lowest values of around 90 m^2/d were characteristic for the Cheta Limestone Formation at Katete. The crystalline limestone in this area however was interspersed with carbonaceous schist. At the other two sites the transmissivity for carbonate rock varied between 260 m^2/d and >1000 m^2/d with the highest values attributed to karst features within the Lusaka Dolomite Formation.

The results obtained for the Makeni site seem to confirm that the area mapped as "Cheta schist" in the geological maps is much more pervious than the geological description would suggest. The area is part of an agricultural belt highly dependent on groundwater for irrigation purposes.

The test pumping results are comparable with a statistical analysis of test pumping data in the area (Bäumle 2011). The median value of transmissivity for 56 tests carried out in carbonate rock aquifers amounted to 332 m^2/d according to this study. The regional study also exhibited the large variability of hydraulic rock properties. Maximum obtained transmissivities exceeding 3000 m^2/d as for some wells in Lusaka West and South (e.g. Mumbwa Roadside, Quarries, U8-D northwest of Mt. Makulu) could not be found at the three sites investigated in this report.

Storativity: The test pumping results at P-2 and P-3 suggest that storativity of well fractured crystalline limestone is in the order of 0.02 to 0.03. Previous test results from e.g. the Mass Media and NRDC areas yielded higher values between 0.05 and 0.16. It was however mentioned that the analysis results of previous tests were partially questionable due to poor quality of data or interferences from adjacent wells (Bäumle 2011).

Water quality analysis

Water quality samples were taken at all three sites at the end of each constant discharge test and analysed by three laboratories for major ions, trace elements and microbiology. The sampling was oriented towards a comparison of the UNZA Water Laboratory and BGR Water Lab in Hannover, also considering the Department of Water Affairs Laboratory that was capable to test for the individual parameters microbiology, alkalinity and nitrates.

The comparison shows that DWA laboratory faces strong challenges in reliable conductance of analysis on the one hand (three out of six results missing) and in the quality of their analysis results on the other hand. The UNZA lab establishes a rather close result for the P2/2 sample for some parameters while the other two sample analyses divert widely from BGR results for almost all the parameters. Ion balances for BGR results are between -2% and +1%, for UNZA they range from 5% to 18%.

The water quality in all three sites is fit for consumption with the exception of coliforms which makes it necessary to chlorinate, boil or otherwise treat the water before consumption.The results indicate that the types of groundwater found in Makeni and Kasanova (P3 and P2) are similar to each other while the sample from Katete (P1) shows the highest carbonate hardness (>375 mg/l CaCO3, "very hard") as well as the highest Mg/Ca ratio. All samples show a HCO3:SiO2 ratio between 24:1 and 60:1, as most of the carbonate waters in Lusaka do (Museteka & Bäumle 2009).

The farming that takes place around the sites in Makeni and Kasanova does not seem to have a large influence on the deeper groundwater in terms of excess fertilizer infiltrating. Further studies would be needed looking at pesticides to confirm this statement.

PART A

Desk Study and Siting

Prepared by

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Abreviations

BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources)
DWA	Department of Water Affairs
EM	Electromagnetic sounding
ESP	Electric submersible pump
GReSP	Groundwater Resources for Southern Province
H_D	Horizontal Dipole
HLEM	Horizontal-loop electromagnetic (system)
HP	Horsepower
Hz	Hertz
k	Permeability
LWSC	Lusaka Water and Sewerage Company
Pz	Piezometer
q	average yield
S_y	Specific Yield
T	Transmissivity
TBD	To be determined
V_D	Vertical Dipole
VES	Vertical resistivity sounding
WGS84	World Geodetic System (1984 revision)
pH	measure of the activity of the (solvated) hydrogen ion

1 Introduction

The BGR (Federal Institute for Geosciences and Natural Resources) together with the Department of Water Affairs, (DWA) is implementing a scientific program which will advance groundwater resource management generally in Zambia and particularly in Southern and Lusaka provinces. The project is known as GReSP.

As part of their program GReSP has designed a project and called for tender to construct 3 boreholes and 6 piezometers in 3 selected target areas / aquifers in Lusaka District and thereafter to test pump the boreholes and measure the aquifer responses in all boreholes and piezometers. From the time-drawdown data GReSP will determine the aquifer parameters of Transmissivity and Storage etc.

The basic Scope of Works for the supervisory component of this project is:-

a) Identification of sites for drilling / test pumping (field visits and geophysical methods)

b) Preparation of drilling and test pumping contract documents

c) Hydrogeological monitoring of drilling works

d) Hydrogeological monitoring of test pumping works

e) Hydrogeological reporting

This report has been prepared by Jim Anscombe, free-lance Hydrogeologist and the appointed supervisory consultant for this study. The report details the first of the above points namely a desk study of existing data combined with the findings of field survey and geophysical survey.

2 Data Sources

The location maps have been created using imagery and shape files made available by GReSP. These include Landsat, topography, geology, roads and streams, boreholes and lineaments. These have been annotated with new information from the field such as located boreholes, geophysical lines and proposed sites. All maps and plans are plotted in WG84 datum.

The desk study involved the perusal and extraction from various reports under the GReSP title, "Development of a Groundwater Information and Management Program for the Lusaka Groundwater Systems":-

- Desk Study and Proposed Work Programme (Bäumle and Kang'omba, 2009)
- Karstification, Tectonics and Land Use in the Lusaka Region (Hahne, 2010)
- Results of Pumping Test Evaluation and Statistical Analysis of Aquifer Hydraulic Properties (Bäumle, 2011)

3 Target Areas

The three target areas selected by the GReSP project are defined in the Table and Figures 1 and 2. The quoted coordinates are the center points of investigation areas measuring about 5 km^2 in area.

Table 1: Target Area Center Coordinates

ID	Area	District	Latitude*	Longitude*
P-1	Katete	Chibombo	-15.2521	28.1183
P-2	Kasanova	Kafue	-15.4172	28.1915
P-3	Makeni	Kafue	-15.4682	28.1700

* WG84 datum

Access to Target Areas

Target area P-1 (Katete) is accessed west off the Great North Road at “ten miles” (small trading post), along a gravel road for about 25km. Just after Katete Basic School the road is under rehabilitation and closed therefore access to the site can only be gained by proceeding straight on where there is a hand pump and the gravel road turns sharply to the south about 2km from the school. Thereafter the road becomes a network of tracks but the site is easily found by aiming for Chisombola Hill.

Target area P-2 (Kasanova) is accessed north (right) off the Mongu Road via a dirt track a few meters before the access road to Rosedale Police Post. This is about 10km west from the traffic lights on Lumumba road and not far past the sign for the Open University.

Target area P-3 (Makeni) is accessed north off the Kafue Road at the Makeni traffic lights turning right turn at the ZESCO sub-station just after the tar road turns to gravel. The site is in the fields on the right about 2km along this road. Alternatively it can be accessed from the Mongu Road with a left turn at the permanent police checkpoint. This gravel road passes the site on the left after 10km or so just after the Chilongolo stream.

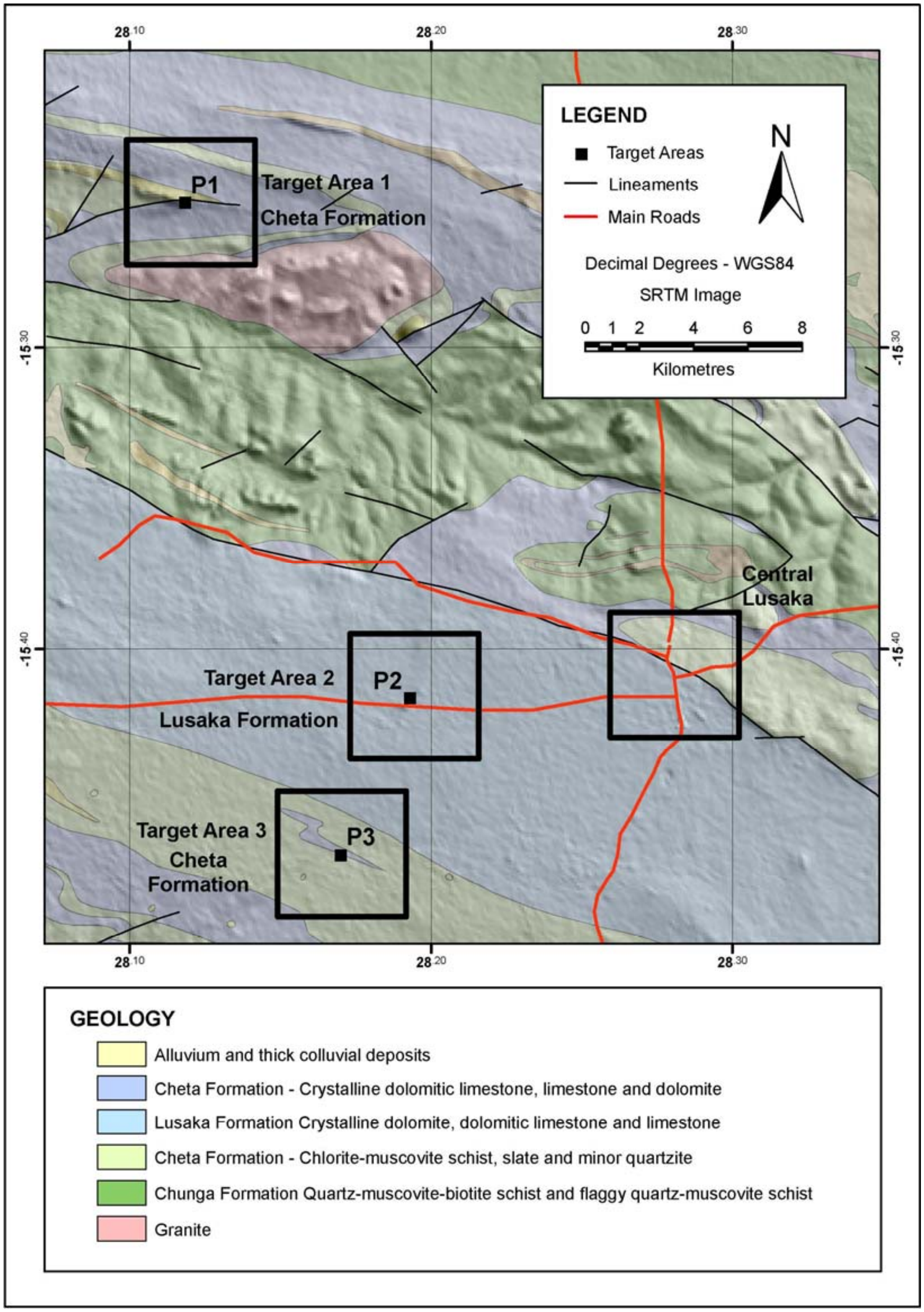


Figure 1: Location of the Target Areas in relation to Geology and Topography

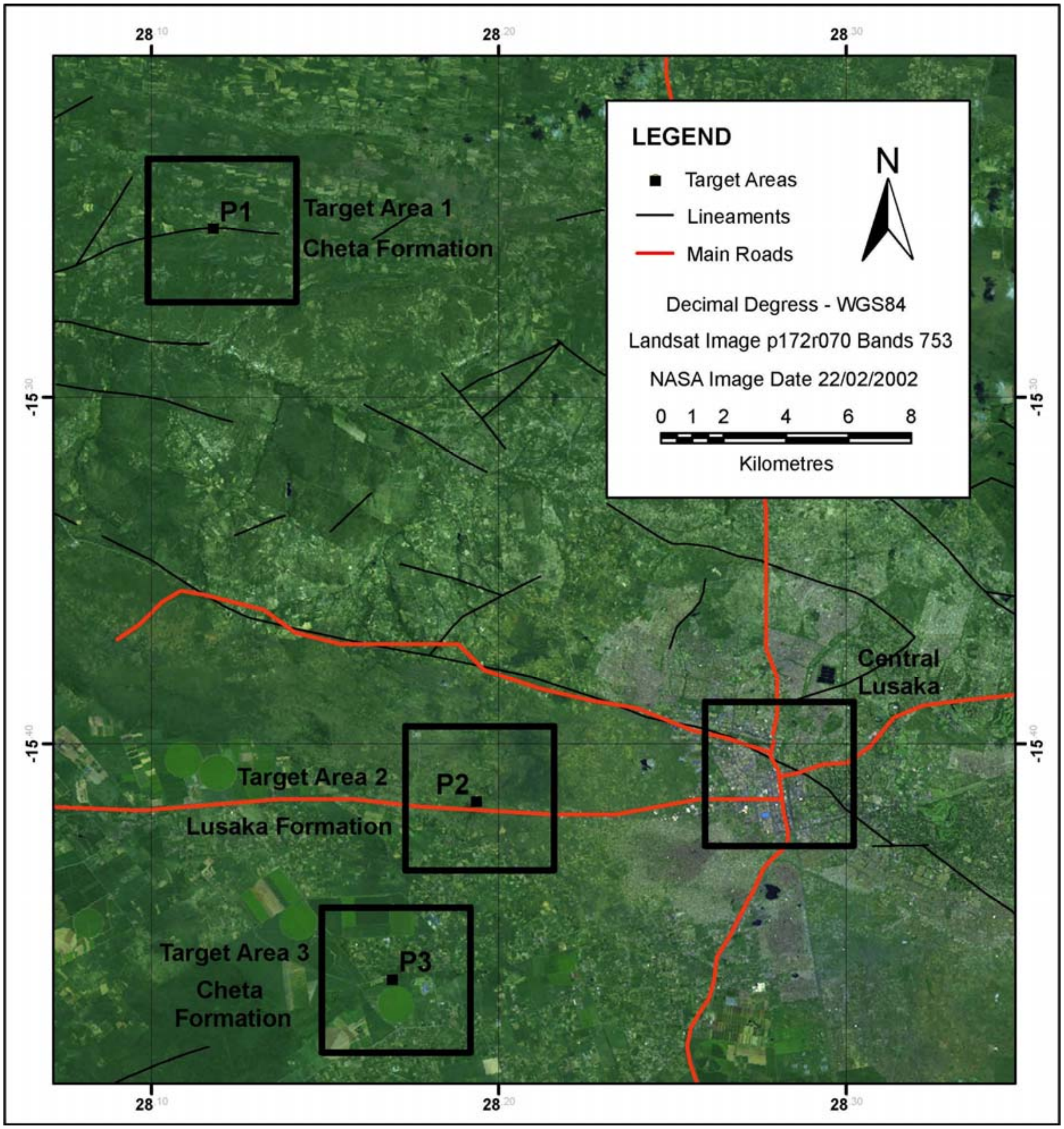


Figure 2: Location of the Target Areas in relation to Land Use (Landsat Image).

4 Geology / Hydrogeology

4.1 General Geology

Three different geological successions / aquifers are under investigation. These are limestone and mixed metamorphic aquifers of the Cheta Formation and a dolomite hosted aquifer within the Lusaka Dolomite Formation (Table below). Figure 1 also shows the geology.

Table 2: Targeted Aquifers

ID	Area	Group	Formation	Target aquifer type
P-1	Katete	Katanga	Cheta	Crystalline limestone
P-2	Kasanova	Katanga	Lusaka Dolomite	Dolomite
P-3	Makeni	Katanga	Cheta	Quartzite, schist, psammite

The Lusaka Dolomite Formation and the Cheta Formation are respectively parts of the Upper and Middle Divisions of the Katanga System – which is of Pre Cambrian age. These are sequences of sedimentary, carbonate-rich continental shelf deposits which have been highly metamorphosed and deformed by various tectonic events over a time span of around a billion years. The geology is not straightforward and has been subjected to many interpretations and re-interpretations over the decades. Apart from metamorphism the geology is further complicated due to at least three folding, faulting and thrusting events. The general consensus is that the Lusaka Dolomite Formation is younger than and overlies the Cheta Formation (limestone, schist, psammite and quartzite sequence) which overlies the Chunga Formation (schist and quartzite succession). These were originally laid down unconformably on quite an irregular succession of older Basement rocks. The Cheta and Chunga formations are injected with granite, gabbro and felsite intrusives and extrusives which occur as small scattered inliers with the exception of the larger Lusaka Granite with an area of about $40km^2$ to the SW of the Katete target area.

Lusaka City is built toward the south of a highland plateau which extends over 65km from Mwembeshi in the NW to Shamtumbu in the SE. This plateau has remained as a highland due mainly to the resistant nature of the Lusaka Dolomite and Cheta Limestone – which form its core. The land and the various drainage catchments descend in all directions notably to the Northwest (Kafue Flats) and the South and Southeast (Zambezi and Luangwa Rift valleys). Outcrops of Cheta and Chunga rocks become more common on the lower flanks of the plateau and many springs exit at or near the contact with the overlying dolomite.

Folding and Deformation Events

Much of the complexity can be assigned to a major pre-Cambrian tectonic event which saw the closing of a major warm sea (as evidenced by preponderance of carbonate rock types) and the over folding and over thrusting of the Zambezi (southern) and Lufilian (northern) cratonic belts along an ancient zone of crustal weakness - the Mwembeshi Shear Zone – which runs SSW-NNE not far north of the Lusaka plateau (Figure 3). This imparted the general NW-SE trend on the Lusaka – Mwembeshi area whilst subsequent burial produced the metamorphic fabric currently observed. This ancient tectonism was followed by further significant tectonic, faulting and folding events with eventual uplift, erosion and exposure of once deeply buried rock. The structural complexity can be summarised into several phases of deformation:-

- Early recumbent folding about NW-SE axis, overturned to SW
- Contemporaneous thrusting directed from SW to NE affecting all rocks, often causing thickening of the dolomite (marble) sequences. Vertical displacement over the major thrust zones appears to be in the order of kilometers, (Bäumle, pers. comm.).
- Open folding of existing recumbent folds – also about NW-SE axis
- Open folds orientated NE-SW as the principal stress direction moved from earlier NE-SW to NW-SE
- Faulting and slumping of the aforementioned in comparatively recent times associated with a NE-SW extensional regime that respectively opened of the Zambezi and Luangwa rift valleys to the SE and E

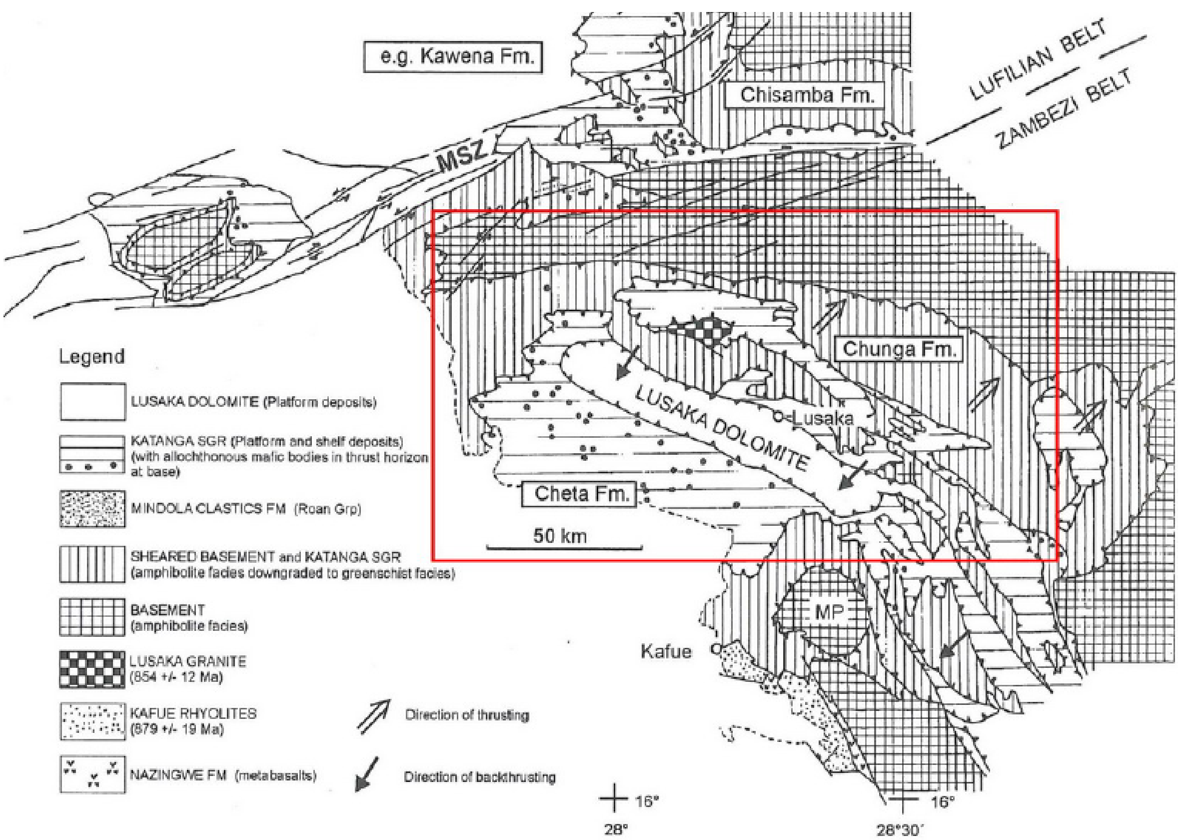


Figure 3: Geological and Structural Patterns (Porada and Berhorst, 2000)

The early compressional deformation events imparted faulting and jointing as well as metamorphism and folding. Faulting and jointing has continued right through to the most recent extensional event associated with the opening of the Luangwa and Zambezi rifts.

Associated Faulting Episodes

According to Hahne (2010) there are three major fault directions:-

- A set striking parallel to main fold trend i.e., NW-SE, +/- 120^o
- A second NW-SE set, striking 140^o
- A conjugate NE-SW set striking 035 - 045^o

Associated Jointing Episodes

According to Nkhuwa (1996) there are three major joint directions:-

- Steep dip to NW and SE and striking 030^o to 060^o
- Moderate dip to SW, striking parallel to main fold trend i.e., NW-SE, 110^o to 140^o
- Steep dip to E and S, striking 150^o to 180^o – seen crossing the others diagonally

Rainfall and Evapotranspiration

Continuous recording at the 3 Lusaka weather stations between 1963 and 1993 gives an average of 857mm of rainfall per annum. Rainfall peaks in January with 82% falling in the 4-month period December to March. Besides these basic statistics much variability in rainfall amount, intensity and duration is observed both temporally and spatially.

There are two main categories of rainfall. The first is associated with weather fronts that move in from the oceans surrounding the continent – typically in the period December - March. Superimposed on this “wet season” are the local thunderheads – so important for consistent agriculture - which are the result of moisture streaming upward from the land surface, subsequently condensing and falling back to earth not far from point of origin. These are confined to the hot season when the moisture is available and the ambient temperature is highest. The moisture derives from saturated soils directly through evaporation and from vegetation through transpiration. Collectively trees (i.e. forest) pump huge quantities of water to the atmosphere daily – peaking in the hot, wet months.

Evaporation is a function of ambient temperature and availability of moisture at the surface and subsurface. Both of these are controlled by the season, soil type and soil cover type (open, vegetated, urban, etc.) among other parameters. Evapotranspiration amounts and trends are available but need to be further researched. It is most likely that they are comparatively high and peak during the rainy and post-rainy season when soils are often saturated.

Catchment and Runoff

The Katete and Kasonova target areas fall within the Chunga sub-catchment whilst the Makeni area falls within the adjacent Chilongolo sub-catchment – named after the streams found in these areas. Both drain off the Lusaka plateau to the Lower Kafue River Catchment to the west and south.

Drainage patterns are related not only to topographic variation but also to the underlying geology. Dendritic drainage patterns are seen associated with schist and less permeable carbonate rocks – particularly on the flanks of the plateau whereas surface drainage is more or less absent in areas of karstified dolomite. In these latter areas the drainage has reverted largely to subterranean and into the groundwater flow regime (see Section 5.2.3).

Recharge and Abstraction

Recharge to the groundwater system is principally via rainfall although in the agricultural areas return from irrigation systems is significant. Hydrograph and water balance methods have been used in various studies and the former produced a range in the order of 100 to 250mm per annum with actual amount dependent on variables such as the actual Mean Annual Rainfall and the geology at subcrop. The subject is far from understood but it seems that recharge can be lower and higher than the stated range respectively in drought and above average rainfall years. It has been suggested that for any significant recharge to occur rainfall must exceed 400mm per annum – which it does in most years. It has also been suggested (with some evidence) that rock type and proximity to surface play a significant role in recharge rates – being higher in areas underlain by dolomite and limestone subcrop and lower in schist dominated areas.

Borehole abstraction from the Lusaka aquifers has been steadily growing parallel with development. Major abstractors are:-

a) Lusaka Water and Sewerage Company
b) Local Water Trusts – supplying water to the various compounds
c) Industrial and commercial
d) Irrigation
e) Household (domestic via the Electric Submersible Pump)
f) Rural supply (wells and hand pumps)

Accurately quantifying abstraction can be made for some of these but in the absence of up-to-date water point census information is very difficult for other categories. For example, the LWSC (a) pumped about 137m^3/day from 63 boreholes in 2008. Conversely without a registry system for boreholes or abstraction quotas, those that abstract in categories c) to f) do so unchecked. LWSC is not able to meet demand and developers (small holdings, factories etc.) behave like farmers and drill thousands of boreholes annually in the general Lusaka area. Private drilling companies have proliferated over the last few years – direct evidence of the amount of drilling activity that is occurring around and within the city boundaries - in all directions.

Groundwater Flow

Groundwater flow is controlled by the topography and the NW-SE strike of the Lusaka plateau and contained structural trends. Hence the main flow direction – based on the hydraulic gradient appears to be to the NW (toward the Kafue flats) and to the SE. Likewise the subordinate flow direction appears to be off the flanks of the Lusaka plateau to the NE and SW to the Zambezi Valley. The actual magnitude of flow cannot be determined from water level contour mapping.

Aquifers and Aquifer Parameters

- Lusaka Dolomite

The Lusaka Dolomite is demonstrably the most prolific aquifer in the area. Productive boreholes intersect secondary porosity associated with karstic surface features and their subterranean expression: interlinked solution cavities. These have developed (and are still developing) due to circulating groundwater pervading, dissolving and widening the joint and fracture sets. Larger scale karstic features and solution cavities, within the upper 25 meters or so offer the highest yield potential. These seem to have developed where the dolomite has a coarser texture and a higher calcium carbonate (calcite) content and also in the vicinity, and along strike, of the major fault and thrust zones (NW-SE and NE-SW sets) – as these expose the soluble rock matrix to circulating groundwater. Target P-2 (Kasanova area) is within one such NW trending feature.

Most water boreholes drilled into the Lusaka dolomite are 60m or less in depth and indicate concentration of solution cavities within the range 24 to 36m. Deeper boreholes suggest other zones in the range 65 to 80m and 125 to 150m although such boreholes are so few that patterns cannot really be defined (Figure 4). It has been suggested (Lambert 1962) that each zone has been produced by a different pluvial period with the most recent being the shallowest.

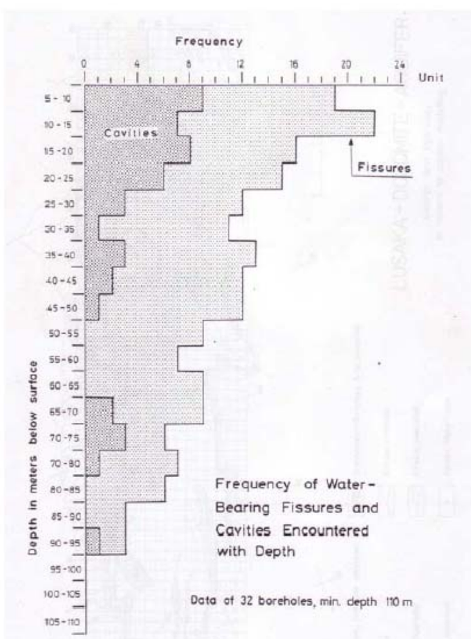


Figure 4: Frequency of Water Bearing Fissures and Cavities (Von Hoyer et al, 1978)

Yields from boreholes drilled into the dolomite can be exceptionally high. An example is LWSC Shaft 5 with yield of 586m^3/hr and 476m^3/hr (respectively Pump 1 and Pump 2). About 6km east of Target P-2 are the Mumba roadside boreholes and these yield 75-150m^3/hr. These can be pumped at such high rates because the groundwater can move in unrestricted open space (fissures and cavities) and water pumped out is replaced almost instantaneously.

Some reports state that the groundwater potential of dolomite is very high and high yields can be obtained in almost every borehole. This is incorrect - dolomite has very little in the way of intergranular porosity and dry or low yield boreholes drilled through massive monotonous dolomite away from structurally controlled karstic features or fracture sets are common. Dry boreholes have been drilled literally meters away from productive ones – just off the karstic feature within massive, unweathered dolomite.

- **Crystalline Limestone Aquifer**

The Crystalline Limestone aquifer of the Cheta Formation does not show the same degree of karstification as the Lusaka Dolomite and hence its groundwater potential is lower.

However, surface karst features have been mapped through field observation and aerial imagery and the potential should increase in such areas. As with the Lusaka dolomite the areas of highest potential will tend to be in the vicinity, and along strike, of the major fault and thrust zones (NW-SE and NE-SW sets) – as these again expose the soluble rock matrix to circulating groundwater. Target P-1 (Katete area) is located in an area where major faulting has been interpreted and also some minor karst features have been observed at surface (Hahne, 2010).

- **Schist, Psammite and Quartzite Aquifer**

The Schist – Psammite - Quartzite aquifer of the Cheta Formation is an aquifer within the surficial weathering zone and within deeper dislocations which have been variably weathered by circulating groundwaters (shears, thrusts, faults fracture and cleavage sets, hinges of antiformal and synformal structures, etc.). When hard and fresh these rocks have no primary porosity and drilling boreholes away from the aforementioned zones of dislocation will yield only from the surficial weathering zone if at all. Siting and drilling boreholes blind can result in failure in terms of acceptable yield.

However, the Cheta Formation rocks have been repeatedly stressed and dislocated over geological time and the resulting action of circulating water has produced a generally deep weathering zone to 30 meters or so together with fair groundwater potential. Yield potential is in the order of 0.5 to 1.0 Ls^{-1} (Lambert 1962). Where boreholes penetrate this zone and thereafter an underlying dislocation zone the yield can be much higher. In the P-3 (Makeni) target area farmers report yields in the range 2 to 20 Ls^{-1}.

Calc-biotite and chlorite schist are generally considered to have very poor yield potential.

Comparison of Hydraulic Parameters for the 3 Aquifers

Chenov (1978) compared the carbonate aquifers with the Schist - Psammite – Quartzite aquifer and described them respectively as highly productive and locally productive (Table 3)

Table 3: Aquifer hydraulic characteristic (Chenov 1978)

Aquifer	n		q [L/s/m]	T [m^2/d]	K [m/d]	S_y [-]
Dolomite/ Limestone	40	Average:	6.4	616	15	0.11
		Median:	1.9	188	4.5	0.12
Schist / Quartzite	56	Average:	2.3	231	6	0.08
		Median:	0.07	6.9	0.12	0.07

It is statistically evident that Average Yield (q), Transmissivity (T), Permeability (K) and Specific Yield (S_y) are significantly higher for the carbonate aquifers than for the Schist - Psammite – Quartzite aquifer. Von Hoyer (1978) further emphasized the point by depicting the frequency of Specific Yields of the two types in the form of a histogram – this clearly shows the differences promoted by Chenov (1978) but also illustrates that the ranges are broad and overlap (Figure 5).

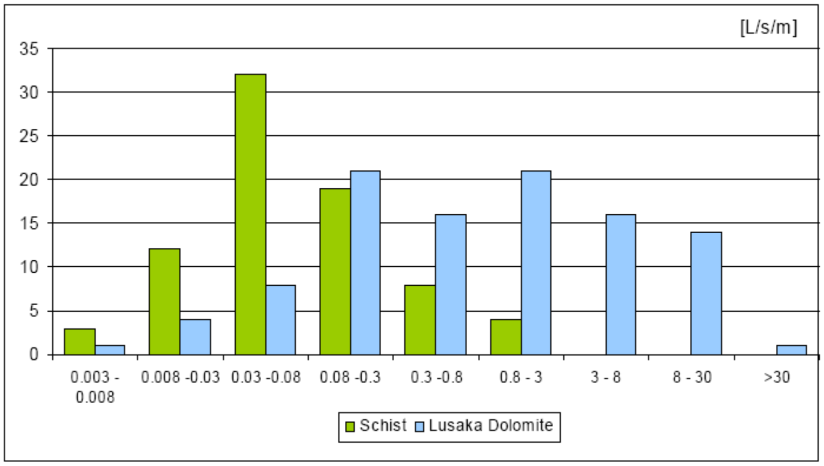


Figure 5: Frequency Distribution of Specific Capacity (Von Hoyer et al, 1978)

More recently, Bäumle (2011) has summarised and reinterpreted the existing test pumping data for these aquifer types. The aforementioned differences are confirmed with the calculated median values being an order of magnitude higher for the carbonate aquifers (Table). Also the ranges for these parameters are confirmed as large.

Table 4: Reinterpreted Aquifer Parameters (median values)

ID	Aquifer	Yield (Ls^{-1})	Specific Capacity ($Ls^{-1}m^{-1}$)	Transmissivity ($m^3m^{-1}day^{-1}$)
P-1	Dolomite	12	2.9	332
P-2	Limestone			
P-3	Schist - Psammite - Quartzite	1	0.12	10

Calculation of aquifer storage from test pumping data is limited simply because very few tests have provided the necessary observation boreholes to make this calculation possible (extra cost of drilling these is usually prohibitive). Storage has only been calculated for the Lusaka Dolomite, S = 0.05 – 0.16, and these values are only a guide as they are not statistically representative.

Critical points are:-

- The Lusaka Dolomite and the Cheta Crystalline Limestone aquifers have been lumped together in these comparisons. This relates to the scarcity of pump test data for the latter. Thus they are considered similar primarily on the basis of mineralogy. However, most of the calculated parameters derive from test pumping the Lusaka Dolomite Aquifer. Indeed Lambert (1962) rated this aquifer as “excellent” and the Cheta limestone and dolomite aquifers as “poor” with typical yields for the latter around 1 Ls^{-1} and a significant failure rate when drilled in terms of useful yield. Various boreholes into the Cheta Limestone since the 1960’s indicate that Lamberts’ rating was perhaps conservative and that in fact it is similar to but not as prolific as the Lusaka Dolomite aquifer. This present study will elucidate further.

- All calculated hydraulic parameters must be skewed on the high side for the simple reason that that they are derived from tests on successful boreholes. Many that are drilled dry and with very low yield have been discarded / abandoned / forgotten.

These observations should not be overlooked.

5 Target Area Definition

5.1 P-1: Katete Target Area

5.1.1 Target Area Selection

The target area was selected by GReSP for two main reasons:-

- Geology – the Cheta Formation and crystalline limestone aquifer and mapped faults
- Satellite imagery – lineament traces and (minor) sink holes

5.1.2 Field Reconnaissance

The center point of the target area lies at the southeast tip of a hill composed of metamorphic schist, psammite and quartzite.

Figure 6: Chisombola Hill: Metamorphic Schist / Psammite / Quartzite

Exposed at subcrop on the low ground flanking the hill in all directions is crystalline limestone assigned to the Cheta Formation. This rock is seldom more than 1m from surface, typically exposed in erosional features as “whalebacks” of massive grey limestone devoid of structure other than remnant layering. The exposures are devoid of fracture sets with smooth, rounded profiles. The overlying soils are red-brown, iron rich and thin.

Figure 7: Typical “whaleback” of crystalline limestone subcrop

Figure 8: Coarse crystalline limestone

Trending along the southern break of slope of the hill is a prominent thick band of outcropping pale to white quartzite. This is interpreted as the infilling of a fault or thrust zone which separates the described prominent psammite and schist from low lying crystalline limestone. It is also observed crossing the limestone as a low amplitude but prominent ridge about 2km to the north east. During the various formative tectonic events the brittle quartzite was repeatedly fractured producing at least two distinct cleavage sets:-

a) 0-10° – tight and intense cleavage set every 50 to 100mm
b) 90-100° open and less intense cleavage set every 300-500mm

Figure 9: Quartz fault zone infill – with two prominent cleavage sets

5.1.3 Observed Hydrogeology

A number of existing water points have been located in the area (Table 5). These are all serving the local communities. At least one was constructed by AFRICARE / EU project in the late 1990's as evidenced by inscription on the concrete. All are in use but in an extremely poor state of repair with the civil works undercut by erosion from cattle and general overuse and neglect. All the hand pumps suffer extreme leakage when pumped indicating that the seals and bearings are well worn and expired. All waters were tested and all have a slightly bitter iron-rich taste and 370-470 mg/L of dissolved salt. No information on borehole yield, geology encountered or siting success could be ascertained. The rest water level in the well is +/- 10m below ground level.

Table 5: Water Points Observed in the Vicinity of P-1

ID	Location	Distance from P-1 center	Latitude*	Longitude*
Open well	Chisombola community	0.21 km	-15.25090	28.11982
Hand pump	Chisombola community	0.64 km	-15.24992	28.12384
Hand pump	Katete School	2.35 km	-15.25117	28.14014
Hand pump	Community	2.83 km	-15.23211	28.13458

* WG84 datum

Figure 10: One of several community water points in the P-1 area

The vegetation cover in the general area is stunted and devoid of mature trees. This may be related to charcoal production and general deforestation but the area seems to have a low carrying capacity due primarily to the shallow subcrop and general lack of shallow ground water. Fracture zones with available ground water that may once have been demarcated by linear bands of more mature trees are now all but erased from the landscape. Geophysical EM profiling may assist in locating these fracture zones if they are present.

5.1.4 Test Borehole Positioning

Positioning and drilling boreholes into the limestone aquifer is very simple – as the rock type outcrops extensively. However it would not be good policy to site on outcrop alone as there is a strong possibility of a low yield or dry outcome.

Suitable points for the test borehole and piezometers within the target area have therefore been determined with geophysical techniques, i.e. EM profile lines have been conducted to and conductors selected as the drill sites (Section 6.1).

5.2 P-2: Kasanova Target Area

5.2.1 Target Area Selection

The target area was selected by GReSP for two main reasons:-

- Geology – the Lusaka Dolomite Formation and mapped faults
- Satellite imagery – lineament traces and sink holes, area of mature vegetation

5.2.2 Field Reconnaissance

The center point of the target area lies in an area of shallow groundwater, mature trees and thick undergrowth. The soils are black and fertile and no outcrop is observed.

The general area is undergoing peri-urban development with the vegetated feature disposed like an island amid this development. Having mentioned its pristine condition it has recently been divided into 5 acre plots and one owner has begun development of a "Wedding Center" about 70m south of the center point. The rest of the vegetated feature is not easily penetrated on foot due to thick, thorny undergrowth. Access for a drilling rig further than the described plot will not be feasible without substantial clearing and road preparation. To the east is a complex belonging to the Office of the President. To the south are plots under development with the Mission Convent Private School for Girls sandwiched between the wedding center development and the Mumba Road. To the west is Rosedale Police Post within the compound of Tandiza Investments – who is the original owner of the general area before plot demarcation and selling.

Figure 11: Mature vegetation and very shallow groundwater in the P-2 target area

South of the central area, nearer the main road and below the adjacent school massive dolomite is observed at shallow subcrop. The appearance of the dolomite coincides with a marked absence of vegetation cover.

Figure 12: Typical surface texture of Lusaka Dolomite

5.2.3 Observed Hydrogeology

The vegetated area floods each rainy season particularly after heavy storms. Some old drainage ditches and holes left by falling trees show groundwater at just 0.5m below surface (June 2011). There are no existing boreholes within this feature. The closest boreholes are to the west and within the compound of the Rosedale Police Post (Table). This compound is supplied by a productive borehole, drilled to about 60m depth and just west of the vegetated feature on ground prone to flooding. No outcrop is observed. The borehole is inaccessible within an overgrown and dilapidated shed but is the main supply borehole to the compound. Two further boreholes located slightly further west are less productive and shallower. Further south and west but within 800m boreholes drilled both completely dry (many) and wet (few) are reported. This variability in yield is typical of drilling in dolomitic terrain.

Table 6: Boreholes Observed in the Vicinity of P-2

ID	Location	Distance from P-2 center	Reported depth (m)	Reported yield (L/s)	Latitude*	Longitude*
ESP (5HP)	Rosedale Police Post	0.23 km	+/- 60	+/- 10	-15.41717	28.18938
Not equipped		0.29 km	+/- 20	Dries quickly	-15.41807	28.18893
ESP		0.40 km	+/- 30	Dries October	-15.41875	28.18813

* WG84 datum ESP = Electric Submersible Pump HP = Horse Power

The surmised hydrogeology of this area is dynamic and interesting. The vegetated island occurs within a strong northwest lineament trend which is interpreted as faulted dolomite (Hahne, 2010 – Figure 35). Circulating groundwater has weathered this fault zone producing karstic features at surface (a pattern of small sink holes) together with underlying dissolution cavities – the pipework for rapid groundwater flow. None more so than during storm events over the general Lusaka area when excess storm rainwater infiltrates and becomes shallow, fast-moving groundwater – which becomes surface water as it exits from the karstic pipework in this particular area - flooding the general area. Recession then occurs during which the surface water gradually subsides as the underlying ground water flows away in a north westerly direction. To the northwest – on the lineament trend - are further exit points. An example is on Sunrise Farm 4km to the NW, within an area of karstic, subcropping dolomite, where a similar rainy-season phenomenon is observed.

That the island is heavily vegetated further indicates the availability of shallow groundwater throughout historical times – with the vegetation gradually producing the thick and fertile soils seen therein.

In both these areas boreholes drilled centrally to the lineament belt should intersect high yields even at comparatively shallow depth whereas boreholes drilled off center or on the flanks of the belt may intersect respectively lower yields or completely dry conditions.

5.2.4 Test Borehole Positioning

The vegetated area obviously has substantial groundwater potential and a test borehole and piezometer-set positioned therein with minimal geophysics has an above average potential for a successful, high yield outcome. Drilling depth required is unlikely to be deeper than 60m. The same cannot be said for a borehole positioned outside of the vegetated island where the potential for a poor low yield or dry outcome is higher.

The only accessible point which has been cleared of thick vegetation is on the plot belonging to Mr. Nacidze. This measures about 130 x 110 meters. Unfortunately there are three bisecting E-W drainage ditches which would further restrict the available area to the southern side about 120 meters south of the picked center point - but still well within the vegetated feature.

Suitable points for the test borehole and piezometers within the plot boundaries have been picked (permission has been granted). Some short geophysical EM lines have been conducted to fine-tune and calibrate the drill sites (Section 6.2).

5.3 P-3: Makeni Target Area

5.3.1 Target Area Selection

The target area was selected by GReSP for three main reasons:-

- Geology – the schist / psammite / quartzite member of the Cheta Formation
- Satellite imagery – lineament trace – possible zone of greater groundwater potential
- Spatial considerations – unused ground within an area of intense agricultural activity

5.3.2 Field Reconnaissance

The center point of the target area lies just inside an old earth dam constructed across the Chilongolo Stream. The dam was breached some years ago and no longer fulfills its intended purpose. The area is covered by tall reed grass. To the south and south west of the dam scrubland undergrowth occurs for several hundred meters before irrigated cropland belonging to Sunrise Farms. To the northwest, north and east are small holdings belonging to various individuals. The soils are reddish brown and no outcrop, subcrop is observed anywhere in the vicinity. There is sparse quartzite float observed at the crop edge but it cannot be concluded that this is representative of the subcrop as it may have brought in from elsewhere. The terrain is completely flat apart from the mentioned man-made earth dam and the narrow, eroded depression of the mentioned stream.

Figure 13: Looking east across the Chilongolo Dam from top of earth dam wall

5.3.3 Observed Hydrogeology

The southern half of the target area lies on Sunrise Farm which irrigates crop rings of silage, wheat and soya from boreholes tapping groundwater. The owner has drilled literally dozens of boreholes with yields ranging from dry to >20 liters/second. The nearest boreholes occur on two small holdings west of the center point. These are not pumped continuously and have yields that range 2-10 liters per second. Most of the boreholes have been divined using traditional methods and most are drilled 60m or less in depth. No clear pattern or trend of higher yielding ground has been determined either in the vicinity of the stream or further into the fields. No information on intersected rock type has been determined.

Table 7: Boreholes Observed in the Vicinity of P-3

ID	Location	Distance from P-3 center	Reported depth (m)	Reported yield (L/s)	Latitude*	Longitude*
ESP	Sunrise Farm	0.92 km	+/- 60	+/- 8	-15.47441	28.16435
ESP	Sunrise Farm	1.26 km	+/- 60	17	-15.47950	28.17001
ESP	Hawke small holding	0.74 km	+/- 60	+/- 2	-15.46946	28.16327
unused		0.74 km	+/- 60	+/- 7		
ESP -15HP	Zulu small holding	0.54 km	+/- 60	+/- 10	-15.46694	28.16515
blocked	Zulu small holding	0.88 km	+/- 60	Good	-15.46756	28.16185
ESP	Chilongo small holding	0.35 km	?	Good	-15.46505	28.16987
ESP	Zimba small holding	0.43 km	?	?	-15.46474	28.17183

* WG84 datum ESP = Electric Submersible Pump HP = Horse Power

5.3.4 Test Borehole Positioning

The whole area is flat lying and without any rock outcrop to confirm or otherwise the type of aquifer targeted. From the geological map the envisaged rock types are metamorphic schist, psammite and quartzite. These generally have very low primary porosity and therefore low associated groundwater potential. However where extensively weathered in the surficial zone or in areas where the rock types are highly tectonised secondary porosity exists and with it better groundwater potential. Where lineaments interpreted from satellite imagery are thought to have greater groundwater potential then they need to be located on the ground. The most apt method of lineament positioning and borehole site fine-tuning is via geophysical survey. The method that have been employed in this area include EM profiling to identify fault trends and resistivity soundings to fine tune the drill sites within these identified features (Section 6.3).

6 Geophysical Siting

6.1 P-1: Katete Target Area

The survey was executed between 21st and 23rd July 2011. Long EM profiles were conducted using the Max-Min unit in HLEM mode with a 100m cable, on three frequencies (888, 1777 and 3555Hz) and a station spacing of 25m. These were designed to generally investigate the ground and yielded a number of interesting features (discussed below) in relation to the observed distribution of limestone outcrop. Over selected sections of these traverses shorter EM lines were conducted using the EM34 Conductivity Meter in horizontal and vertical–loop modes with a 40m cable and 10m station spacing. Selected anomalies were checked with Vertical Resistivity Soundings (VES) and Resistivity Profiling. The Table below details the geophysical survey quantities and positions - the positions are shown on the site map (Figure 6)

Table 8: Geophysical Survey Location and Detail; P-1 Katete

ID	Location*		Length (m)	Equipment
	Start	End		
EM Profiling				
Line 1	15.25243 S, 28.11696 E	15.26128 S, 28.12220 E	1,000	Max-Min
Line 2	15.25009 S, 28.12138 E	15.25849 S, 28.12698 E	1,050	Max-Min
Line 3	15.25013 S, 28.12163 E	15.23817 S, 28.12072 E	1,350	Max-Min
Line 1/1	15.25767 S, 28.11958 E	15.26043 S, 28.12148 E	360	EM34
Line 2/1	15.25607 S, 28.12531 E	15.25780 S, 28.12643 E	240	EM34
VES		**Type of feature**	**Comment**	
1/700	17.48831 S, 26.00374 E	Suspected fault zone	Piezometer position at 1/715	
1/735	17.48858 S, 26.00089 E	Suspected fault zone	Site A at 1/740	

* Decimal degrees (WG84 datum)

6.1.1 Summary of Geophysical Survey

Profile Line 1 was conducted from NW to SE from the south flank of Chisombola Hill across and toward the edge of the mapped limestone belt. Profile Line 2 is parallel and east of Line 1. It crosses highly cleaved quartz dyke material before an extensive platform of exposed limestone. Profile line 3 was conducted northward across a platform of exposed limestone before a prominent quartz / schist ridge at the northern end. The EM expression to limestone outcrop is always subdued and flat with little difference between the 3 frequencies used – indicative of very little weathering and a massive, uniform rock body. Despite this site B was chosen on an area of limestone outcrop showing extensive karstic textures and micro sink holes. In theory weathered limestone is clay-free and even resistive sections can yield water from open cavities and fractures.

Figure 7 is annotated and has a text box to briefly explain the features seen on Line 1 and the selection Site A. The remaining geophysical profiles together with resistivity soundings are presented in Annex 1/Appendix 1.

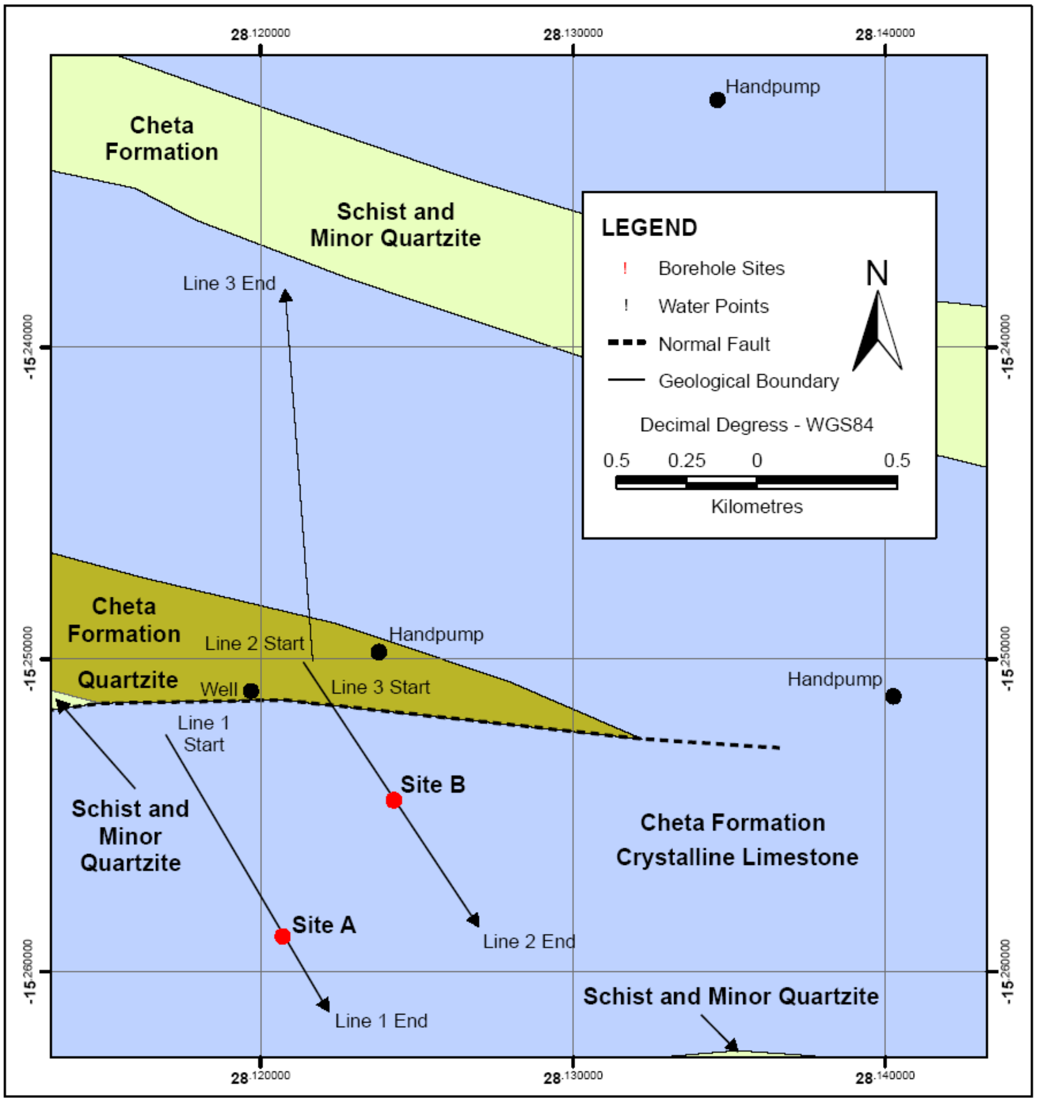


Figure 14: Site Map – Target Area P-1 (Katete)

The map above shows the geophysical lines and borehole sites in relation to mapped geology. Limestone outcrop is observed on all lines coincident with and producing a resistive EM signature. Wherever the EM signature is more conductive then the limestone outcrop is not seen (suggesting a different, more weathered, geology). Conductive portions often have in-situ quartz dyke material at outcrop. The two drill sites (A and B) are selected differently. Site A is within the mapped limits of limestone but only a thin quartz dyke is observed and no limestone – this may be the faulted edge of the limestone and a zone of groundwater channeling / circulation. Schist may also be indicated. Site B is chosen on a definite outcrop of limestone which exhibits miniature karstic features despite having a very resistive EM response, (see the text box next page for more details and also Annex 1/Appendix 1).

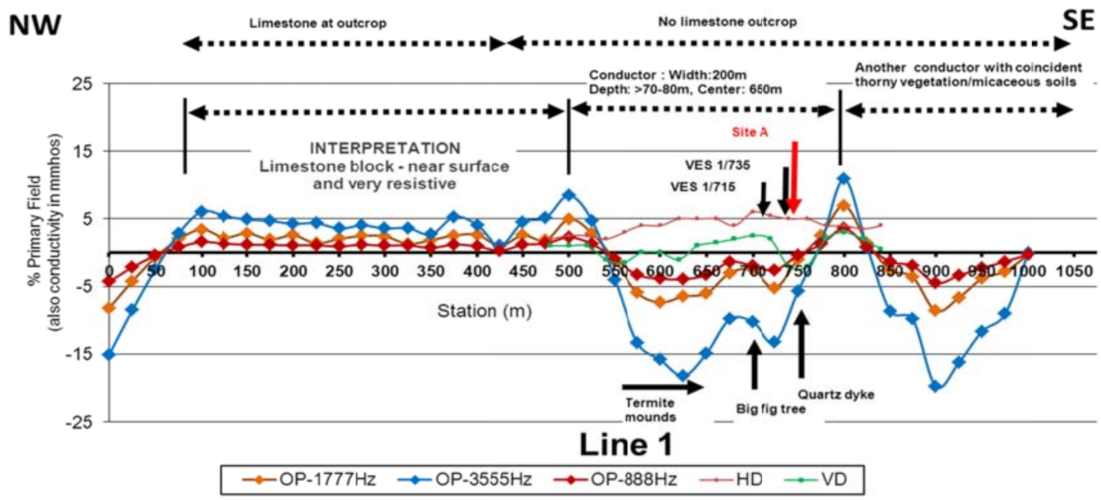


Figure 15: Profile Line 1, Target Area P-1 (Katete)

From Max-Min profiling (flat response) and visual observation - a block of limestone is interpreted between stations 75 and 500meters. From station 550 meters to line-end, at station 1050 meters no limestone outcrop or float is observed at all – but this is well within the area of limestone on the geological map. This zone is coincident with a striking change in the EM profile with two significant conductors centered at 650 and 900 meters. The questions that can be posed are: Are the conductors caused by faulting and thrusting producing a weathered edge to the limestone? Or, are they caused by an un-mapped change in geology? Both scenarios are possible and both could have enhanced groundwater potential. The conductor at the start of this line (0-75m) and those seen on Lines 2 and 3 all exhibit outcrops of highly cleaved quartz dyke material at or near the center points. Indeed a thin quartz dyke is observed within this conductor (750m). This seems to support a dislocated limestone interpretation. Superimposed on this conductor is a short EM-34 profile. This shows the deeper dipole conductivity flicking to negative central to the feature – a response often seen over faulted rock zones. A resistivity sounding (VES) and profile were also conducted and these yielded a narrow resistivity low of 225 Ohm-m at a probing depth of +/- 80-90 meters (Site A). Piezometer positions can be selected on the basis of the drill results. Site B has been chosen on an area of definite limestone outcrop – on Line 2 (Annex 1/Appendix 1).

6.2 P-2: Kasanova Target Area

The survey was executed 19th - 20th July 2011. Short EM profiles were conducted using the EM34 Conductivity Meter in horizontal and vertical–loop modes with a 40m cable and 10m station spacing. The selected borehole position was checked with a Vertical Resistivity Soundings (VES). The Table below details the geophysical survey quantities and positions - the positions are shown on the site map (Figure 8).

Table 9: Geophysical Survey Location and Detail; P-2 Kasanova

ID	Location*		Length (m)	Equipment
	Start	End		
EM Profiling				
Line 1	15.41818 S, 28.19165 E	15.42086 S, 28.19016 E	320	EM34
Line 2	15.41807 S, 28.19118 E	15.41852 S, 28.19212 E	120	EM34
Line 3	15.41889 S, 28.19060 E	15.41903 S, 28.19140 E	70	EM34
VES		**Type of feature**	**Site name**	**Drill depth**
1/000	15.41835 S, 28.19159 E	Dolomite karstic feature	A	<60m
3/005	15.41901 S, 28.19084 E	Dolomite karstic feature	B	<60m

* Decimal degrees (WG84 datum)

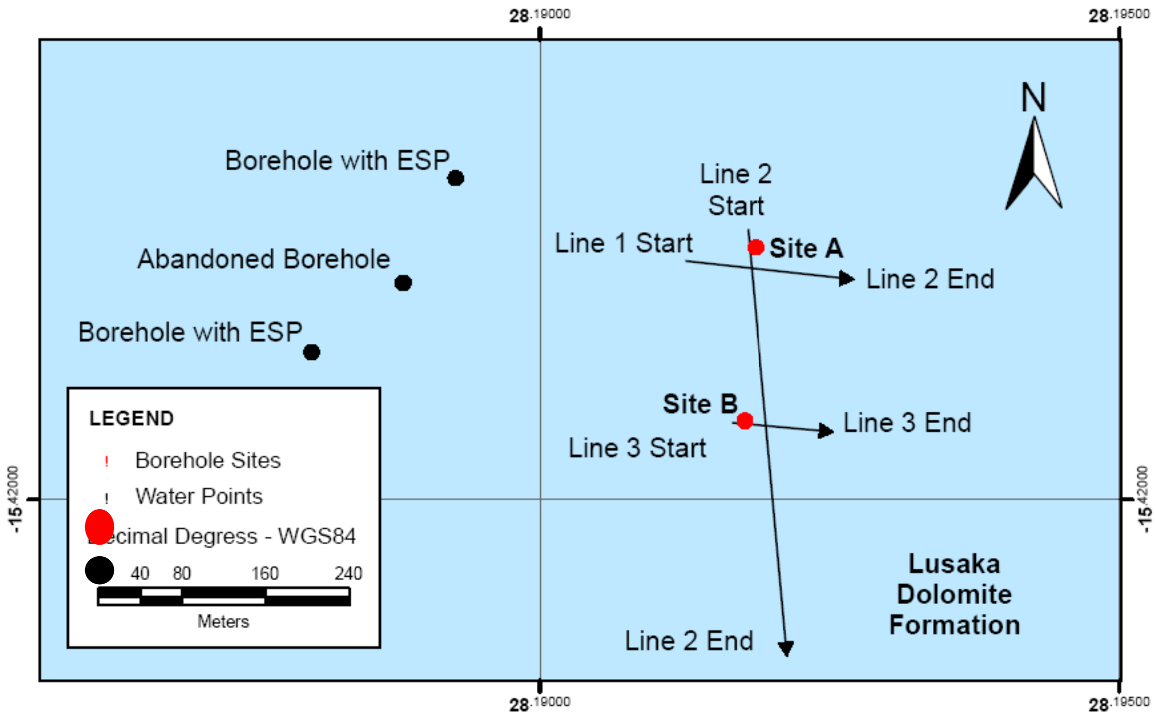
6.2.1 Summary of Geophysical Survey

Profile Line 1 was conducted from the northern edge of Mr. Nacedzis' plot southward to the east side of the convent school. The first 160 meters traverse an area of mature trees and thereafter an area of virtually no vegetation. Dolomite is observed at outcrop at line-end (310-320 meters).

Figure 9 is annotated and has a text box to briefly explain the features seen and the selection of the drill sites. The conductivity variation over the line length is 1-4 mmhos (250-1000 ohm-m) with the shallower horizontal dipole and 1 to -2.5 mmhos with the deeper vertical dipole. The higher values are at the northern-end nearest to the selected spring feature and amid the largest trees. The values progressively decrease southward and out of the vegetated feature. This fits with the observed dolomite outcrop at the southern end of the line – which gives a non-conductive, highly resistive response. Subcrop of dolomite is suspected from station 160m to line end.

The values obtained are typical of dolomite. Vertical Electric Soundings were conducted at station L1/100m and near the start of line 1 (actually on line 2) within the section of highest conductivity. Both show a uniform rise in resistivity with depth. The weathered profile on top of the fresh bedrock is estimated to be less than 20m thick in each position. Below this it is not possible to predict, by geophysical means, whether it is karstic dolomite or massive dolomite. Any water intersected will be fresh.

Two alternative drill sites have been picked on Line 1 and Line 3 within the sections of deepest surficial weathering. The remaining geophysical profiles together with resistivity soundings are presented in Annex 1/Appendix 2.



ESP = Electric Submersible Pump

Figure 16: Site Map – Target Area P-2 (Kasanova)

The map above shows the geophysical lines and borehole sites in relation to mapped geology (blue = Lusaka Dolomite Formation). Dolomite was only observed at outcrop toward the end of Line 2. The two drill sites (A and B) are selected mostly in relation to the morphology and vegetation of the feature under investigation although the conductivity profiles allowed the fine tuning of the drill sites onto zones of thickest weathering.

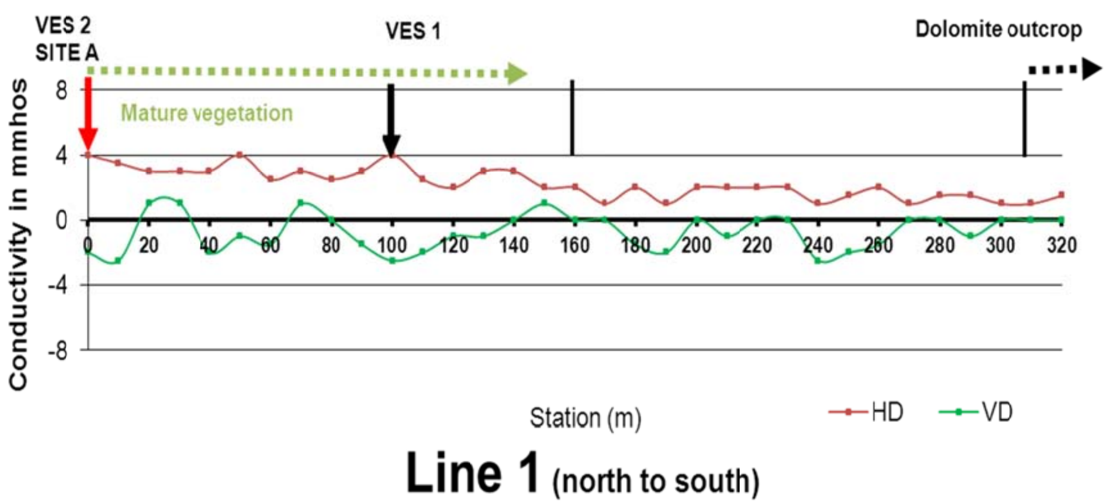


Figure 17: Profile Line 1, Target Area P-2 (Kasanova)

The observed E34 conductivity profile line 1 – can be split roughly into two equal portions. Portion A (0 to 160m) has mature vegetation, elevated horizontal dipole (H_D) and jagged, frequently negative, vertical dipole, (V_D). Over portion B, (160 to 320m) which is not vegetated, the two dipoles converge about the y-axis i.e. highly resistive conditions at shallow depth are indicated. It is interpreted that portion B has dolomite at subcrop, as seen at outcrop at the extreme southern end. This might also explain the lack of vegetation. Portion A, on the other hand, has a deeper weathering zone producing the higher H_D values. Resistivity soundings (VES) indicate that the weathering could go down to +/- 20 meters. The negative V_D, although not very convincing, is indicative of ground which is dislocated at depth. Thus Site A may intersect soils and weathered dolomite to the 20m level followed by fractured, possibly karstified, dolomite thereafter. The big mature trees support this interpretation. Having stated this – dolomite drilling is notorious for springing surprises. A similar feature is chosen at the west end of Line 3 (Site B). The drilling order is A then B (if required). Piezometer positions can be selected on the basis of the drill results. Piezometer 1 will be along profile 20-25m from the borehole and Piezometer 2 will be 40-50m from the borehole in perpendicular sense.

6.3 P-3: Makeni Target Area

The survey was executed between 30th June and 7th July 2011. Long EM profiles were conducted using the Max-Min unit in HLEM mode with a 100m cable, on three frequencies (888, 1777 and 3555Hz) and a station spacing of 25m. These were designed to generally investigate the ground and yielded a number of interesting features (discussed below) which demonstrate that although the ground is flat and uniform the concealed geology and faulting is far from uniform. Over selected sections of these traverses shorter EM lines were conducted using the EM34 Conductivity Meter in horizontal and vertical–loop modes with a 40m cable and 10m station spacing. Finally the selected anomalies were checked with Vertical Resistivity Soundings (VES) – expanding the current (AB) electrodes out to 200 meters. All of these geophysical procedures probe the ground up to 70-80 meters depth. The Table below details the geophysical survey quantities / positions - the positions are shown on the site map (Figure 10).

6.3.1 Summary of Geophysical Survey

Profile Line 1 was conducted from west to east along an old track marking the northern boundary of Sunrise Farm. At station L1/675 meters it crosses an earth wall into an old dam, currently dry. The dam area was selected from satellite imagery as the center of the target area. The profile is interesting having a number of peaks and troughs being almost a mirror image either side of the center point.

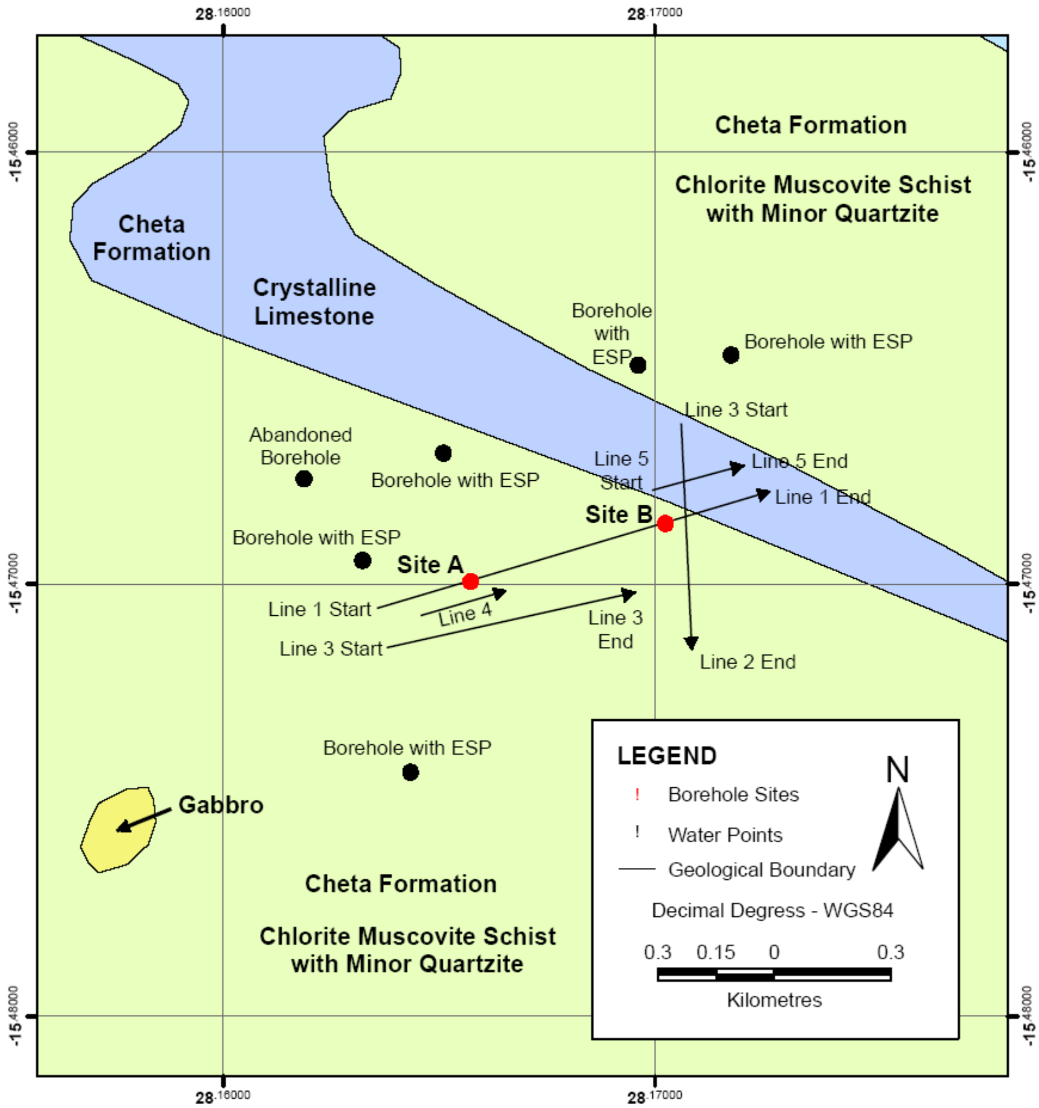
Figure 11 is annotated and has a text box to briefly explain the features seen and the selection of the drill sites. Together with complimentary parallel and perpendicular lines the area is seen to be crisscrossed by numerous conductors which are interpreted as dislocations (possibly fault zones) that cut the otherwise fresh bedrock below the weathering zone. There are so many conductors that the strike or strike directions cannot be accurately determined without surveying in grid fashion - which is beyond the scope of this exercise. From resistivity soundings the weathered profile on top of the fresh bedrock is estimated to be at least 40-50m thick.

Two alternative drill sites have been picked on Profile Line 1. Enhanced groundwater potential and yield are indicated. The remaining geophysical profiles together with resistivity soundings are presented in Annex 1/Appendix 3.

Table 10: Geophysical Survey Location and Detail: P-3 Makeni

ID	Location*		Length (m)	Equipment
	Start	End		
EM Profiling				
Line 1	15.47055 S, 28.16356 E	15.46783 S, 28.17265 E	1,075	Max-Min
Line 2	15.46628 S, 28.17062 E	15.47151 S, 28.17087 E	650	Max-Min
Line 3	15.47125 S, 28.16378 E	15.46991 S, 28.16955 E	325	Max-Min
Line 1/1	15.47001 S, 28.16468 E	15.46896 S, 28.16764 E	360	EM34
Line 1/2	15.46835 S, 28.16983 E	15.46778 S, 28.17265 E	320	EM34
Line 2/1	15.47097 S, 28.16511 E	15.47058 S, 28.16695 E	260	EM34
Line 4	15.47055 S, 28.16463 E	15.46982 S, 28.16650 E	240	EM34
Line 5	15.46782 S, 28.16993 E	15.46724 S, 28.17212 E	240	EM34
VES		**Type of feature**	**Comment**	
1/230	15.46948 S, 28.16573 E	Thick overburden	Site A	
1/760	15.46824 S, 28.17053 E	Thick overburden	Site B	

* Decimal degrees (WG84 datum)



ESP = Electric Submersible Pump

Figure 18: Site Map – Target Area P-3 (Makeni)

The map above shows the geophysical lines and derived borehole sites in relation to mapped geology. It should be noted that no outcrop was observed on any of the lines or within the area generally. Sparse quartz vein float was observed toward the end of line 2 – which may or may not be representative of the underlying rock formation at this point. The two selected drill sites (A and B) are geophysically derived (text box next page).

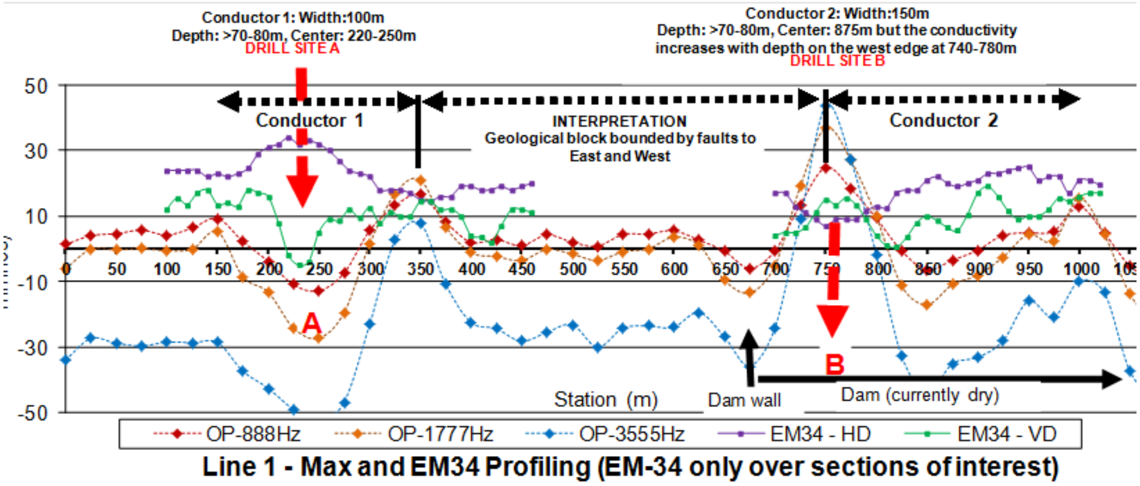


Figure 19: Profile Line 1, Target Area P-3 (Makeni)

From Max-Min profiling two significant conductors are interpreted centered at +/- L1/225-250 and L1/850-900m. A smaller one is seen at station L1/675 coincident / beneath the earth dam wall. The first half or another large one is seen at the east end of the line (it could not be fully profiled due to an intervening brick wall). All of these are most likely the response of fracture trends / geological trends in the bedrock which have been weathered outward and below the general level of weathering - by circulating groundwater. Superimposed are two shorter EM-34 profiles. These show the deeper dipole conductivity (probing to +/- 50 meters) in the range of 5-15 mmhos (or 60-200 Ohm-m) which is an ideal range for groundwater intersection more or less at any point along the profile. Two sites have been chosen. Site A is in the center of Conductor 1 and Site B is on the western edge of Conductor 2 where conductivity is seen to increase with depth. The two targets have differing responses but both indicate deeper zones of weathering – possibly associated with faulting or fracturing and above average ground water potential. The drilling order is A then B (if required). Piezometer positions can be selected on the basis of the drill results. Piezometer 1 will be along profile 20-25m from the borehole and Piezometer 2 will be 50-75m from the borehole in perpendicular sense. Some parallel EM34 lines (Lines 4 and 5) were executed to help position the 2nd piezometer in each instance.

7 Summary of Drill Site Locations

The boreholes have been precisely positioned using geophysical survey – the details are given in Section 6. The sites are also shown on the three location maps located in section 6. The table below summarises the coordinates. The positions of the piezometers may change based on what is encountered in the main drill site. These changes will be reported in the final construction report.

Table 11: Summary of Borehole and Piezometer Locations

Area ID	Type	ID	Latitude*	Longitude*	Notes on feature targeted
Katete					
Target A	Main BH	P1/BH1	-15.25983	28.12107	Inferred fault zone toward southern edge of crystalline limestone. Could be associated with a quartz dyke. Fair yield potential
	Piezo 1	P1/Pz1	-15.25965	28.12094	
	Piezo 2	P1/Pz2	TBD	TBD	
Target B	Main BH	P1/BH1	-15.25546	28.12483	With certainty a limestone intersection – much karstified outcrop. Yield potential very poor (on geophysics) but "hidden" karst features may be present and yield significantly
(alternative)	Piezo 1	P1/Pz1	TBD	TBD	
	Piezo 2	P1/Pz2	TBD	TBD	
Kasanova					
Target A	Main BH	P2/BH1	-15.41835	28.19159	With certainty a dolomite intersection – targeting suspected karstic features
	Piezo 1	P2/Pz1	-15.41845	28.19181	
	Piezo 2	P2/Pz2	-15.41861	28.19154	
Target B	Main BH	P2/BH1	-15.41901	28.19084	With certainty a dolomite intersection – targeting suspected karstic features
(alternative)	Piezo 1	P2/Pz1	-15.41924	28.19078	
	Piezo 2	P2/Pz2	-15.41917	28.19131	
Makeni					
Target A	Main BH	P3/BH1	-15.46948	28.16573	Inferred fault zone through quartzite, schist and psammite. Exact rock type cannot be predicted. Fair yield potential
	Piezo 1	P3/Pz1	-15.46954	28.16550	
	Piezo 2	P3/Pz2	-15.46982	28.16650	
Target B	Main BH	P3/BH1	-15.46824	28.17053	Inferred fault zone through quartzite, schist and psammite (limestone also possible). Exact rock type cannot be predicted. Fair yield potential
(alternative)	Piezo 1	P3/Pz1	-15.46822	28.17071	
	Piezo 2	P3/Pz2	TBD	TBD	

* Decimal degrees (WG84 datum). Pz = Piezometer. TBD = To Be Determined (during drilling programme)

P-1 Katete

Crystalline Limestone is the target aquifer.

Site A lies on mapped limestone although there is none at outcrop in this position. It could be that the borehole intersects quartz dyke material as well as limestone. Schist is also possible. The rock may be faulted / thrusted and therefore have fair to good groundwater potential. The drill depth may be up to 100 meters.

Site B is assured a limestone intersection as it lies on an outcrop of limestone with karstic features and micro sink holes. The groundwater potential is uncertain. The geophysics indicates massive and dry limestone from surface. However, limestone does not weather to clay within karstic features – it dissolves into, and is carried away by, the circulating groundwater, thus the observed resistive signature in both geophysical techniques is not surprising[1]. Indeed, open solution cavities or fissures could yield significantly. The drill depth would be less than 60 meters.

P-2 Kasanova

Dolomite is the target aquifer.

Site A and **Site B** are very similar in observation and measurement (vegetation, geophysical response, soils, etc.). A dolomite intersection is assured as it outcrops less than 100 meters to the south of the sites and geophysical EM measurements indicate dolomite below a shallow weathering zone throughout. EM and resistivity soundings indicate fresh dolomite no deeper than 20 meters below surface. Dolomite does not weather to clay within dislocation features – it dissolves into, and is carried away by, the circulating groundwater, thus the observed resistive signature in both geophysical techniques is not surprising. Indeed, open solution cavities or fissures could yield significantly. Such features are probable as indicated by the mature vegetation, lineament trend (from imagery), and shallow ground water which rapidly rises and discharges / floods the area after storm events. The drill depth would be less than 50-60 meters.

P-3 Makeni

A mixed Schist – Psammite – Quartzite association is the target aquifer. There are no rock outcrops within this target area.

Site A has been chosen on a geophysically determined conductor (negative). This is interpreted as a sub-vertically orientated fault zone or geological unit or combination which has been weathered more deeply than the general weathering profile – possibly deeper than 50 meters (from resistivity measurements). The site has good groundwater potential. The drill depth may be up to 100 meters.

Site B has also been chosen on geophysically determined conductor (positive). This is interpreted as a sub-vertically orientated fault zone or geological unit or combination which has been weathered more deeply than the general weathering profile – possibly deeper than 30 meters (from resistivity measurements). The exact nature of this concealed target is quite different from that of Site A. According to the geological map crystalline limestone occurs in the vicinity although there is no outcrop at all to support this deduction. Thus Site B is not thought to be on limestone. The site has fair groundwater potential. The drill depth may be up to 100 meters.

[1] It is the clay content of a dislocation zone which the EM / Resistivity technique sense – and by inference the experienced Hydrogeologist can suggest that there is a weathered dislocation zone and that this is full of groundwater below a certain depth.

PART B

Supervision of Drilling and Test Pumping

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Abreviations

BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources)
BH	borehole
CDT	Constant discharge test
DO	Dissolved oxygen
DWA	Department of Water Affairs
DWL	Dynamic water level
EC	Electrical conductivity
EM	Electromagnetic sounding
GReSP	Groundwater Resources for Southern Province
HP	Horsepower
m b.g.s.	Meter below ground surface
pH	measure of the activity of the (solvated) hydrogen ion
Q	Borehole yield
RT	Recovery test
s	Drawdown
ST	Step drawdown test
SWL	Static water level
ToR	Terms of Reference
UNZA	University of Zambia (Lusaka)
WGS84	World Geodetic System (1984 revision)

INTRODUCTION

The BGR (Federal Institute for Geosciences and Natural Resources) together with the Department of Water Affairs, (DWA) is implementing a scientific program which will advance groundwater resource management generally in Zambia and particularly in Southern and Lusaka provinces. The project is known as GReSP.

As part of their program GReSP has designed a project and called for tender to construct 3 boreholes and 6 piezometers in 3 selected target areas / aquifers in Lusaka District and thereafter to test pump the boreholes and measure the aquifer responses in all boreholes and piezometers. From the time-drawdown data GReSP will determine the aquifer parameters of Transmissivity and Storage etc.

The basic Scope of Works for the supervisory component of this project is:-

a) Identification of sites for drilling / test pumping (field visits and geophysical methods)
b) Preparation of drilling and test pumping contract documents
c) Hydrogeological monitoring of drilling works
d) Hydrogeological monitoring of test pumping works
e) Hydrogeological reporting

A desk study and the siting of boreholes in the three target areas was completed in July 2011 (Anscombe 2011).

This report has been prepared by Jim Anscombe, free-lance Hydrogeologist and the appointed supervisory consultant for this study. The report details the hydrogeological monitoring of the drilling works and the test-pumping

1 GENERAL

1.1 Design of Main Boreholes for Pumping Tests

In all three target areas two rigs, drilling simultaneously were applied. All boreholes were piloted at 6” (150mm) diameter. Most sites required temporary steel casing to be set to prevent surface collapse. This temporary casing was generally less than 20m in length and mostly removed after PVC casing and screen installed. Surface reaming allowed this temporary casing to be installed

Within each target area the borehole with the best yield was selected for test pumping and subsequently reamed out at 305mm so that it could accommodate 200/185mm blue, flush-threaded PVC pipe casing. Approximately 50% of the casing screen was bench slotted at Lamasat Ltd. The slot design was 5 continuous vertical rows measuring 1mm by 60mm set 10mm apart. The open area is calculated at 8%.

Main boreholes were stabilized by pouring sieved rounded quartz gravel into the annulus outside the PVC casing and screen. The source of the gravel was the Luangwa River. 2 - 5m^3 of gravel was required per borehole. The bottommost piece of PVC casing was closed with a manufactured end cap. Adjustable centralisers were used, one per casing length, (2.92m) in order to centralize the casing in the bore.

No deterioration in air-lift yield was noted before and after screen placement.

1.2 Design of Piezometers for Observation

In each target area the boreholes not selected for test pumping were converted into piezometers or observation boreholes. This was a simple process of flushing out the 6” (150mm) pilot hole and then inserting 3” (75mm) PVC socket and spigot casing (glued joints). Once in position, sand was poured into the annulus (as above).

The length of the casing installed did not need to exceed the depth of the adjacent main borehole. Therefore some of the piezometer holes were backfilled with gravel to the appropriate depth. To ensure a responsive water column within the piezometers two to three 6-meter lengths of installed PVC casing were rough slotted on site using a hacksaw (about 100 slots per borehole). The bottommost piece of PVC casing was closed by cutting and folding over the end.

All piezometers constructed in the described manner were checked firstly by dipping the depth and static water line with plumb line and dipper respectively and secondly by inserting an air-line and surging / cleaning immediately after casing insertion was complete. All yielded water showing that they are responsive and operative.

1.3 Design of Protective Caps

The Contractor came up with an effective method of borehole protection which differed from that in the ToR. For all drilled boreholes a 1-meter section of appropriate diameter steel casing was set over the projecting PVC pipe. Thus there is about 0.7m below ground surface set in concrete and about 0.3m above ground surface. This is set in a concrete square. Each has a loose fitting steel cap through which a bolt fits complete with padlock and key. All main boreholes and piezometers are therefore secure for the interim period.

1.4 Budget Usage

It was budgeted to drill two piezometers at each site. The drilling meter budget was 100 meters per hole. Because many of the boreholes, particularly the piezometers, were considerably less than 100m (notably Kasanova and Makeni) it was possible to drill extra piezometers.

Thus the Makeni and the Katete sites each received 3 piezometers whilst Kasanova received 2. An extra exploration borehole was also possible in Target area B in Katete area.

The final borehole drilled was P1/4 in Target Area A in Katete and this fully utilized the drilling budget. Budget contingencies were not utilized.

2 DRILLING RESULTS: P1- Katete

2.1 Statistics

Four boreholes were drilled in target area A and one in target area B. Summary statistics are given in the Table below. The main borehole is shown in red highlight and the piezometers in blue highlight. Graphic logs of all 5 Katete boreholes are given in Annex 2-1.

Table 1: Hydrogeology: P1 - Katete

BH ID	Coordinates (WGS84)		Orientation (to main borehole)		Depth (m)	SWL (m b.g.s)	Quality (ppm)	Yield est. (L/s)	Predominant Geology
	South	East	Distance (m)	Bearing (deg)					
Target Area A									
P1/1	15.25984	28.12106	11.85	289	100	7.00	460	3	Mica Schist
P1/2	15.25969	28.12099	32.10	277	100	5.89	450	2	Mica Schist
P1/3	15.25992	28.12116	0	0	90	7.69	380	12	Limestone
P1/4	15.26008	28.12104	23.90	197	50	5.25	460	20+	Limestone
Target Area B									
P1B/1	15.25538	28.12370	-	-	100	9.00	380	1	Limestone

P1/3 - Main borehole **P1/2 - Piezometer**

2.2 Site Plan

Figure 1 below gives the orientation and position of the 3 piezometers relative to the main test pumping borehole P3/1.

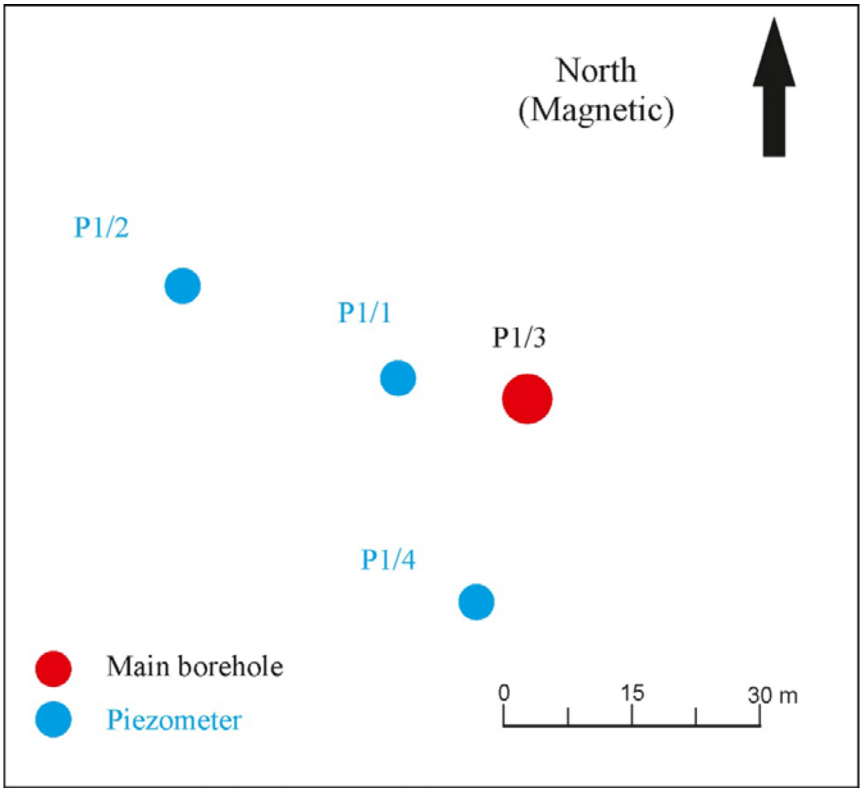

Figure 1: Main Borehole and Piezometer Positions: P1 (Katete)

2.3 Geological Interpretation

The first two boreholes in Target Area A intersected predominant mica schist – as opposed to the intended limestone aquifer. One borehole in Target Area B was then attempted. This intersected pure limestone and a karstic feature at 97m full of coarse river sand! The yield was not very high so the remaining drilling budget was applied back in target Area A. The 3rd and 4th boreholes fortunately intersected predominant crystalline limestone – a successful outcome.

Both Target Areas are within the Cheta Formation as shown on the geological maps. The intersected mica schist is a subordinate unit of this formation. The observed quartz float between the mica schist in boreholes P1/1, P1/2 to the north and P1/4 to the south is probably fault or shear-plane related and the observed hydrogeology related to this as well as the two different rock types. Other, much broader outcrops of quartz float are seen mostly to the north flanking the hill and these may also be of hydrogeological significance.

2.4 Review of Geophysics

Figure 2 below shows a section of the Max-Min profile relevant to Target Area A – on which 2 borehole positions are superimposed in their correct positions (P1/1 and P1/2 – both piezometers). Both of these intersected mica schist and this can therefore be correlated with the EM negative.

The main borehole and the last-drilled borehole (P1/3 and P1/4) intersected much crystalline limestone, fault breccia and much water. They are not exactly on the EM profile line but both are close, (P1/4 is shown). The inference is that the EM high marks the position of sub-crop of crystalline limestone with quartz fault breccia separating the schist from the limestone[1].

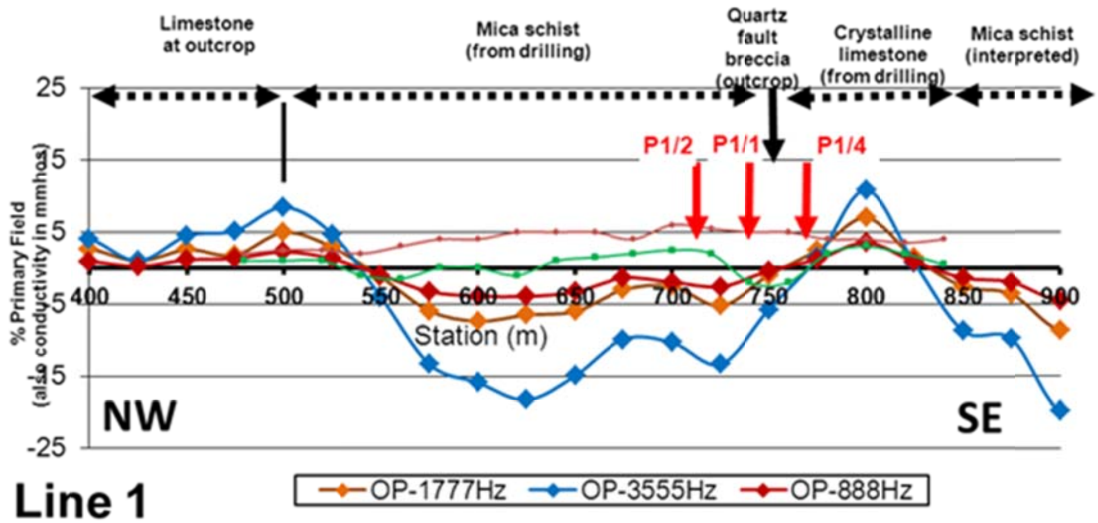

Figure 2: Reconciliation of Geophysics with Drilling Results: P-1 (Katete)

[1] The rocks in this area may be folded as well as faulted and therefore several other more complex interpretations are possible.

3 DRILLING RESULTS: P2- Kasanova

3.1 Statistics

Three boreholes were drilled in target area A. Summary statistics are given in the Table below. The main borehole is shown in red highlight and the piezometers in blue highlight. Graphic logs of all 3 Kasanova boreholes are given in Annex 2-2.

Table 2: Hydrogeology: P2 - Kasanova

BH ID	Coordinates (WGS84)		Orientation (to main borehole)		Depth (m)	SWL (m b.g.s)	Quality (ppm)	Yield est. (L/s)	Predominant Geology
	South	East	Distance (m)	Bearing (deg)					
Target Area A									
P2/1	**15.41832**	**28.19164**	**18.05**	**322**	**100**	**1.20**	**350**	**2**	**Dolomite**
P2/2	**15.41837**	**28.19176**	**0**	**0**	**50**	**1.44**	**340**	**20+**	**Dolomite / Karst**
P2/3	**15.41858**	**28.19185**	**29.35**	**186**	**41**			**12**	**Dolomite / Karst**

P2/2 - Main borehole **P2/3 - Piezometer**

3.2 Site Plan

Figure 3 below gives the orientation and position of the 2 piezometers relative to the main test pumping borehole P2/2.

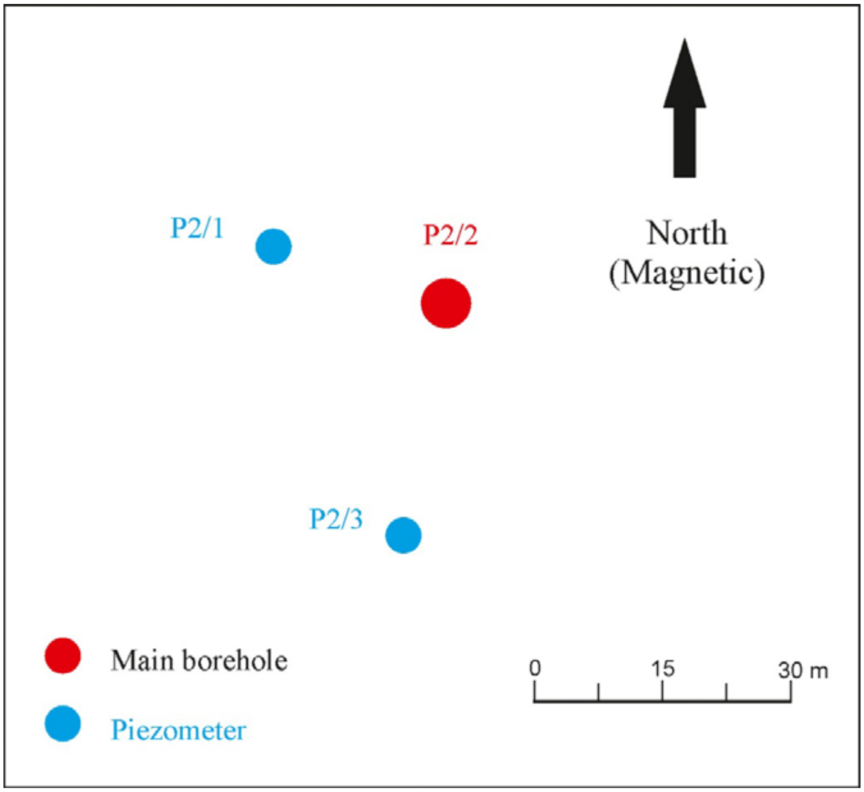

Figure 3: Main Borehole and Piezometer Positions: P2 (Kasanova)

3.3 Geological Interpretation

All three boreholes intersected the Lusaka Dolomite. The 1st P2/1 was drilled to 100 meters depth and intersected about 2 L/s of water within narrow cracks in massive dolomite. The remaining two boreholes although they intersected dolomite were quite different in that they both penetrated a karstic solution cavity about 20 meters deep within the upper 30 meters or so. P2/2 intersected this feature from surface to 25m whereas P2/3 collared in hard dolomite before hitting the karst at 9-10 meters depth. Very high yields were obtained in both these boreholes and P/2 was selected as the main borehole for pump testing.

Whilst drilling P2/2 a surface dolomite sink hole measuring about 20 x 10 meters was “discovered“ in heavy undergrowth about 50 meters to the north-east. It is suspected that P2/2and P2/3 link to this same feature.

3.4 Review of Geophysics

The two productive boreholes (P2/1 and P2/2) fall 20 to 30m east of the EM profile line and resistivity sounding and are therefore not directly comparable.

Figure 4 below shows the position of the lower yield piezometer relative to EM Line 2. Typical of dolomite geophysical profiles - very little can be gained by retrospective diagnostics. The coincident resistivity sounding indicated weathering down to about 17 meters depth which was optimistic because hard dolomitic rock was intersected at only 8 meters.

It would be interesting to retrospectively survey with EM and resistivity exactly over P2/2 and P2/3 as the red-mud infill intersected in both boreholes within 20-30m deep karstic features should register as lower resistivity to larger AB with the resistivity and higher conductivity on both EM34 coil positions.

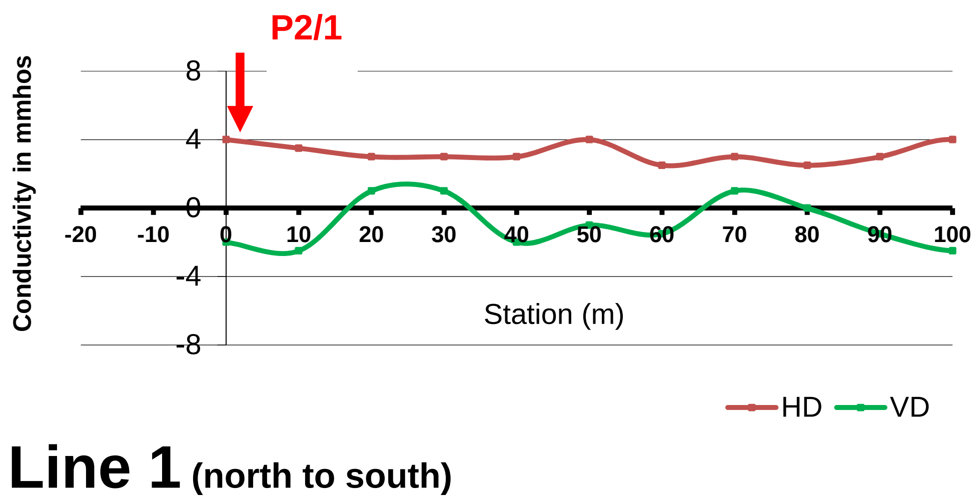

Figure 4: Reconciliation of Geophysics with Drilling Results: P-2 (Kasanova)

4 DRILLING RESULTS: P3- Makeni

4.1 Statistics

Five boreholes were drilled in Target Area A. Summary statistics are given in the Table below. The main borehole is shown in red highlight and the piezometers in blue highlight. Graphic logs of all 5 Makeni boreholes are given in Annex 2-3.

Table 3: Hydrogeology: P3 - Makeni

BH ID	Coordinates (WGS84)		Orientation (to main borehole)		Depth (m)	SWL (m b.g.s)	Quality (ppm)	Yield est. (L/s)	Predominant Geology
	South	East	Distance (m)	Bearing (deg)					
Target Area A									
P3/1	**15.16939**	**28.16570**	**0**	**0**	**66.56**	**12.06**	**370**	**12**	**Schist / Limestone**
P3/3	**15.46946**	**28.16880**	**13.45**	**77**	**50.19**	**11.74**	**370**	**5**	**Schist / Limestone**
P3/4	**15.46982**	**28.16576**	**33.1**	**184**	**40.49**	**12.44**		**5**	**Schist / Limestone**
P3/5	**15.46932**	**28.16569**	**21.8**	**350**	**50.01**	**11.38**		**5**	**Schist / Limestone**
Abandoned									
P3/2	15.46960	28.16550	23.7	65	-	-	370	15	Schist / Limestone

P3/1 - Main borehole **P3/3 - Piezometer**

4.2 Site Plan

Figure 5 below gives the orientation and position of the 3 piezometers relative to the main test pumping borehole P3/1.

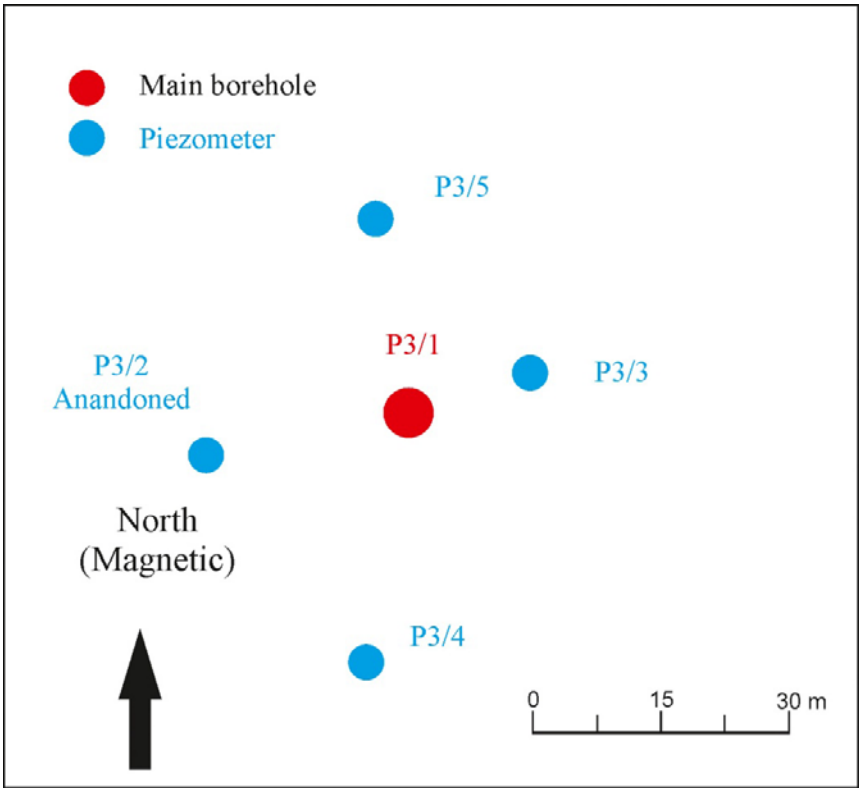

Figure 5: Main Borehole and Piezometer Positions: P3 (Makeni)

4.3 Geological Interpretation

All 5 boreholes drilled within Target Area A are within 60m of one another and yet the geological units intersected are both varied in type, depth and thickness. Apart from soil the following rock type are identified:-

- Calcareous mica schist – mostly as powder but also as large angular chips (to 10cm)
- Crystalline limestone - often as coarse sand sized material or large angular chips
- Dark grey, fine and hard quartzitic psammite – as chips (to 1cm)

It is suspected that these units are steeply dipping and that the target area chosen (on geophysics – below) is faulted. Fault zones are often infilled with fault breccia and when drilled, the button bit catches and excavates the breccia as large angular pieces – as seen particularly in boreholes P1/2 and P1/4. Brecciated zones also usually yield large quantities of water – which is seen.

As crystalline limestone is seen in most of the intersections another interpretation or composite interpretation is that small karstic features have been intersected. These would also develop along old faults or dislocations in limestone and these would subsequently infill with exotic material. Indeed apart from the above rock description minor exotic pieces were also ejected from the well heads during drilling – particularly P1/2 and P1/4 – including minor rounded gneiss and igneous pieces.

The boreholes in Target Area A appear to have tapped an aquifer within schist, quartzite and psammite (and limestone) of the Cheta Formation as shown on the geological maps.

4.4 Review of Geophysics

Figure 6 below shows a section of the Max-Min and EM34 EM profile relevant to Target Area A – on which 3 borehole positions are superimposed in their correct positions (Main borehole P3/1, and Piezometers P3/2 and P3/3).

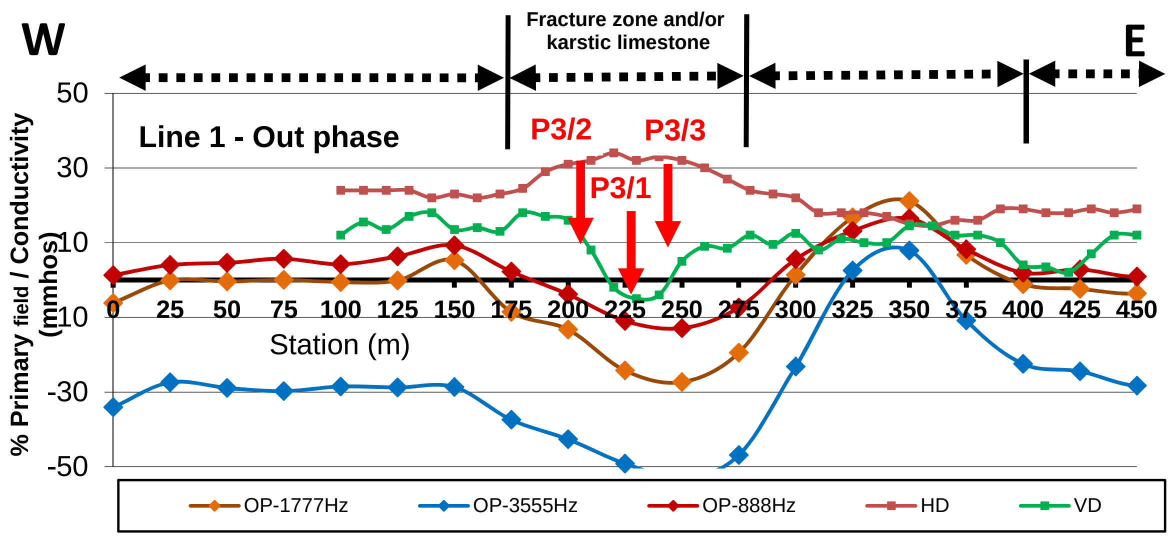

Figure 6: Reconciliation of Geophysics with Drilling Results: P-3 (Makeni)

P3/2 (on-line) and P3/4 (off-line to south) both intersect similar thick units of fault breccia amid a mica schist – limestone section. Together they define a dislocation zone orientated NNW-SSE. These two boreholes are on the western edge of the EM Max-Min negative. The main borehole (P3/1) is central whilst piezometer P3/3 lies on the eastern edge of the same negative.

5 TEST PUMPING PROGRAMME

5.1 Summary

Table 4 presents the planned test pumping schedules for each site versus that actually achieved. In summary all boreholes and piezometers except P2/1 at the Kasanova site1 (subdued response) proved responsive with good data provided by both manual and automated water level recorders.

The Makeni borehole proved to have the highest yield whilst both the Kasanova and Katete boreholes performed well below the air-lift yield observed during drilling. This is particularly relevant to the Kasanova borehole where air-lift indicated a yield of +/- 20 L/s but during test pumping calibration is could not manage more than 4-5 L/s. The yield zone is now known to be very shallow at only 10m b.g.s – which partly explains the behaviour. These matters are discussed more in the sub-sections below.

Water levels were recorded at the main borehole by manually operated electronic dippers and by automatic barometric data loggers – each running inside 32mm poly pipes. All dipper pipes were open ended allowing water levels to adjust. For the observation boreholes the PVC pipes installed had an ID of 60mm thus only one 32mm (OD) dipper pipe could be installed. This was used for the manual dipper whereas the automatic logger was first suspended in the main casing, followed by the manual dipper pipe.

The 125mm (OD) GI pipe, 2 x 32mm (OD) dipper pipes, power cable and security line tied at intervals with tie straps and/or insulation tape, fitted with a small margin of clearance inside the 180mm (ID) PVC borehole casing. This is mentioned as it will help in planning any future test-pumping programmes. Higher yields will require a larger diameter ESP pump and correspondingly larger diameter PVC borehole casing.

Table 4: Test Pumping – Planned Versus Actual

Area	Bore-hole	Air-lift yield range (L/s)	Pump test pipe diameter (ID - mm)	Steps (L/s)	CDT (L/s)	Pump depth (m)	Discharge outlet (m)
Planned							
Katete	P1/3	12-18	100/125	3, 6, 9, 12, 15	(8)	70-75	150
Kasanova	P2/2	20-30	125	10,15,20,25,30	(25)	40-45	150
Makeni	P3/1	12-18	100/125	4, 8, 12, 16, 20	(15)	55-60	150
Actual							
Katete	P1/3	12-18	45	0.5, 0.9, 1.7, 2.3, 2.8	2.69	42.5	100
Kasanova	P2/2	20-30	45	0.5, 1.1, 1.8, 2.7, 3.6	3.27	42.5	100
Makeni	P3/1	12-18	95	4, 9, 11, 12, 13	14.12	56.5	150

CDT: Constant Discharge Test

5.2 Contractor and Equipment

As with the drilling, Zambezi Drilling and Exploration Ltd executed the pumping test programme at the 3 sites[2]. The mode of pumping was with an electric submersible pump (ESP) powered by a 380V output generator. Two pumps were used:-

- 25HP KSB 12 stage ESP – with 3” outlet coupled to 4” GI riser pipe
- 7.5 HP KSB 6-stage ESP – with 2.5” outlet coupled to 2” poly riser pipe

Figure 7: 4” discharge pipe at well head

Figure 8: 4” discharge pipe at discharge point

Figure 9: 2” discharge pipe at discharge point

Figure 10: 2” discharge pipe at well head

[2] Used a sub-contractor – Water Mark Services Ltd managed by Mr. Mweene.

Some factors related to the Contractor and their equipment were experienced, which impacted somewhat on test control mechanisms and, ultimately, the data collected:-

- Locally available couplings and valves were of lesser diameter than the rising main and surface roll-flat discharge pipe. This undoubtedly increased friction losses and reduced discharge yield. Larger diameter gate valves (6”) were tried but these proved very difficult to adjust and also seemed to cause pressure rupturing more often than the smaller (4”) gate valves.
- The 25HP pump caused very high pressures to build up inside the discharge line particularly at lower yield settings. The roll-flat discharge line ruptured at the first attempt on the first site and was replaced by class 10 PVC poly-pipe. This latter pipe could withstand the pressures but the “4” diameter” was in fact the outer diameter. The inner diameter of about 95mm again represented a yield-reducing constriction. The poly to poly and GI pipe to poly fittings proved susceptible to the high pressures and at least 8 ruptured during the course of the aborted step and constant discharge tests at the Katete site.
- With the ESP set-up, the yield tended to drop as the water level descended, i.e. slight increase in total head as the tests proceeded. This is a very difficult factor to control at the discharge point – particularly when the valve is fully open and delivering at maximum yield.
- The Contractor had only done single, pumped-borehole water level measurements in past programmes and had only executed constant discharge tests (not multi-yield step tests). Consequently the provided crew and the number of dippers were insufficient. This was resolved by the loan of 2-dippers from the Consultant and 2-dippers from the Client! The Client also managed the yield at the end of the discharge line during both step and main tests. These points track-back to the original observation during tendering that local professional test-pumping expertise is not available in Zambia.

The use of DWA automatic water level recorders in all boreholes was deliberately included because of possible lack of experience by the Contractor and this indeed proved effective, because regardless of these shortcomings – the programme eventually concluded with reasonable data sets from all sites.

All points considered any future test pumping programme should use a belt and shaft-driven mono-pump. Discharge would be controlled via gearbox, different drive-head diameters and engine speed via a laser rev-counter on the engine flywheel. Pressure build-up would not be an issue with this set-up and yield could easily be controlled and maintained constant. Two mono pump sizes and discharge pipes would be needed to cater for medium and high discharge rates.

5.3 Data Analysis

Data analysis is to be done by the Client using preferred software. In this report the data sets are presented and some of the graphical presentations as a means of demonstrating data integrity.

6 TEST PUMPING RESULTS: P1 - Katete

6.1 General

Step Test 1 (ST1) and Continuous Discharge Test 1 (CDT1) were attempted in the period 25th – 28th March 2012 but both failed to complete the contract duration. ST1 aborted a few minutes into the 4th step when the water level reached the pump intake. CDT1 aborted at the 22nd hour when the discharge pipe disconnected at one of the poly connectors. Both problems are linked in that the yield of the borehole was considerably lower than indicated by the drilling results and the consequent difficulty in adjusting and containing pressure build-up with the 25HP ESP set-up. It was decided to demobilize to Kasonova before returning with a smaller pump.

The ST2 and CDT2 were successfully performed between 8th and 12th April 2012 with a 7.5 HP ESP. The diameter of the discharge line reduced from 93 to 45mm with poly pipe from top of the pump to the discharge point – 100m downslope of the pumped borehole. GI pipe, elbows and fittings were used at the well head and at the end of the discharge where the poly-pipe was joined to 2" GI pipe with valves to control the flow.

On 11th April the person cultivating the area around the four Katete boreholes stole three of the four water level data sheets (mid-way through the Recovery Test (RT)) and these were not retrieved until 20th April, following protracted discussions with Police and other parties.[3]

There were light showers (<10mm) at intervals during the CDT2 but none were significant enough to affect the aquifer and test measurements. There were several short-duration calibration tests before ST1 and also on the day prior to ST2.

At least 4 attempts to start CDT1 were made but aborted due to pipe-burst at the various in-line couplings. The pumping times range from 2 to 20 or more minutes of pumping – which will be seen in the data of the automatic loggers.

6.2 Step Tests

Tables 5 and 6 together with Figures 7 and 8 present a summary of the two step tests performed on the Katete borehole P1/3. The test data are presented in the original drilling and supervision report (Anscombe 2012).

6.2.1 Step Test 1

ST1 was conducted with a 25HP pump in anticipation of a yield in the order of 10 L/s (from measurements made during drilling). However at a rate of 5.6 L/s the water level quickly descended to pump intake at 72.5m b.g.s. It was attempted to run the pump at reduced steps but this proved very difficult due to the pressure created in the discharge line at yields below 3 L/s. The step test data is good but expired in the 4th step as the water level reached pump intake.

[3] The Contractor generously decided to donate a hand pump, inclusive of labour and civil works to satisfy the demands of the rural community.

Table 5: Step Test 1; P1/3, Main Borehole, (Katete)

STEP	BH depth (m)	Pump Depth (m)	SWL start (m b.g.s)	DWL end (m b.g.s)	Drawdown, s (m)	Step yield (L/s)	Q (m^3/day)	Specific Capacity (m^3/m/day)
1	90	72.5	6.62	26.74	20.12	3.27	282	14.02
2			26.74	42.07	35.45	4.36	377	10.62
3			42.07	57.47	50.85	5.35	462	9.09
4*			57.47	71.99	65.37	5.64	488	7.46

*** Aborted, (water level at pump intake after 22 minutes)** BH = Borehole, SWL = Static Water Level, DWL = Dynamic Water level, m b.g.s = meter below ground surface

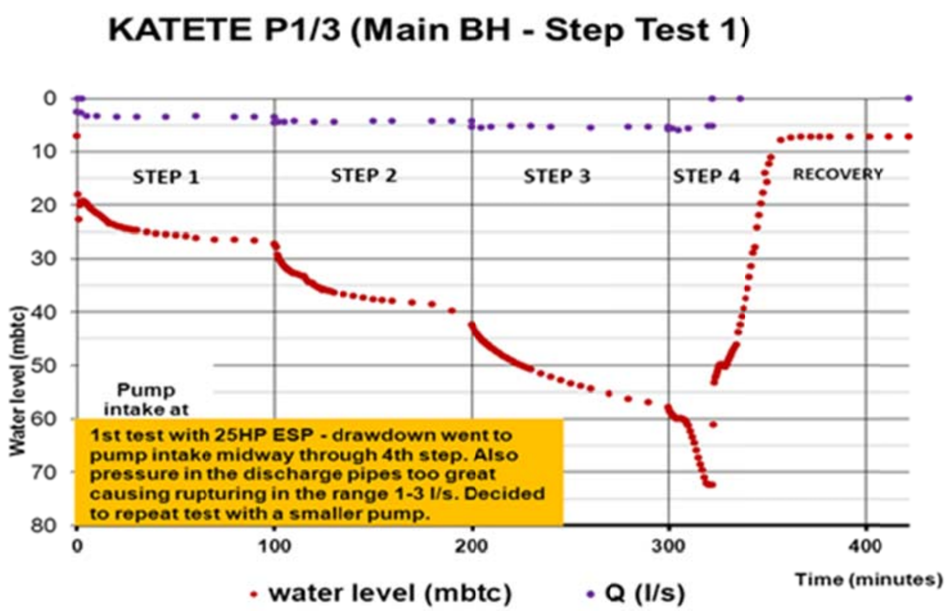

Figure 11: Step Test 1; Time-Drawdown Characteristics, P-1, Main Borehole, (Katete)

6.2.2 Step Test 2

ST2 was conducted with a 7.5HP pump with intake at 42.5m b.g.s. Five steps were designed in the range 0.5 – 2.6 L/s and were successfully executed. Manual and automatic water level data quality is good and comparable.

Table 6: Step Test 2; P1/3, Main Borehole, (Katete)

STEP	BH depth (m)	Pump Depth (m)	SWL start (m b.g.s)	DWL end (m b.g.s)	Drawdown, s (m)	Step yield (L/s)	Q (m^3/day)	Specific Capacity (m^3/m/day)
1	90	42.5	6.61	7.09	0.48	0.47	41	84.78
2			7.09	8.05	1.44	0.93	81	55.92
3			8.05	10.14	3.53	1.62	140	39.60
4			10.14	12.28	5.67	2.16	187	32.93
5			12.28	16.24	9.63	2.61	226	23.43

BH = Borehole, SWL = Static Water Level, DWL = Dynamic Water Level, m b.g.s = meter below ground surface

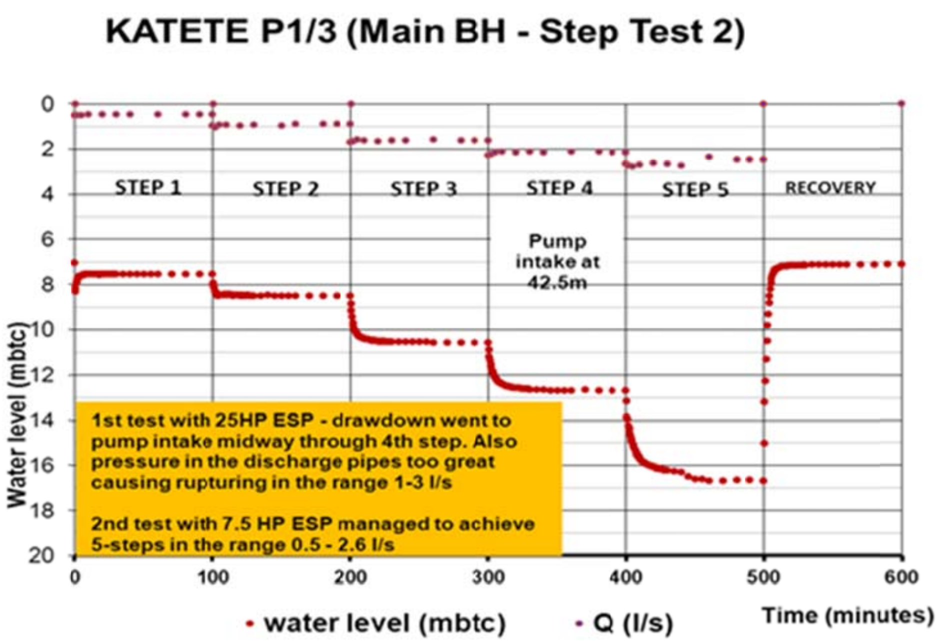

Figure 12: Step Test 2; Time-Drawdown Characteristics, P-1, Main Borehole, (Katete)

The nearest piezometer (P1/2) and the furthest (P1/4) responded with a drawdown of about 0.6m during the course of ST 2 (Table 7, and Figure 9). The intermediate piezometer (P1/4), on the south side, had a drawdown of about 25% this value at 0.16m. P1/4 also had, by far, the highest yield of all 4 boreholes. A heterogeneous or asymmetrical aquifer is indicated.

Table 7: Step Test 2; Measurements at Main Boreholes and Observation Boreholes, (Katete)

BH	ID	Distance (m)	Direc tion	Yield range of steps (L/s)	SWL (m b.g.s)	Drawdown, s (m)	100 minute Recovery (%)	Comment
P1/3	Main	0	-	0.5 – 2.6	6.61	9.63	99	Good response
P1/1	Piezo meters	11.85	W	-	6.07	0.60	95	Good response
P1/2		32.10	W	-	5.64	0.16	75	Poor response
P1/4		23.90	S	-	6.48	0.57	91	Good response

BH = Borehole, SWL = Static Water Level, m b.g.s = meter below ground surface

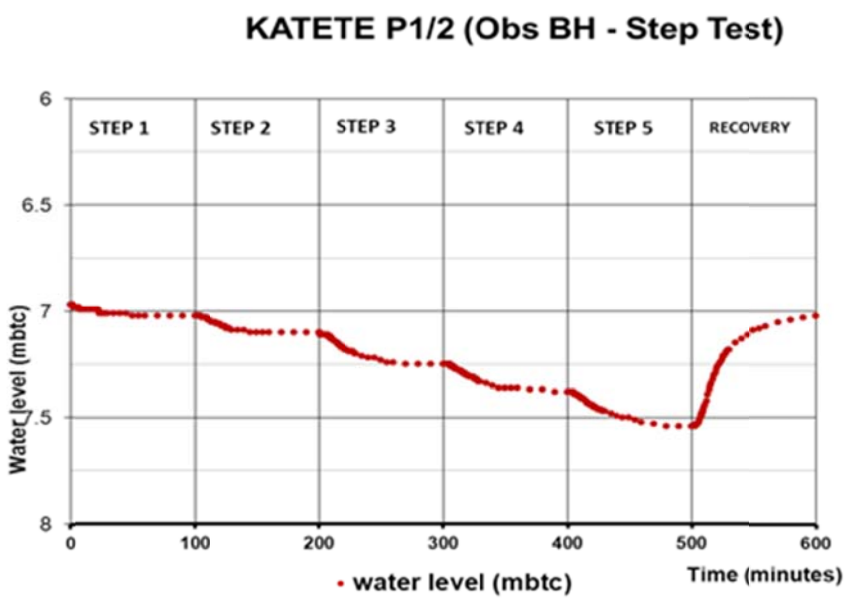

Figure 13: Step Test 2; Time-Drawdown Characteristics, P1/2 Observation Borehole, (Katete)

6.3 Constant Discharge Tests

Figure 10 shows the yield variation during the 2-day CDT2. The average yield was 2.69L/s within a range of 2.61 to 2.83 L/s and a standard deviation of 0.05. The discharge yield is the sum of the yield at the end of the discharge line and that passing through the flow cell near the wellhead which was constant at 0.3 L/s.

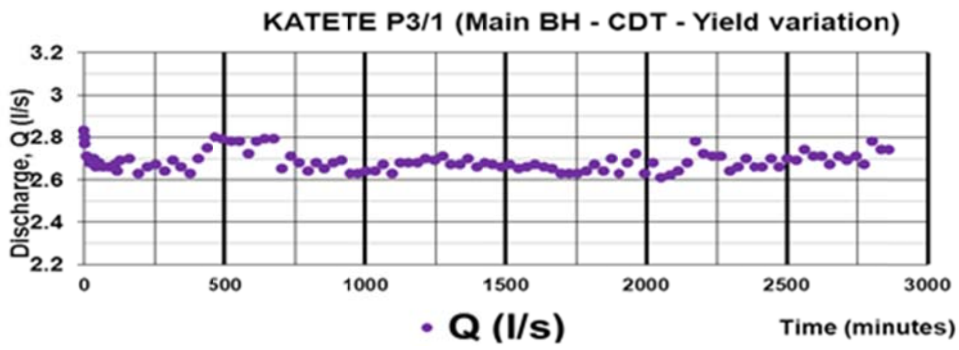

Figure 14: Constant Discharge Test 2; Discharge Variation, P1/3 Main BH, (Katete)

Table 8 and Figures 11 to 14 present a summary of the CDT2 including the reaction of 2 of the 3 piezometers. The test data including discharge measurements and the data for the aborted CDT1 are presented in the original drilling and supervision report (Anscombe 2012). For CDT2 the pump remained at 42.5m b.g.s and the discharge outlet 100m down-slope to the south.

A Specific Capacity is calculated from the CDT by dividing total yield by total drawdown to give a very high figure of 22.81 m^3/m/day. This is a first approximation of aquifer transmissivity, T, but being of the pumped well is affected by compound well losses. It is more accurately obtained from software analysis of the observation borehole time-drawdown data, which looks possible on P1/1 and 1/2.

As with the ST the responses of the piezometers is asymmetrical indicating a heterogeneous, possibly linear aquifer. The nearest (P1/1) and most distant (P1/2) piezometers – both on the north side of the pumped borehole – both have the same drawdown over 48 hr (0.7m). Contrasting with this is the intermediate piezometer (P1/4) to the south, which has a much reduced drawdown (and recovery) of just 0.36m. These differences are undoubtedly related to geological and structural variations in the area – which combined control the disposition and behaviour of the aquifer.

Table 8: Constant Discharge Test; Measurements on Main Borehole and Observation Boreholes (Katete)

BH ID	BH depth (m)	Pump / Dipper Depth (m)	SWL start (m b.g.s)	Drawdown, s			Avg. yield (L/s)	Specific Capacity (m^3/m/day)	1 -day recovery (%)
				Available (m)	Achieved (m)	Utilized (%)			
P1/3	Main	42.50	6.80	35.70	10.18	28.5	2.69	22.81	99
P1/1	Piezo meter	40.00	6.08	33.92	0.68	2.0	-	-	96
P1/4		40.00	5.65	34.35	0.36	1.0	-	-	61
P1/2		40.00	6.48	33.52	0.70	2.1	-	-	91

P3/1 - Main borehole P3/3 – Piezometer

BH = Borehole, SWL = Static Water Level, m b.g.s = meter below ground surface, Avg. =Average

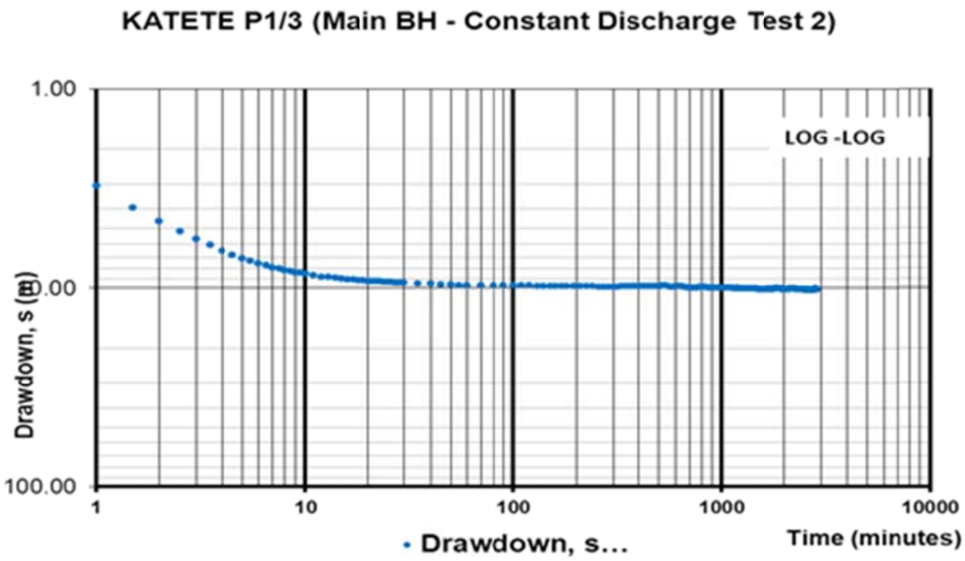

Figure 15: Constant Discharge Test 2; Time-Drawdown Characteristics, P1/3 Main Borehole, (Katete)

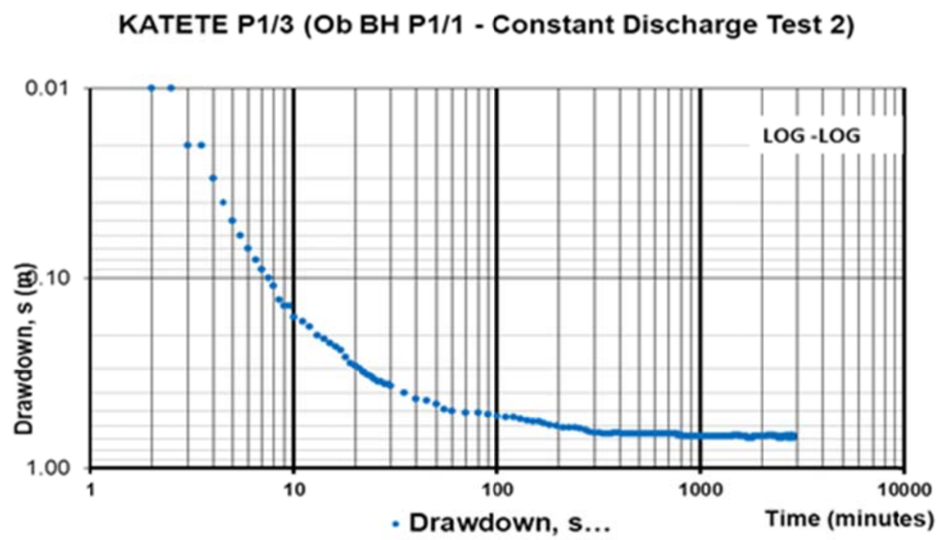

Figure 16: Constant Discharge Test 2; Time-Drawdown Characteristics, P1/1 Observation Borehole, (Katete)

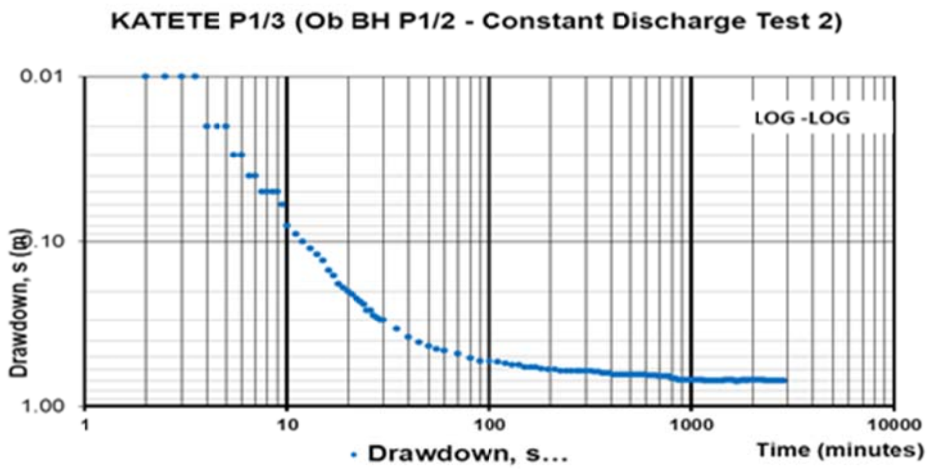

Figure 17: Constant Discharge Test 2; Time-Drawdown Characteristics, P1/2 Observation Borehole, (Katete)

6.4 Recovery

Figures 14 and 15 show recovery of the main borehole P1/3 and the observation borehole P1/1. The data is good. The other two observation boreholes provide similarly good data. All recovery data is included in the original drilling and supervision report (Anscombe 2012).

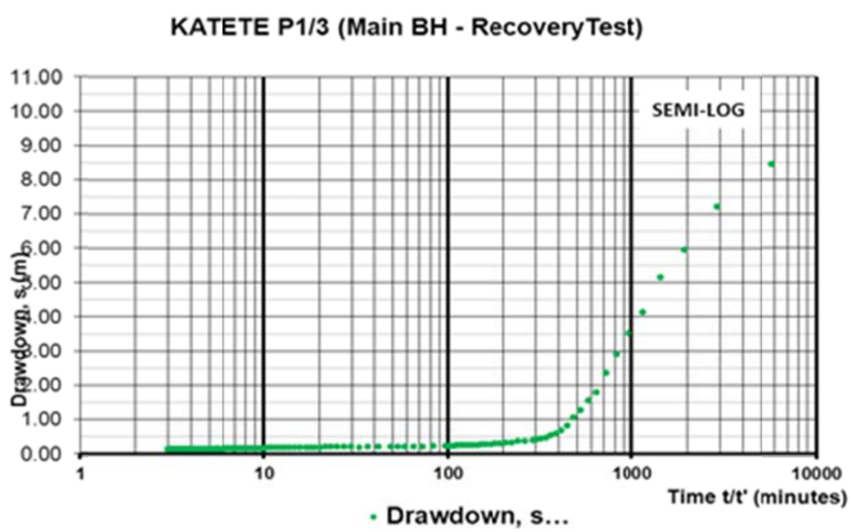

Figure 18: Recovery Test 2; Time-Drawdown Characteristics, P1/3 Main Borehole, (Katete)

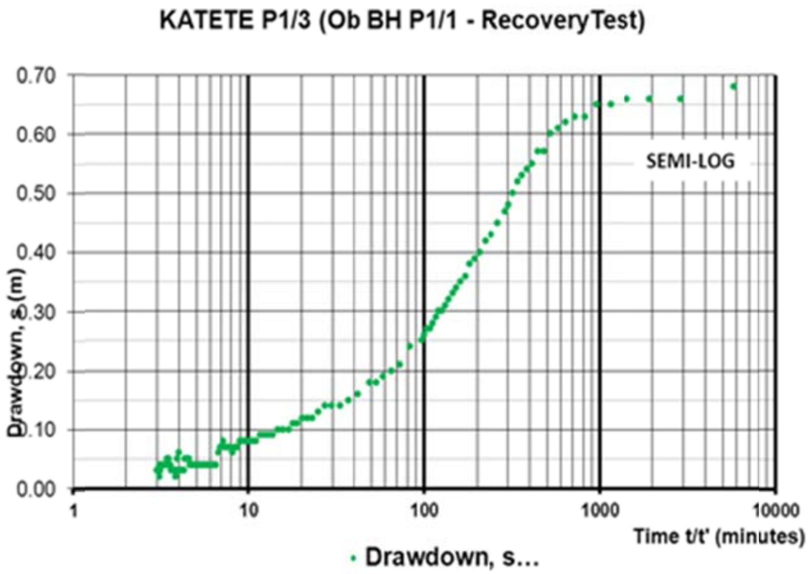

Figure 19: Recovery Test 2; Time-Drawdown Characteristics, P-1/1 Observation Borehole, (Katete)

7 TEST PUMPING RESULTS: P2- Kasanova

7.1 General

Test calibration at the site revealed a much lower yield than estimated during drilling. Initially the 25HP ESP was installed at 25m but at 4-5 L/s the drawdown pulled below the single strike zone at 10m and then rapidly descended to pump intake. The water level stabilized at the intake level but the flow rate reduced to about 3L/s. Recovery was extremely rapid with a noisy rush of water pouring into the borehole from the 10m level.

The reason for the apparent reduction in yield between drilling and testing can be explained by one or a combination of the following:-

- Drilling yield was over-estimated
- Screen open area is substantially reducing the flow
- Clogging of aquifer in intervening 5-months

In an attempt to un-clog the aquifer the borehole was re-developed using a drill rig, compressor and poly pipe development line. Development commenced in the sump and then at 5-meter intervals to the top of the screened section, returning to the sump to clean out debris before removal. The development procedure lasted for 3-hours and the water was generally crystal-clear, clouding only when the position was changed. The final V-notch yield was substantially less than that observed during drilling (photos)

The screen open area was carefully designed at 8% and is not thought to contribute significantly to yield reduction as the exact same screen was used in the P3/1 borehole at Makeni and this configuration yielded more than the measured air-lift yield during pumping (14L/s).

Yield reduction is undoubtedly related to the single, very shallow water strike at 10m b.g.s. During drilling of P2/2 the exact strike level was not clear due to the amount of mud and sludge that was blasted out of the borehole – the strike zone was estimated between 9 and 38m b.g.s. Adjacent borehole P2/3 had a very clear and strong strike from a karstic feature within solid dolomite at 9-10 meters. Yield reduction may also be due to karstic cavity infilling in the interim. The karstic features in both these boreholes were filled with an orange-red coloured breccia and this may have re-distributed and “choked” the aquifer in the period between drilling and testing (about 5 months.

In consequence of the lower than expected yield the pump was replaced with a smaller 7.5 HP version and with this latter pump the ST and CDT were successfully executed in the period 3rd to 7th April 2012. Although the CDT was at a rate much lower than originally indicated, the karstic aquifer tested is still significant with a sustainable yield in the order of 3L/s. The borehole has a high Specific Capacity.

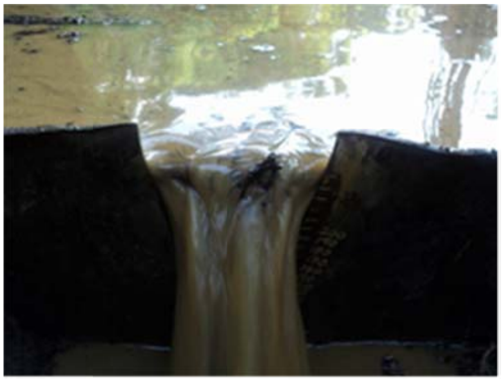

Figure 20: P2/2: V-notch flow during drilling (260mm equates to 15+ L/s)

Figure 21: P2/2: Re-development with an air-line

7.2 Step Test

Table 9 and Figure 16 present a summary of the 5-steps of the Step Test. The test data are presented in the original drilling and supervision report (Anscombe 2012).

Table 9: Step Test; P2/2, Main Borehole, (Kasanova)

BH ID	BH depth (m)	Pump Depth (m)	SWL start (m b.g.s)	DWL end (m b.g.s)	Drawdown, s (m)	Step yield (L/s)	Q (m^3/day)	Specific Capacity (m^3/m/day)
1	50.00	42.5	0.64	0.84	0.20	0.47	41	204.34
2			0.84	1.21	0.57	1.15	99	174.15
3			1.21	1.69	1.05	1.83	158	150.42
4			1.69	2.68	2.04	2.65	229	112.40
5			2.68	3.44	2.80	3.26	281	100.53

BH = Borehole, SWL = Static Water Level, DWL = Dynamic Water Level, m b.g.s = meter below ground surface

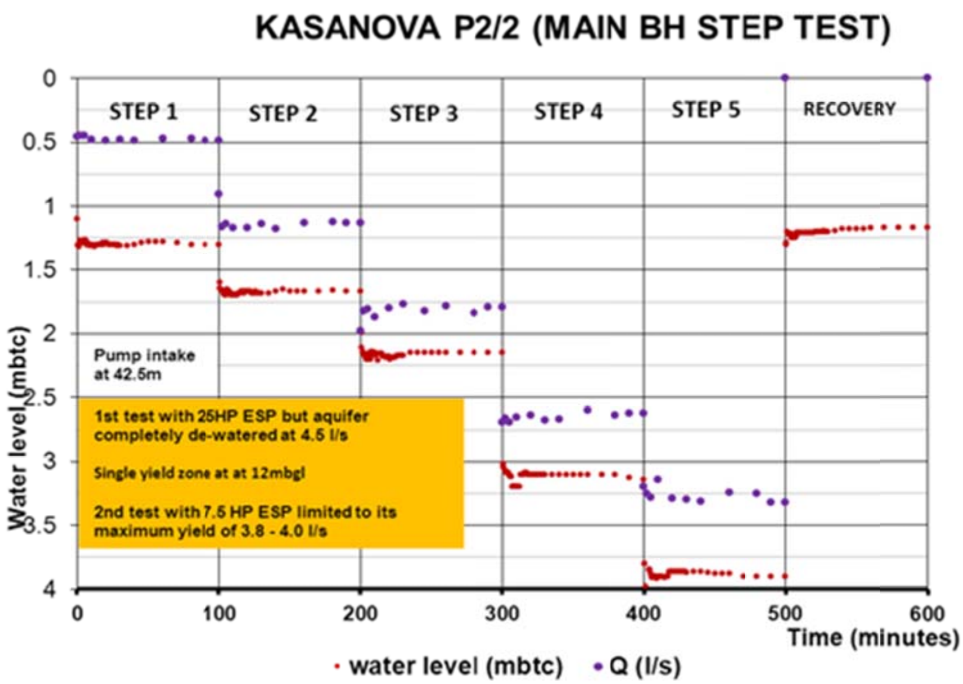

Figure 22: Step Test; Time-Drawdown Characteristics, P-2 (Kasanova)

The furthest piezometer (P2/3) responded the same as the nearest (P2/1) and about 0.15m during the course of the ST (Table 10, and Figure 17). The nearest piezometer did not recover very well. Indications are that P2/3 and P2/2 are linked whilst P2/1 is somewhat isolated despite being the closest to the pumped borehole

Table 10: Step Test; P2/2, Measurements on Main Borehole and Observation Boreholes, (Kasanova)

BH	ID	Distance (m)	Direc tion	Yield range of steps (L/s)	SWL (m b.g.s)	Drawdown, s (m)	100 minute recovery (%)	Comment
P2/2	Main	0	-	0.5 – 3.3	0.64	2.8	98	Good response. Recovery related to distance from
P2/1	Piezo meters	18.05	NW	-	0.34	0.15	33	
P2/3		29.35	S	-	0.86	0.16	69	

BH = Borehole, SWL = Static Water Level, m b.g.s = meter below ground surface

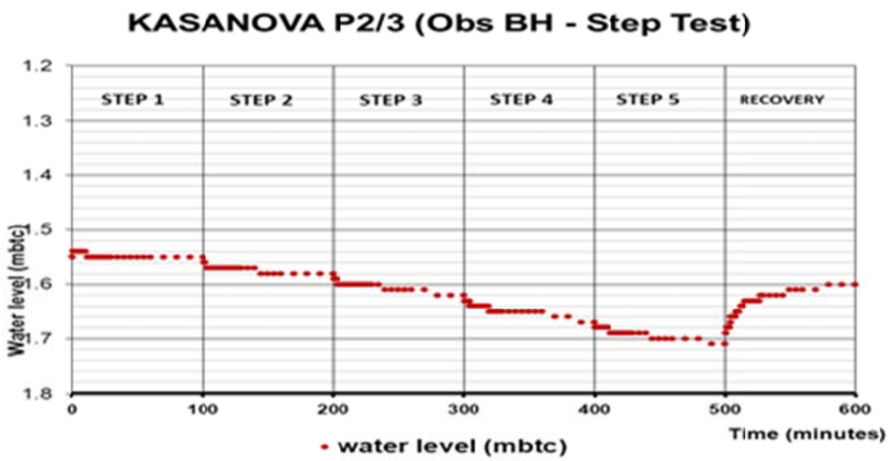

Figure 23: Step Test; Time-Drawdown Characteristics, P-2/3, Observation Borehole (Kasanova)

7.3 Constant Discharge Test

Figure 18 shows the yield variation during the 2-day CDT. The average yield was 3.27L/s within a range of 3.00 to 3.49 L/s and a standard deviation of 0.10. The discharge yield is the sum of the yield at the end of the discharge line and that passing through the flow cell near the wellhead which was constant at 0.5 L/s.

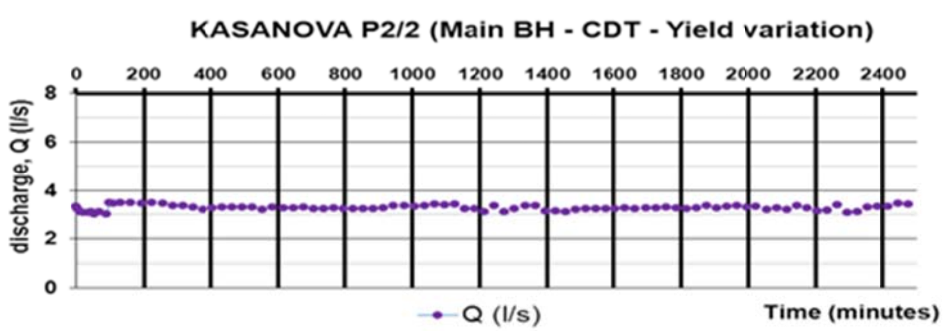

Figure 24: Constant Discharge Test Discharge Variation; P2/2, Main Borehole, (Kasanova)

Table 11 and Figures 19 and 20 present a summary of the CDT including the reaction of the more responsive piezometer (P2/3). The test data are presented in the original drilling and supervision report (Anscombe 2012)

The pump was set at 42.5 for the CDT. A Specific Capacity is calculated from the CDT by dividing total yield by total drawdown to give a very high figure of 88.27 m^3/m/day. This is a first approximation of aquifer transmissivity, T, but being of the pumped well is affected by compound well losses. It is more accurately obtained from software analysis of the observation borehole time-drawdown data, which looks possible on P2/3.

Table 11: Constant Discharge Test; Measurements on Main Borehole and Observation Boreholes (Kasanova)

BH	ID	Pump / Dipper Depth (m)	SWL start (m b.g.s)	Drawdown, s			Avg. yield (L/s)	Specific Capacity (m^3/m/day)	1 -day recovery (%)
				Available (m)	Achieved (m)	Utilized (%)			
P2/2	Main	42.50	0.64	41.86	3.20	7.6	3.27	88.27	99
P2/1	Piezo meters	30.00	0.42	29.58	0.10	0.3	-	-	80
P2/3		30.00	0.86	29.14	0.23	0.8	-	-	83

P2/2 - Main borehole **P2/3 - Piezometer** BH = Borehole, SWL = Static Water Level, m b.g.s = meter below ground surface, Avg.= Average

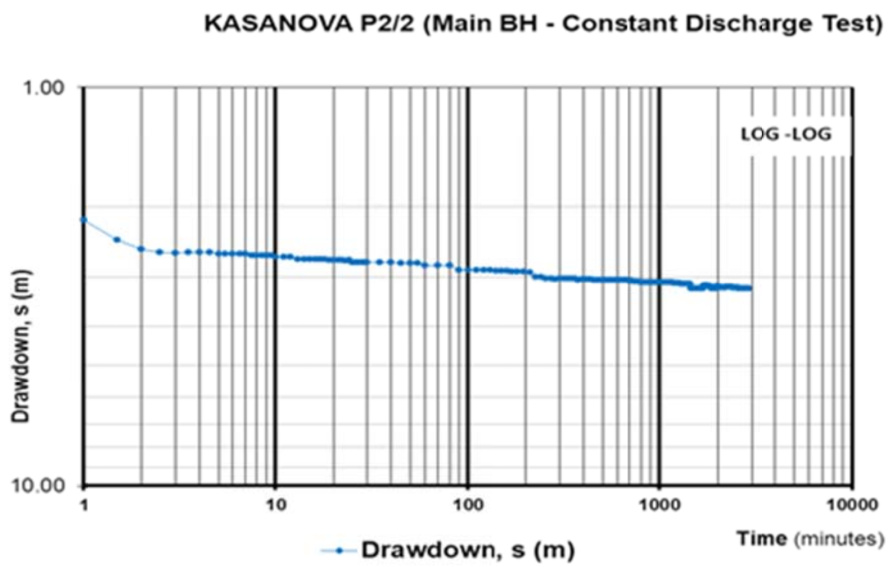

Figure 25: Constant Discharge Test; Time-Drawdown Characteristics, P2/2, Main Borehole (Kasanova)

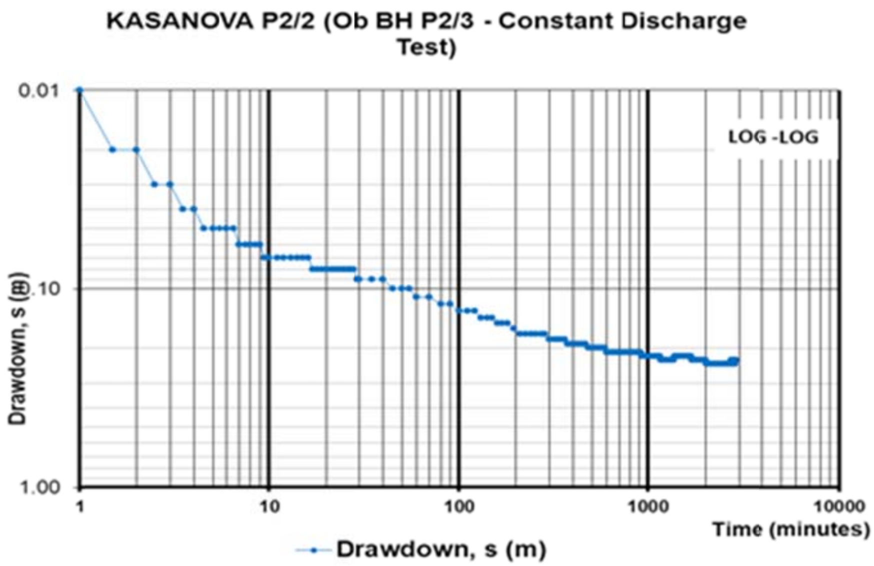

Figure 26: Constant Discharge Test; Time-Drawdown Characteristics, P2/3, Observation Borehole P2/3 (Kasanova)

7.4 Recovery Test

Figures 21 and 22 shows the recovery performance of the main borehole (P2/2) and one of the observation boreholes (P2/3). All recovery data is presented in the original drilling and supervision report (Anscombe 2012)

The data is good for the main borehole and stepped for P2/3 due to limited drawdown and enlarged vertical scale. The other observation borehole provided odd data in that it recovered fully midway through the 24-hour period before descending and starting to recover again.

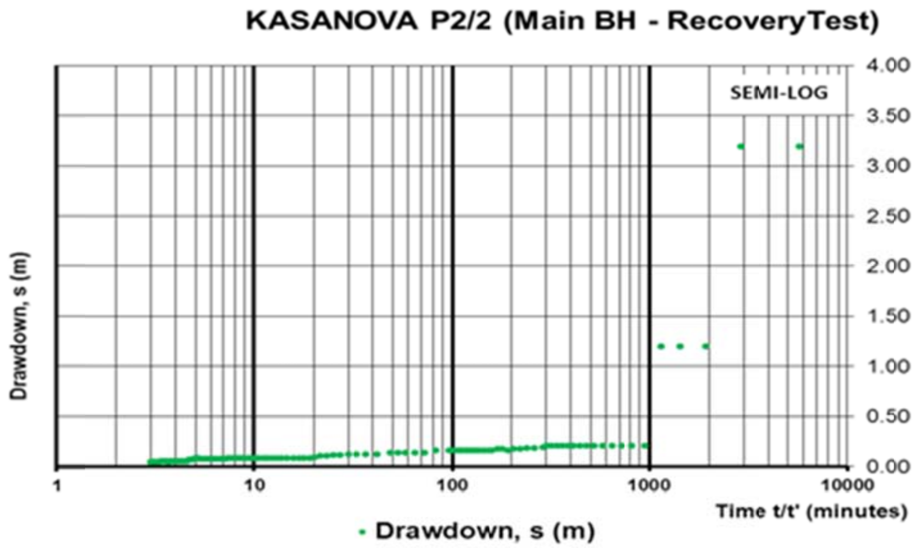

Figure 27: Recovery Test; Time-Drawdown Characteristics, P2/2 Main Borehole (Kasanova)

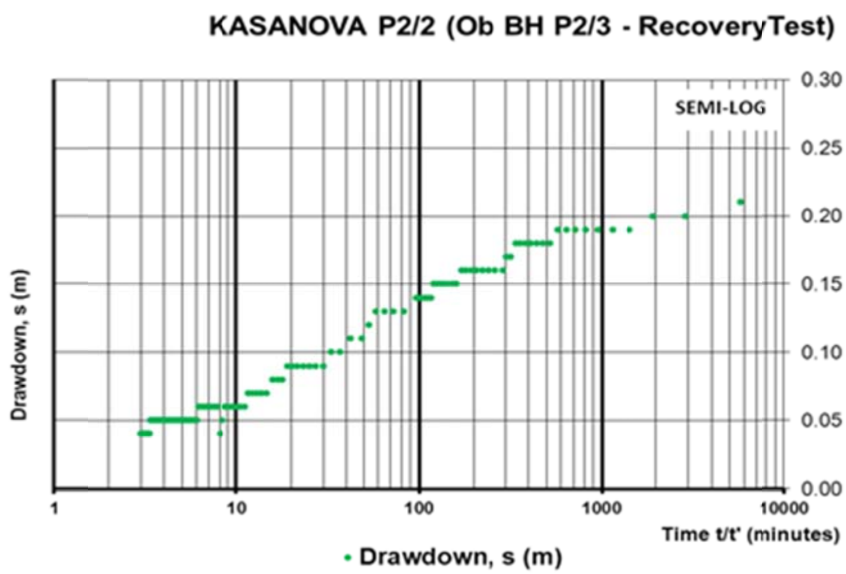

Figure 28: Recovery Test; Time-Drawdown Characteristics, P2/3 Observation Borehole (Kasanova)

8 TEST PUMPING RESULTS: P3- Makeni

8.1 General

The Contractor arrived on site on the 14th March and spent 4 days installing and testing and replacing the roll flat discharge pipe (which burst under pressure) with poly pipe. The discharge was set 150m west of the pumped well with all water flowing away and into the Chilongolo Stream – which also flows away from the site to the west. The poly pipe had a 93mm internal diameter with approximately 75mm constrictions at the gate valve at each end and at the three intermediate connectors (pipe in 30m lengths). The riser pipe from the pump was galvanized iron and had an internal diameter of 100mm.

40mm of rain fell in the early hours of 17th March. There seemed to be a rise in the water level in P3/1 a few hours later from 12.20 to 11.56m b.g.s but this recharge pulse had subsided again to 12.22m b.g.s by the start of the Step Test – 1 day later - on 18th March. Assuming a 50% aquifer recharge rate and a radius of influence around the main borehole of 200m then this recharge event added 2514 m3 to the groundwater reservoir. This is comparable to the total volume removed, 2352m3 during the 48hr CDT between 19th and 21st March.

Several short-duration pumping events, for calibration purposes, occurred in the 48 hours leading up to the Step Test.

8.2 Step Test

Table 12 and Figure 23 present a summary of the 5-steps of the Step Test. The test data are presented in the original drilling and supervision report (Anscombe 2012).

Table 12: Step Test, P3/1, Main Borehole (Makeni)

BH ID	BH depth (m)	Pump Depth (m)	SWL start (m b.g.s)	DWL end (m b.g.s)	Drawdown, s (m)	Step yield (L/s)	Q (m^3/day)	Specific Capacity (m^3/m/day)
1	66.56	62.5	11.72	14.20	2.48	4.29	370	149
2			14.20	19.40	7.68	9.28	802	104
3			19.40	22.42	10.70	11.24	971	91
4			22.42	28.80	17.08	13.02	1125	66
5			28.80	29.68	17.96	13.23	1143	64

BH = Borehole, SWL = Static Water Level, DWL = Dynamic Water Level, m b.g.s = meter below ground surface

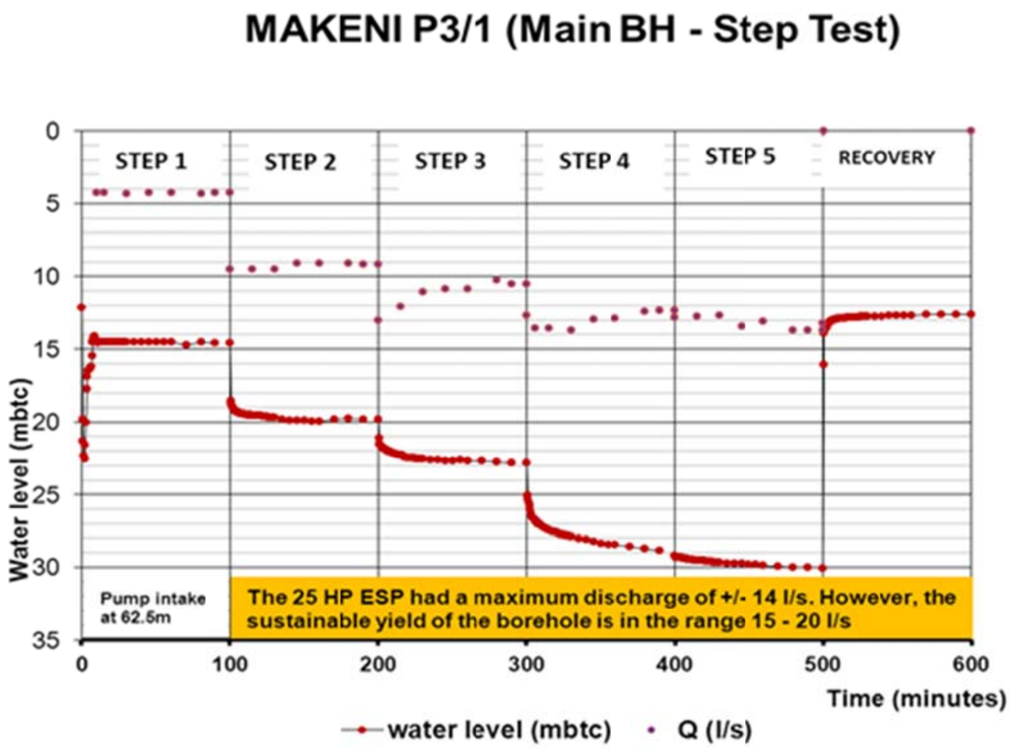

Figure 29: Step Test; Time-Drawdown Characteristics, P3/1, Main Borehole (Makeni)

The yield was set too high at the beginning of the 1st step before being reduced to 4.2 L/s – this explaining the steep drawdown and subsequent recovery seen in the first 10 minutes of the step.

Despite this P3/1 proved to have a very strong yield – exceeding the estimates made during drilling. The 25-HP pump was not able to fully test the borehole failing to increase yield substantially steps 3 through 5. The aborted borehole P3/2 and the observation borehole P3/4 all intersected the same aquifer, all with strong yields, interpreted as a saturated and brecciated fracture zone or karstic cavity in carbonate host rock (possibly dolomite).

All three piezometers responded to the Step Test on the main borehole P3/1. Examples are shown in Figure 24 and 25 representing data from observation boreholes P3/3 and P3/5.

Table 10 shows that the response of the piezometers to pumping is proportional to their distance from the pumped borehole with the nearest P3/3 having the largest drawdown at 2.25m and the furthest, P3/4 the least at 0.79m. Thus despite the possibly linear nature of the aquifer (linear fracture or cavity) the aquifer appears homogeneous in all directions.

Table 13: Step Test; Measurements on Main Borehole and Observation Boreholes (Makeni)

BH	ID	Distance (m)	Direction	Yield range of steps (L/s)	SWL (m b.g.s)	Drawdown, s (m)	100 minute recovery (%)	Comment
P3/1	Main	0	-	4 - 13	11.72	17.96	97	Good response. Recovery related to distance from pumped BH
P3/3	Piezo meters	13.45	E	-	11.70	2.25	85	
P3/5		21.80	N	-	11.36	1.66	77	
P3/4		33.10	S	-	12.32	0.79	41	

BH = Borehole, SWL = Static Water Level, m b.g.s = meter below ground surface

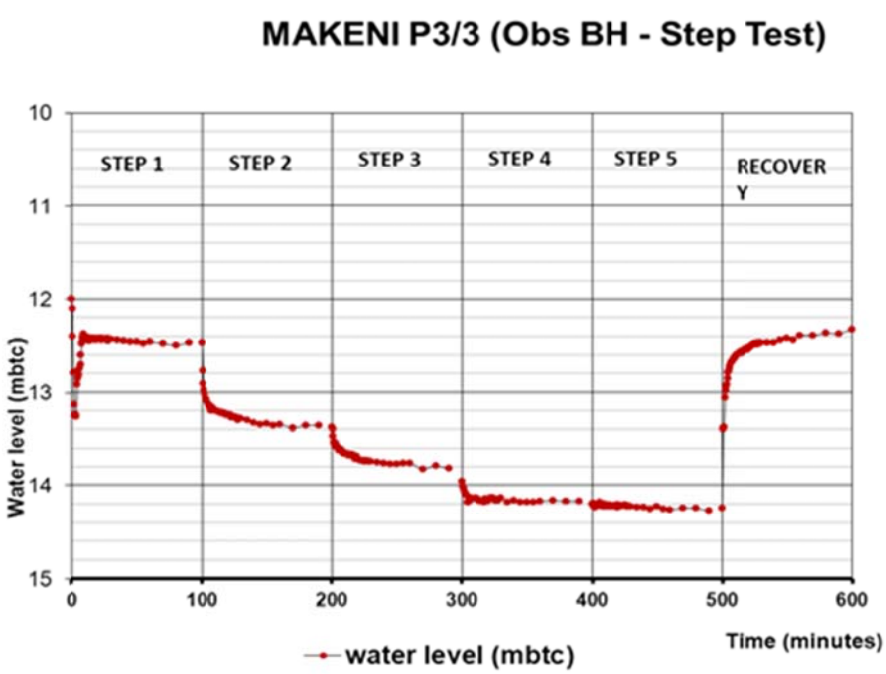

Figure 30: Step Test Time-Drawdown Characteristics; P3/3, Observation Borehole (Makeni)

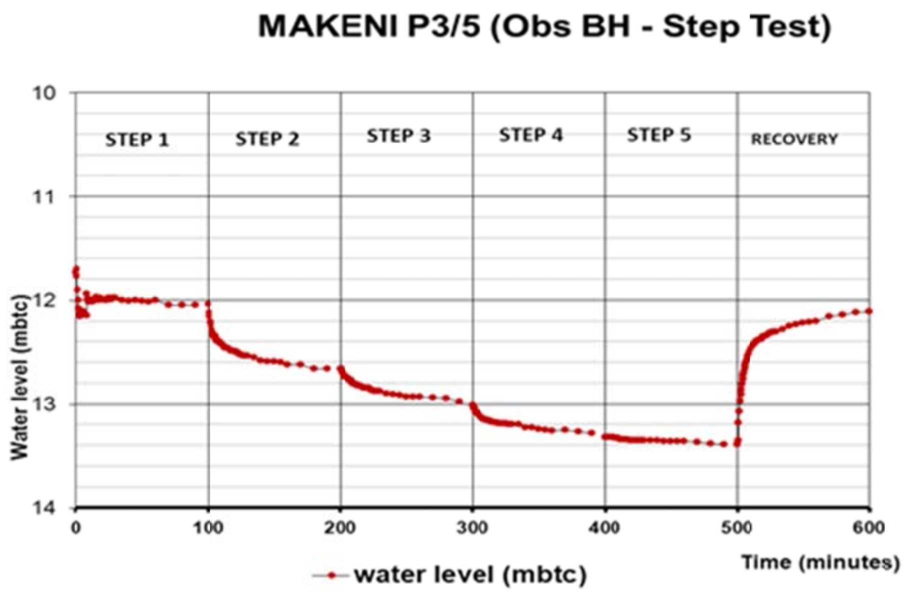

Figure 31: Step Test; Time-Drawdown Characteristics, P3/5, Observation Borehole (Makeni)

8.3 Constant Discharge Test

Figure 26 shows the yield variation during the 2-day CDT. The average yield was 14.12L/s within a range of 13.61 to 15.06 L/s and a standard deviation of 0.31. The discharge yield is the sum of the yield at the end of the discharge line and that passing through the flow cell near the wellhead which was constant at 0.25 L/s.

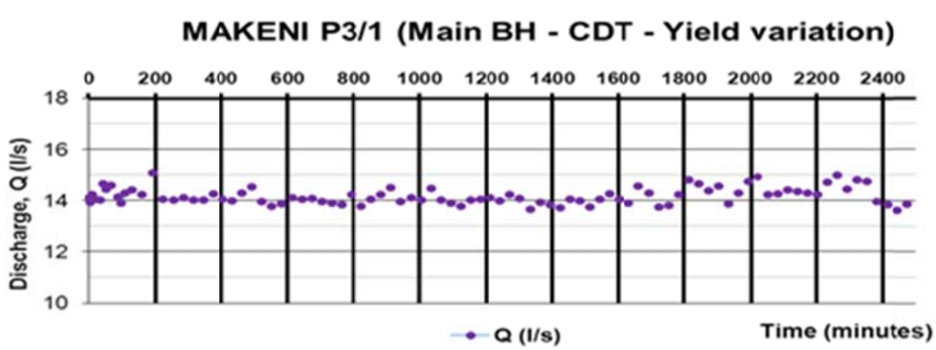

Figure 32: Constant Discharge Test; Discharge Variation, P3/1, Main Borehole (Makeni)

Table 14 and Figures 27 to 30 present a summary of the CDT including the reaction of the 3 piezometers. The test data are presented in the original drilling and supervision report (Anscombe 2012). The pump was lifted from 62.5m b.g.s (ST) to 56.5m b.g.s (CDT) and this had the effect of increasing the yield to an average of 14.12 m^3/hr, for the 48hr duration of the CDT. A Specific Capacity is calculated from the CDT by dividing total yield by total drawdown to give a high value of 58.45 m^3/m/day. This is a first approximation of aquifer transmissivity, T, but being of the pumped well is affected by compound well losses. It is more accurately obtained from software analysis of the observation borehole time-drawdown data

The cone of depression as defined by the pump borehole and 3 piezometers is broad with effect seen at distance – in keeping with a high T aquifer. As with the ST the responses of the piezometers are proportional to their offset distances – indicating a homogeneous aquifer.

Table 14: Constant Discharge Test, Measurements on Main Borehole and Observation Boreholes (Makeni)

BH ID	ID	Pump / Dipper Depth (m)	SWL start (m b.g.s)	Drawdown, s			Avg. yield (L/s)	Specific Capacity (m^3/m/day)	1 -day recovery (%)
				Available (m)	Achieved (m)	Utilised (%)			
P3/1	Main	56.5	11.82	44.28	20.88	47.2	14.12	58.45	99
P3/3	Piezo meters	48	11.70	36.00	2.72	7.6	-	-	94
P3/5		48	11.40	36.23	2.12	5.9	-	-	95
P3/4		38	12.43	25.19	1.47	5.8	-	-	88

P3/1 - Main borehole **P3/3 – Piezometer** BH = Borehole, SWL = Static Water Level, m b.g.s = meter below ground surface, Avg.= Average

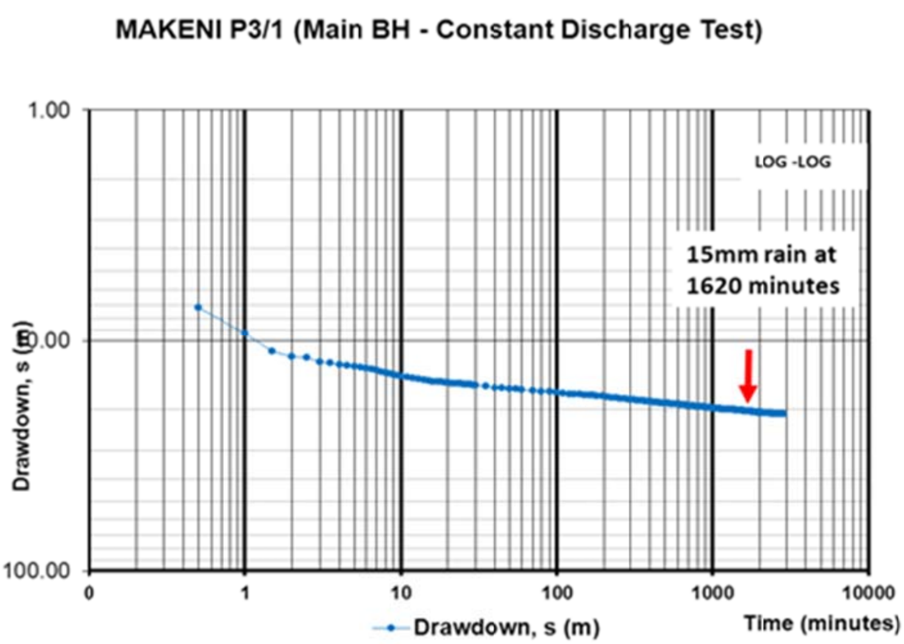

Figure 33: Constant Discharge Test; Time-Drawdown Characteristics, P3/1, Main Borehole (Makeni)

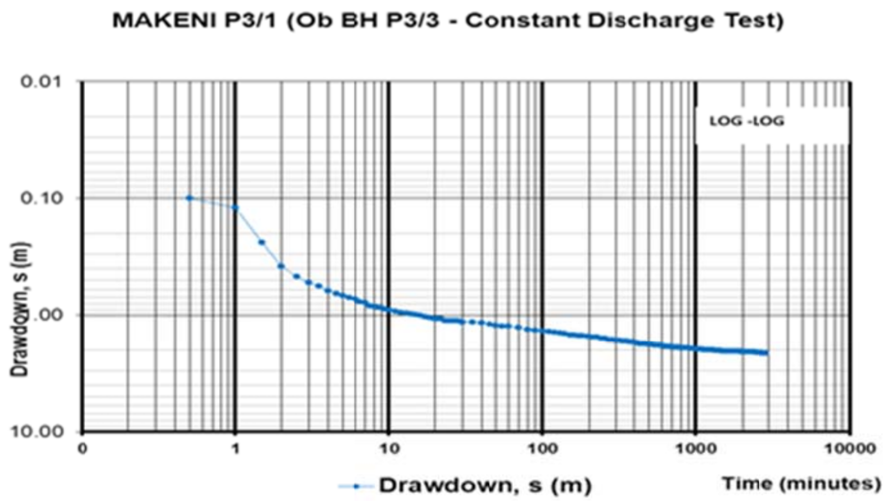

Figure 34: Constant Discharge Test; Time-Drawdown Characteristics, P2/3, Observation Borehole (Makeni)

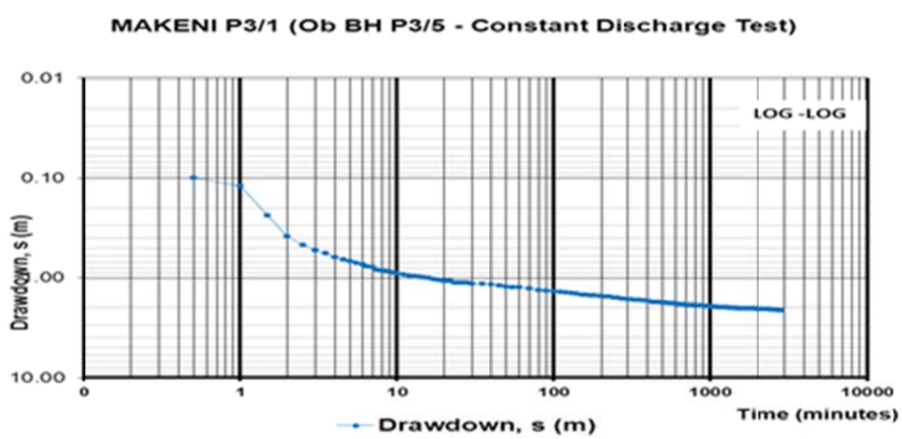

Figure 35: Constant Discharge Test Time-Drawdown Characteristics, P2/5, Observation Borehole (Makeni)

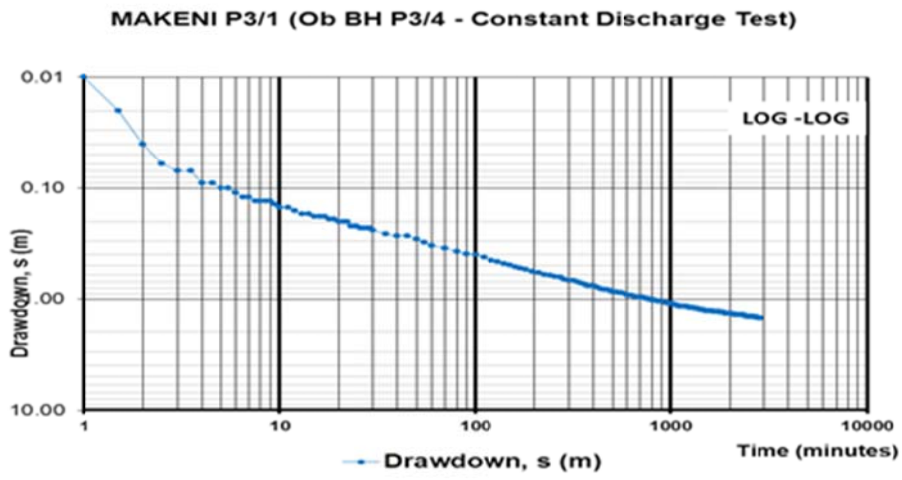

Figure 36: Constant Discharge Test; Time-Drawdown Characteristics, P2/4, Observation Borehole (Makeni)

8.4 Recovery Test

Figures 31 and 32 show the recovery performance of the main borehole (P3/1) and one of the observation boreholes (P3/5). All recovery data is presented in the original drilling and supervision report (Anscombe 2012).

The quality of the recovery data is good apart from a few water level readings at early times. The other two observation boreholes provide similarly good recovery data.

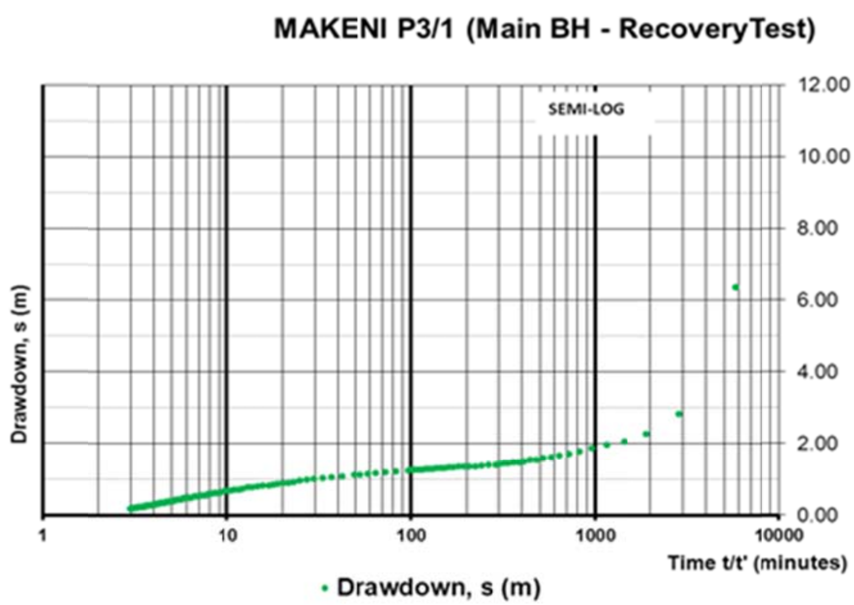

Figure 37: Recovery Test; Time-Drawdown Characteristics, P3/1 Main Borehole (Makeni)

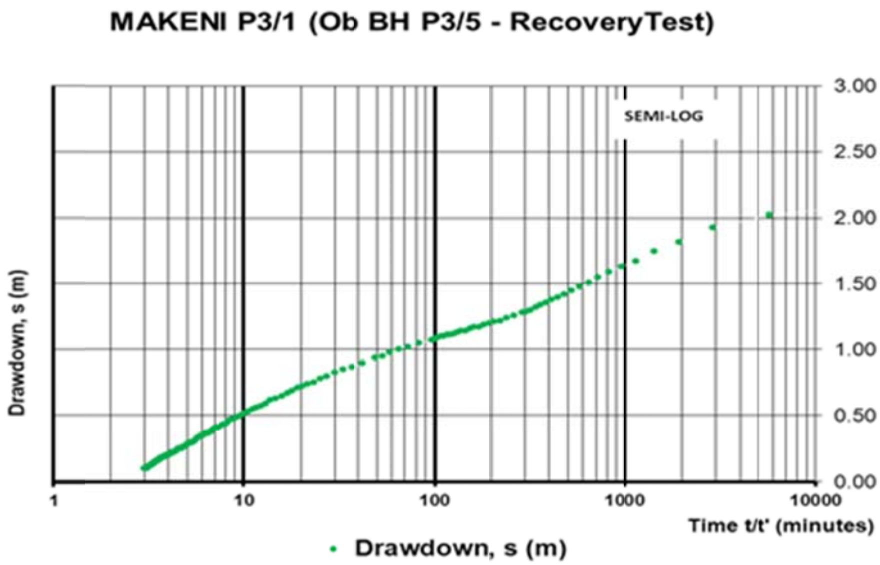

Figure 38: Recovery Test; Time-Drawdown Characteristics, P3/5 Observation Borehole (Makeni)

9 WATER SAMPLING AND MEASUREMENTS

At each borehole a sealed flow-cell was primed off the main discharge line via a small gate valve and 3/4” flexible pipe. Water flow through the cell was maintained constant at between 0.25 and 0.5 L/s. The set-up is shown in the photos below. The measurements included Dissolved Oxygen (DO), Electrical Conductivity (EC), Temperature, pH and Oxidation – Reduction Potential (REDOX). Three hand-held meter with digital readout were used to obtain these measurements with the probes immersed in the flow-cell.

Figure 39: Flow-cell showing tops of probes

Figure 40: Hand held meters

Before the start of the CDTs, each of the three meters were calibrated against a known standard following the manual procedure. Table 15 shows the averages generated for each pumped borehole. The ranges obtained at each of the three sites were very small, with very little variation over the 48hr duration of the tests. Data can be found in Appendices A1.2.7 (Katete), A2.2.4 (Kasanova) and A3.2.4 (Makeni).

Table 15: Wellhead Measurements with a Flow-cell

BH ID	Sample point	Average values from 48hr CDT with 1hr sample interval				
		DO (mg/L)	EC (µS/cm)	Temp (°C)	pH	REDOX (mV)
P1/3	Pumped borehole	1.40	784.98	25.71	7.05	-16.29
P2/2		0.96	578.31	25.12	7.08	-24.16
P3/1		0.95	517.05	24.05	6.91	-15.20

BH = Borehole, CDT = Constant Discharge Test, DO = Dissolved Oxygen, EC = Electrical Conductivity

Water samples were also collected 30 minutes before the end of each CDT. Sampling followed standard sampling procedure for:

- Cations

- Anions
- Bacterial coliforms

The samples were variously dispatched for analysis at the DWA, UNZA and BGR laboratories.

10 References

Anscombe J. (2011) Supervision of drilling and test pumping at selected sites in Lusaka/Kafue/Chibombo Districts – **Desk study and siting report**.- ANSCO Ground Water Ltd.; July 2011; 31 pages; Lusaka.

Anscombe J. (2012) Supervision of drilling and test pumping at selected sites in Lusaka/Kafue/Chibombo Districts – **Drilling and test pumping report**.- ANSCO Ground Water Ltd.; Apr. 2012; Lusaka.

PART C

Test Pumping Analysis

Prepared by

R. Bäumle & C. Siwale

Table of Contents

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Abbreviations

1/B	Leaky Aquifer Coefficient in Hantush's Leaky Aquifer Model
B	Linear (laminar) head-loss coefficient in Jacob-equation
C	Nonlinear (turbulent) well-loss coefficient in Jacob-equation
m b.g.s.	(Water levels given in) meters below ground surface
Q	Pumping rate
q	Specific capacity defined as discharge per unit meter of drawdown
RWL	Residual water level during recovery
S	Aquifer storativity
s, s_{max}	Measured drawdown during test pumping, maximum measured drawdown
SWL	Static water level
T	Aquifer transmissivity
r	Distance to pumped well

1 Introduction

The analysis includes the pumping tests at the three sites Makeni, Kasanova in Kafue District and Katete in Chibombo District which were performed between March 18 and April 11, 2012. The tests at each site comprised a step test and a 48-hour aquifer test.

The lithology of the host rock includes marbles of the Lusaka Dolomite and Cheta formations and schist/quartzite of the Cheta Formation.

The main purpose of the analysis is to quantify the hydraulic characteristics of the host rocks, namely the transmissivity and the storage characteristics, and to identify the general aquifer geometry and prevailing groundwater flow regime at the three selected sites.

2 Methodology

As outlined in Part B, all step tests were conducted with five individual steps of a duration of 100 minutes each.

For aquifer testing the wells were pumped at near constant rate for 48 hours followed by a recovery period that was monitored over a period of 24 hours. Drawn water levels were measured at the pumped well and two to three observation wells.

Discharge measurements were (at least) taken every 30 minutes. For analysis purposes the discharge was averaged over periods with similar pump rates.

The analysis was performed using data recorded by the digital probes. Manual readings were used for data verification only.

2.1 Step test analysis

The tests were analysed using the Hantush-Bierschenk and the Eden-Hazel methods (Bierschenk 1963, Eden & Hazel 1973, Clark 1977, Krusemann & de Ridder 1991) .

This **Hantush-Bierschenk method** is based on Jacob's well loss equation given as:

$$s_w = B\,Q + C\,Q^p$$

where *B* is the linear (laminar) head-loss coefficient, *C* is the nonlinear (turbulent) well-loss coefficient and *p* is the order of nonlinear well losses. The value of *p* is commonly assumed to equal 2 as proposed by Jacob (1947).

The method is based on the following equation:

$$\sum_{i=1}^{n} \Delta s_{w(i)} = s_{w(n)} = BQ_n + CQ_n^2$$

where

$s_{w(n)}$ total drawdown in the well during the last (*n*-th) step

$\Delta s_{w(i)}$ drawdown increment between the i-th step and the step preceding it.

The equation can be rearranged and written as:

$$\frac{s_{w(n)}}{Q_n} = B + CQ_n$$

The Hantush-Bierschenk method is an "equilibrium" method since its accuracy relies on the reliable determination of the final (steady-state) drawdown for each step.

Eden & Hazel have developed the following equation for analysing step drawdown test data:

$$s(r_w, t) = \frac{2.30Q}{4\pi T} log \frac{2.25Tt}{{r_w}^2 S} + CQ_n^2 = aQ_n + bH_n(t) + CQ_n^2, \text{ with}$$

$$H_n(t) = \sum_{x=1}^{n} \Delta Q_x \, log(t - t_x),$$

The index n defines the number of the drawdown step, a and b are time-independent coefficients defining the linear head loss at the well, and C is, as above, the non-linear well-loss coefficient. The term $(t - t_x)$ defines the time elapsed after the beginning of each individual step and ΔQ_x is the difference of the discharge rate $(Q_n - Q_{n-1})$ between two subsequent steps.

Unlike with the Hantush-Bierschenk method, the Hazel-Eden approach belongs to the non-equilibrium methods. Hence, there is no need to estimate the final drawdown for each step and, consequently, it is less crucial that the water levels reach a state of equilibrium at the end of each step. Furthermore, the method is suitable to estimate aquifer transmissivity for homogeneous confined aquifers.

The step test analysis was performed using the software Step Master© V. 2.1 by Starpoint Software Inc.

2.2 Aquifer Test Analysis

Common analytical solutions for pumping tests in confined, leaky, unconfined and fractured aquifers were tried depending on the geological setup and after thorough examination of the drawdown data using diagnostic plots.

The analytical solutions applied are summarized in Kruseman & de Ridder (1981) and Duffield (2007).

Estimated parameters include:

- Aquifer transmissivity, T in units L^2/T
- Aquifer hydraulic conductivity, K in units L/T
- Aquifer storativity, S (dimensionless)
- Hantush leaky aquifer coefficient 1/B, in units L^{-1}
- Aquifer specific yield, S_y (dimensionless)

The aquifer test analysis was performed using the software AQTESOLV© V. 4.5. developed by Glenn M. Duffield, HydroSOLVE Inc.

3 Results of Test Pumping Analysis

The curve fitting results for step tests and aquifer tests are presented in Annex 3 and Annex 4, respectively.

3.1 Katete Site P1

Two sets of tests were carried out at Katete, the first one from March 25 to 27, 2012 and the subsequent one from April 8 to 11, 2012. The tests in March could not be completed due to technical constraints and are therefore referred to as “abandoned tests” in the following.

The test setup can be summarized as follows:

Table 1: Pumping test setup at Katete, P-1

Pumped Well:	**P1-3 (Katete Main Well)**	
Observations Wells and distance to pumped well, *r*:	P1-1:	*r* = 11.85 m
	P1-2:	*r* = 32.1 m
	P1-4:	*r* = 23.9 m
Drilled depth, *d* of borehole	P1-3:	*d* = 90 m
	P1-1:	*d* = 100 m
	P1-2:	*d* = 100 m
	P1-4:	*d* = 50 m
Geology:	Interlayered micaceous schist and crystalline limestone	
Aquifer top and bottom:	P1-3:	From 30 to 76 m b.g.s.
	P1-1:	From 31 to 56 m b.g.s.
	P1-2:	From 12 to 51 m b.g.s.
	P1-4:	From 10 to 45 m b.g.s.
Effective aquifer thickness *b*:	Estimated at about 30 m	

3.1.1 Step Test Analysis

Drawdown data at the pumped well and at the observation wells is shown in the graphs below (Figure 6).

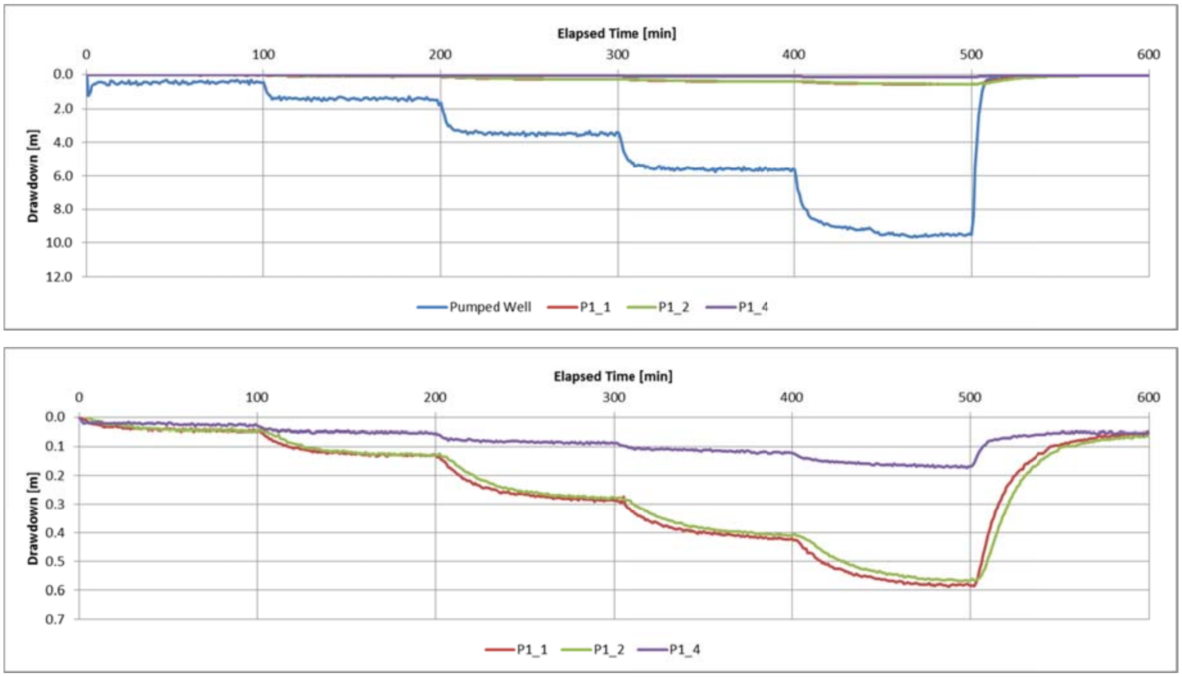

Figure 1: Drawdown during the step test as recorded by the data loggers at Katete, P-1

The analysis of the two step tests yielded the following results:

Table 2: Results of step test at Katete, P-1 (main test)

Date of Test:	**08.04.2012 (Main Test)**
No. and duration of steps	5 steps, 100 minutes each
Observed static water level, *SWL* at pumped well	7.07 m b.g.s.
Pumping rates Q_i:	Ranging from 0.47 L/s to 2.61 L/s
Observed maximum drawdown s_i at pumped well	Ranging from 0.46 m during the 1st step to 9.55 m during the last step
Observed specific capacity q_i at pumped well	Sharply dropping from 1.02 L/s/m during the 1st step to 0.27 L/s/m during the last step
Estimated parameters (Hantush-Bierschenk method):	B = 5.9 min/m^2 C = 320 min^2/m^5
Estimated parameters (Eden-Hazel method):	C = 312 min^2/m^5 T = 147 m^2/d

Table 3: Results of step test at Katete, P-1 (adandoned test)

Date of Test:	**25.03.2012 (Abandoned Test)**
No. and duration of steps	3 steps, 100 minutes each, 4th step abandoned after 24 minutes
Observed static water level, *SWL* at pumped well	6.82 m b.g.s.
Pumping rates Q_i:	Ranging from 3.27 L/s to 5.64 L/s
Observed maximum drawdown s_i at pumped well	Ranging from 19.5 m during the 1st step to >62 m during the last step (no equilibrium reached)
Observed specific capacity q_i at pumped well	Dropping from 0.17 L/s/m during the 1st step to 0.11 L/s/m during the 3rd step
Estimated parameters (Hantush-Bierschenk method):	Based on only three steps: B = 28.5 min/m^2 C = 309 min^2/m^5
Estimated parameters (Eden-Hazel method):	Measured data could not successfully be fitted to analytical solution.

There is generally an excellent correspondence between the results obtained from the Hantush-Bierschenk and the Eden-Hazel methods (Annex 3-1). Values of the nonlinear well-loss coefficient *C* obtained from the two separate tests correspond also very well. The parameter set for *B* and *C* obtained from the main test underestimates to some extent the drawdowns for pumping rates exceeding 3.5 L/s (Figure 2).

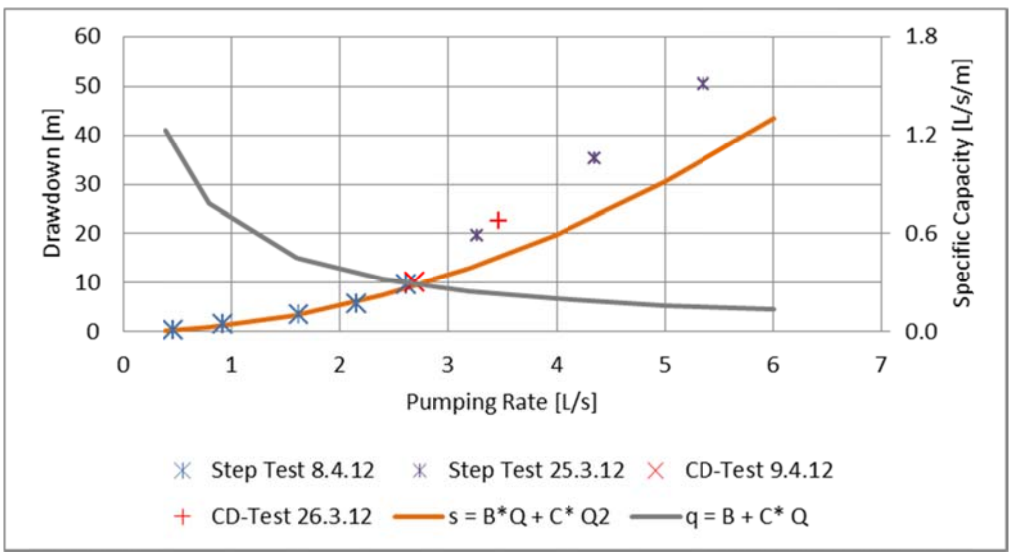

Figure 2: Drawdown and specific capacity for step test at site P1-3 (Katete). Dotted symbols indicate observed drawdown. Orange curve shows drawdown, *s* and grey curve depicts specific capacity, *q* as a function of pumping rate, *Q* as predicted by Hantush-Bierschenk method (Results of Main Test from 08.04.2012).

The non-linear well losses at the pumped well must be considered very high resulting in an overall very low well efficiency in particular at higher pumping rates. The proposed discharge from the well is therefore only about 3.0 L/s which is presumably well below the sustainable yield from the formation. According to the drilling records the yield of the boreholes P1-4 is estimated at over 20 L/s.

3.1.2 Aquifer Test Analysis

Drawdown data at the pumped well and at the observation wells is shown in the graphs below (Figure 8):

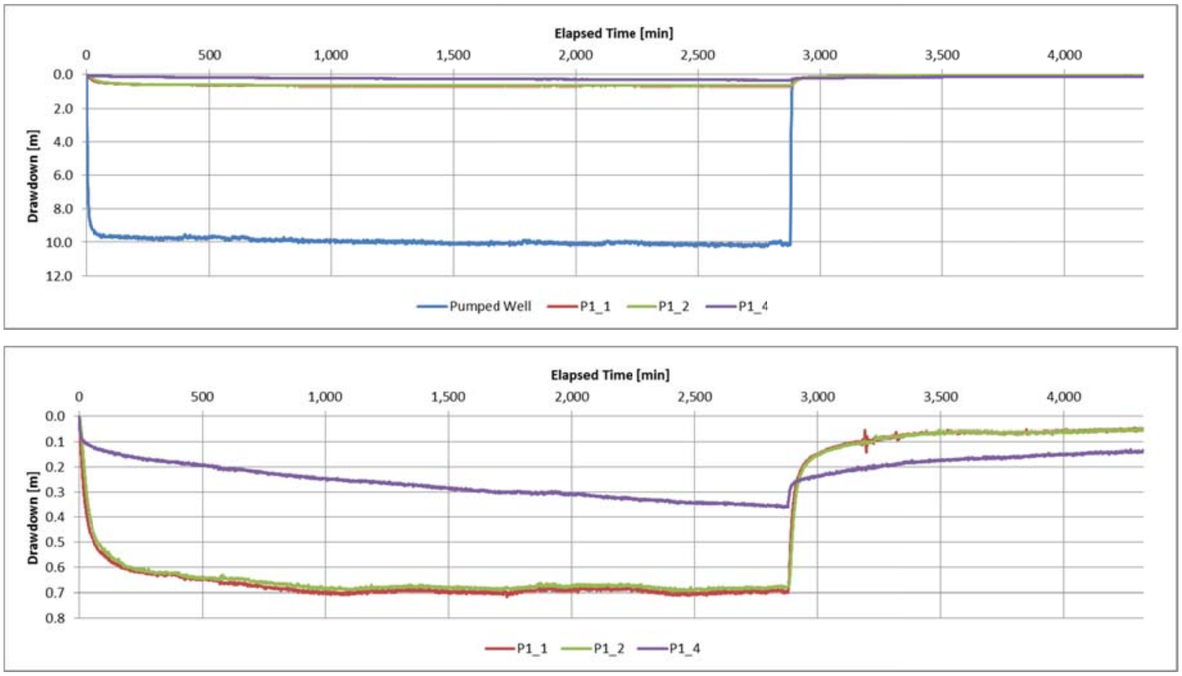

Figure 3: Drawdown during the aquifer test (Main test 08.-11.04.2012) as recorded by the data loggers at Katete, P-1

The analysis of the two aquifer tests yielded the following results:

Table 4: Results of aquifer test at Katete, P-1 (main test)

Date of Test:	**09 - 11.04.2012 (Main Test)**
Duration of test	Pumping 48 hours, Recovery 24 hours
Average pumping rate *Q*:	2.7 L/s
Static water level, *SWL* prior to test	P1-3: *SWL*= 7.11 m b.g.s.
	P1-1: *SWL* = 6.48 m b.g.s.
	P1-2: *SWL*= 6.99 m b.g.s.
	P1-4: *SWL* = 6.20 m b.g.s.
Observed maximum drawdown s_{max}	P1-3: s_{max} = 10.15 m
	P1-1: s_{max} = 0.75 m
	P1-2: s_{max} = 0.68 m
	P1-4: s_{max} = 0.36 m
Residual water level, *RWL* after the test	P1-3: *SWL*= 0.14 m
	P1-1: *SWL* = 0.05 m
	P1-2: *SWL*= 0.05 m
	P1-4: *SWL* = 0.14 m
Observed specific capacity *q* at pumped well	0.27 L/s/m

Estimated parameters:	Pumped well, P1-3: *Jacob Confined Aquifer Model* T = 84 m²/d P1-1: *Hantush Leaky Aquifer Model* T = 80 m²/d S = 0.0057 $1/B$ = 0.022 m⁻¹ P1-2: *Hantush Leaky Aquifer Model* T = 88 m²/d S = 0.0010 $1/B$ = 0.0064 m⁻¹ P1-4: *There is no satisfactory fit to any of the classical analytical solutions. Theis Recovery Method yields in much higher transmissivity ($T \approx 380\ m^2/d$)*

Table 5: Results of aquifer test at Katete, P-1 (abandoned test)

Date of Test:	**26 - 27.03.2012 (Abandoned Test)**
Duration of test	Pumping 22 hours, Incomplete recovery measurements
Average pumping rate Q:	3.47 L/s
Static water level, *SWL* prior to test	P1-3: *SWL*= 6.99 m b.g.s. P1-1: *SWL* = 6.45 m b.g.s. P1-2: *SWL*= 6.49 m b.g.s. P1-4: *SWL* = 6.22 m b.g.s.
Observed maximum drawdown s_{max}	P1-3: s_{max} = 22.50 m P1-1: s_{max} = 0.75 m P1-2: s_{max} = 0.68 m P1-4: s_{max} = 0.36 m
Residual water level, *RWL* after the test	P1-3: *SWL*= 0.16 m (after less than 2 hours)
Observed specific capacity q at pumped well	0.15 L/s/m
Estimated parameters:	No analysis performed.

The site exhibits a heterogeneous geological setup with the pumped well P1-3 and observation well P1-4 connecting to a limestone aquifer and P1-1 and P1-2 being drilled into calcareous schist. It is assumed that the described continuous overlying layer of calcified mica schist generates confined conditions. Earth-tide-induced groundwater level fluctuations were observed in all boreholes (but are less pronounced in P1-3 and P1-4). The oscillations are semi-diurnal with an amplitude of up to two centimeters similar to those observed at the monitoring borehole at Musopelo (Figure 4) that was drilled in schist[1] and is located about four kilometers to the west.

Strikingly, the drawdown at observation wells P1-1 and P1-2 are very similar despite the fact that with a distance of about 32 meters, P1-2 is located more than twice as far from the pumped well than P1-2. With a distance of about 24 meters, P1-4 shows the lowest

[1] Schist is less rigid compared to limestone and will therefore more easily deform to gravitational stresses caused by earth-tides.

overall drawdown. These observations remarkably demonstrate the heterogeneous nature of the aquifer system.

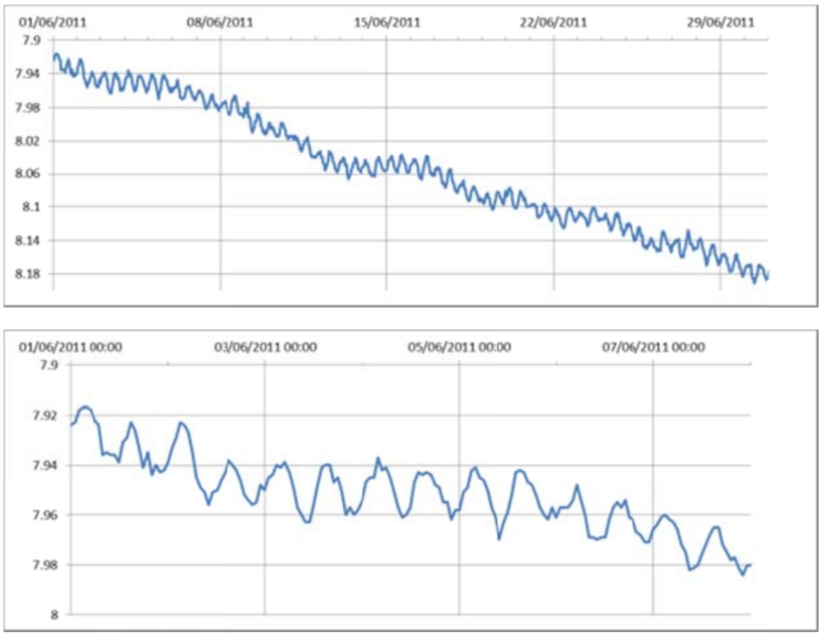

Figure 4: Semi-diurnal pressure head oscillation probably induced by the earth-tide at monitoring well Musopelo BH-38 (E 28.08602, S 15.26030).

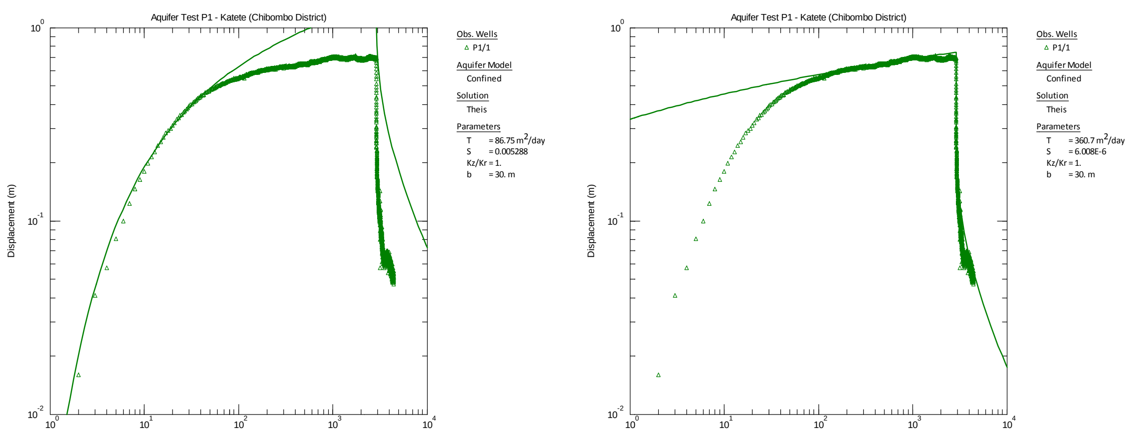

Figure 5: Best fit of observed drawdown vs. time to the Theis solution using early-time data (left) and late-time data (right) at observation borehole P1-1.

At observation wells P1-1 and P1-2, early drawdown (for elapsed time up to about ½ hour) and late drawdown (time > 1½ hour) can be fitted to separate Theis curves for homogeneous confined aquifers. The two sections are divided by a short transition period (Figure 5). The match to early-time drawdown produces a moderate transmissivity ($T \approx 80\ m^2/d$) and high storativity ($S \approx 0.005$) whereas the late data result in higher transmissivity (T ≈ 350 m^2/d) and very low storativity ($S < 1 \cdot 10^{-5}$). A satisfactory fit to the complete drawdown data can only be achieved by applying the proposed Hantush model for a leaky confined aquifer with no aquitard storage (Annex 4-1). The resulting transmissivity is similar to the early-time data section whereas the storativity is similar to the late-time data section fitted to the Theis analytical solution. The leaky effects in this case may be explained by less pervious horizons (vertical separation) or sections between different fracture sets (lateral separation). One plausible scenario could be that the leakage occurs from the high yielding limestone intersected at P1-4. Analysis of drawdown data at P1-4 suggests a higher transmissivity of over 350 m^2/d. Another yet less likely source could be a deeper lying limestone aquifer. A gravel-filled karstic feature within a massive limestone unit was encountered at borehole P1-1B at a depth of around 97 meters in target area B located about 0.5 kilometres to the northeast (refer to Part B, Chapter 3). The geology at target area B, however, is overall different from the pumped borehole site.

3.2 Kasanova Site P2

Test pumping at Kasanova was carried out between April 3 and 7, 2012.

The Pumping test setup can be summarized as follows:

Table 6: Pumping test setup at Kasanova, P-2

Pumped Well:	**P2-2 (Kasanova Main Well)**
Observations Wells and distance to pumped well, *r*:	P2-1: *r* = 18.05 m P2-3: *r* = 29.35 m
Drilled depth, *d* of borehole	P2-2: *d* = 50 m P2-1: *d* = 100 m P2-3: *d* = 41 m
Geology:	Weathered and karstic dolomitic limestone
Aquifer top and bottom:	P2-2: From 9 to 38 m b.g.s. P2-1: From near surface to 32 m b.g.s. P2-3: From 9 to 32 m b.g.s.
Effective aquifer thickness *b*:	Estimated at about 30 m

3.2.1 Step Test Analysis

Drawdown data at the pumped well and at the observation wells is shown in the graphs below (Figure 6).

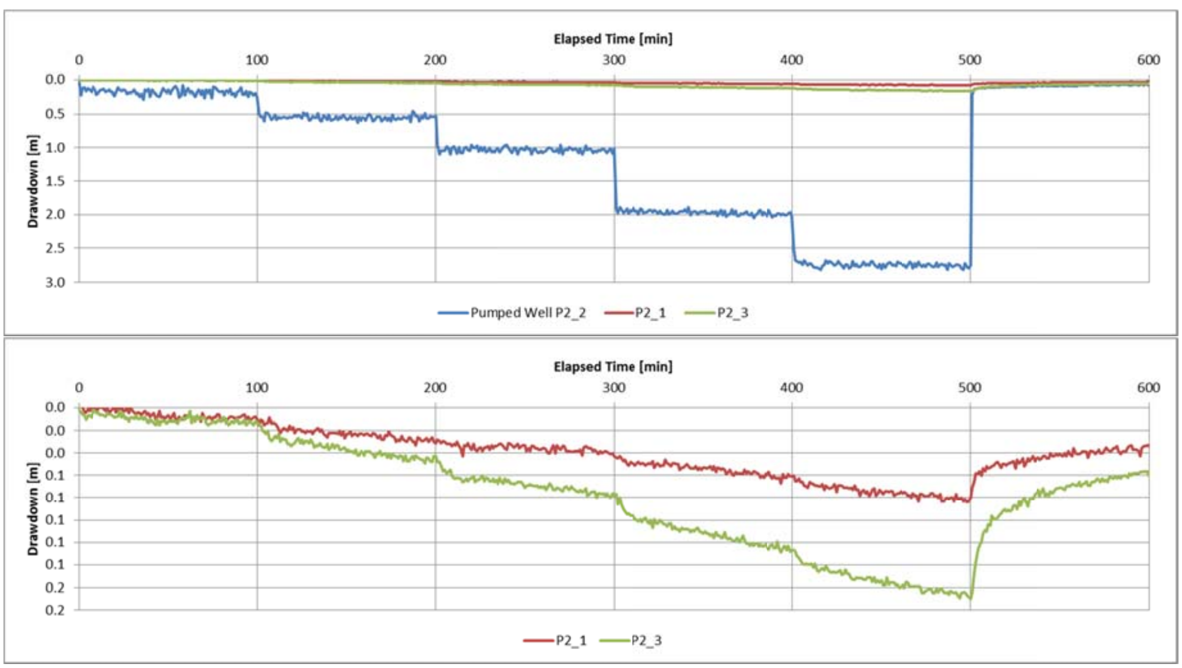

Figure 6: Drawdown during the step test as recorded by the data loggers at Kasanova, P-2

The analysis of the step test yielded the following results:

Table 7: Results of step test at Kasanova, P-2

Date of Test:	**03.04.2012**
No. and duration of steps	5 steps, 100 minutes each
Observed static water level, *SWL* at pumped well	1.11 m b.g.s.
Pumping rates Q_i:	Ranging from 0.47 L/s to 3.26 L/s
Observed maximum drawdown s_i at pumped well	Ranging from 0.23 m during the 1st step to 2.77 m during the last step
Observed specific capacity q_i at pumped well	Considerably dropping from 2.04 L/s/m during the 1st step to 1.18 L/s/m during the last step
Estimated parameters (Hantush-Bierschenk method):	B = 5.05 min/m^2 C = 44.15 min^2/m^5
Estimated parameters (Eden-Hazel method):	C = 45.04 min^2/m^5 T = 558 m^2/d

There is an excellent correspondence between the results obtained from the Hantush-Bierschenk and the Eden-Hazel methods (Annex 3-2), i.e. values of the nonlinear well-loss coefficient *C* obtained from the two methods are very similar. The parameter set for *B* and *C* obtained from the analysis fits observed values very well (Figure 7).

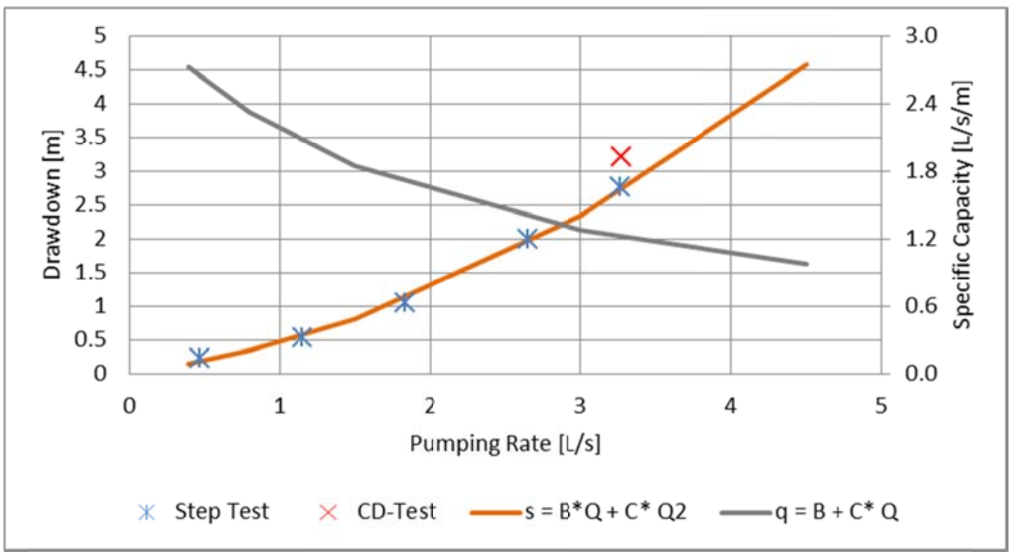

Figure 7: Drawdown and specific capacity for step test at site P2-2 (Kasanova). Dotted symbols indicate observed drawdown. Orange curve shows drawdown, *s* and grey curve depicts specific capacity, *q* as a function of pumping rate, *Q* as predicted by Hantush-Bierschenk method.

The observed non-linear well loss at the pumped well is considerable resulting in an overall low well efficiency. Unfortunately, the well could not be pumped at higher rates because the water level would suddenly plummet to pump intake level. The presence of very shallow water strikes that fall partially dry during pumping hence appear to contribute to the apparent well loss. The proposed discharge from the well is 3.5 L/s but the karstified limestone formation in this area is likely to produce much higher yields.

The area is located only about 1 km north of sites U-8A, U8-B, U-8C drilled under the BGR-program carried out in the late 1970s.

3.2.2 Aquifer Test Analysis

Drawdown data at the pumped well and at the observation wells is shown in the graphs below (Figure 8):

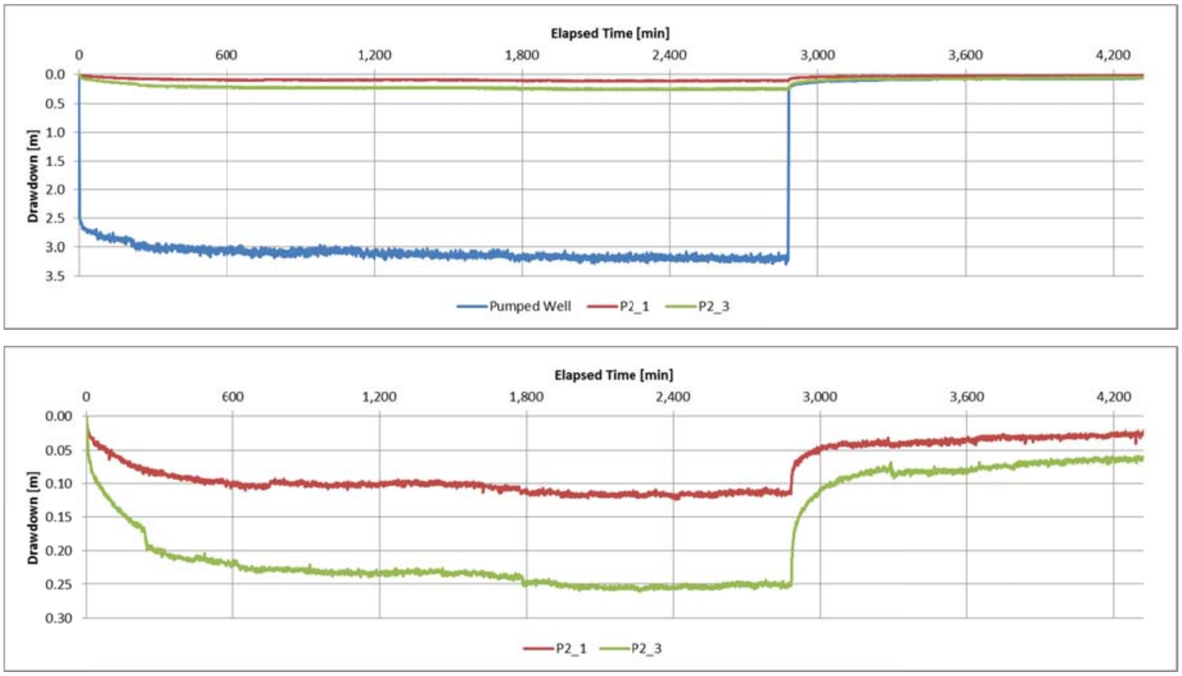

Figure 8: Drawdown during the aquifer test as recorded by the data loggers at Kasanova, P2

The analysis of the aquifer test yielded the following results:

Table 8: Results of aquifer test at Kasanova, P-2

Date of Test:	**04 - 07.04.2012**
Duration of test	Pumping 48 hours, Recovery 24 hours
Average pumping rate *Q*:	3.27 L/s
Static water level, *SWL* prior to test	P2-2: *SWL*= 1.13m b.g.s.
	P2-1: *SWL* = 0.62 m b.g.s.
	P2-3: *SWL*= 1.60 m b.g.s.
Observed maximum drawdown s_{max}	P2-2: s_{max} = 3.21 m
	P2-1: s_{max} = 0.11 m
	P2-3: s_{max} = 0.25 m
Residual water level, *RWL* after the test	P2-2: *RWL*= 0.07 m
	P2-1: *RWL* = 0.03 m
	P2-3: *RWL*= 0.11 m
Observed specific capacity *q* at pumped well	1.02 L/s/m

Estimated parameters:	Pumped Well, P2-1: *Theis Recovery Model* T = 718 m^2/d P2-1: *Theis Confined Aquifer Model* T = 1134 m^2/d S = 0.029 *Theis Recovery Model* T = 1072 m^2/d P2-3: *Theis Confined Aquifer Model* T = 600 m^2/d S = 0.0028 *Theis Recovery Model* T = 671 m^2/d

The limestone aquifer at P-2 is shallow and hence, almost certainly unconfined. As total drawdown at the observation boreholes was relatively small (< 30 cm) other effects on water levels such as variations in the pumping rate, trends, abstractions from adjacent areas or not fully compensated water-level changes induced by barometric pressure variations visibly influence the drawn water curves. This made the analysis of the data somewhat problematic, in particular for the recovery period. As overall drawdown is small compared to total aquifer thickness it was considered adequate to apply solutions developed for confined aquifer conditions for the sake of simplicity.

Observations of drawdown verify that the limestone aquifer at Kasanova is heterogeneous. Permeability near P2-3 located to the south of the pumped hole is clearly lower than in westerly direction near P2-1 as indicated by a larger drawdown (0.29 m vs. 0.11 m) despite the larger distance to the pumped well (29 m vs. 18 m). This observation is confirmed by the test analysis using the classical Theis solution (Annex 4-2). The analysis yields a transmissivity of 600 m^2/d for P2-3 which is just over half of the transmissivity obtained for P2-1. The storativity at P2-1 is about ten times higher amounting to 0.029 and coincides with the solution cavity/brecciated section that was reported to occur within the top 25 meters in boreholes P2-2 and P2-3.

3.3 Makeni Site P3

Test pumping at Makeni was carried out between March 18 and 22, 2012.

The test setup can be summarized as follows:

Table 9: Pumping Pumping test setup Makeni, P-3

Pumped Well:	**P3-1 (Makeni Main Well)**
Observations Wells and distance to pumped well, *r*:	P3-3: *r* = 13.5 m
	P3-4: *r* = 33.1 m
	P3-5: *r* = 21.7 m
Drilled depth, *d* of borehole	P3-1: *d* = 67 m
	P3-3: *d* = 50 m
	P3-4: *d* = 50 m
	P3-5: *d* = 50 m
Geology:	Interlayered calcareous mica schist, crystalline limestone and quartzitic psammite
Aquifer top and bottom:	P3-1: From 30 to 54 m b.g.s.
	P3-3: From 33 to 48 m b.g.s.
	P3-4: From 13 to 36 m b.g.s.
	P3-5: From 34 to 50 m b.g.s.
Effective aquifer thickness *b*:	Estimated at about 30 m

3.3.1 Step Test Analysis

Drawdown data at the pumped well and at the observation wells is shown in the graphs below (Figure 9):

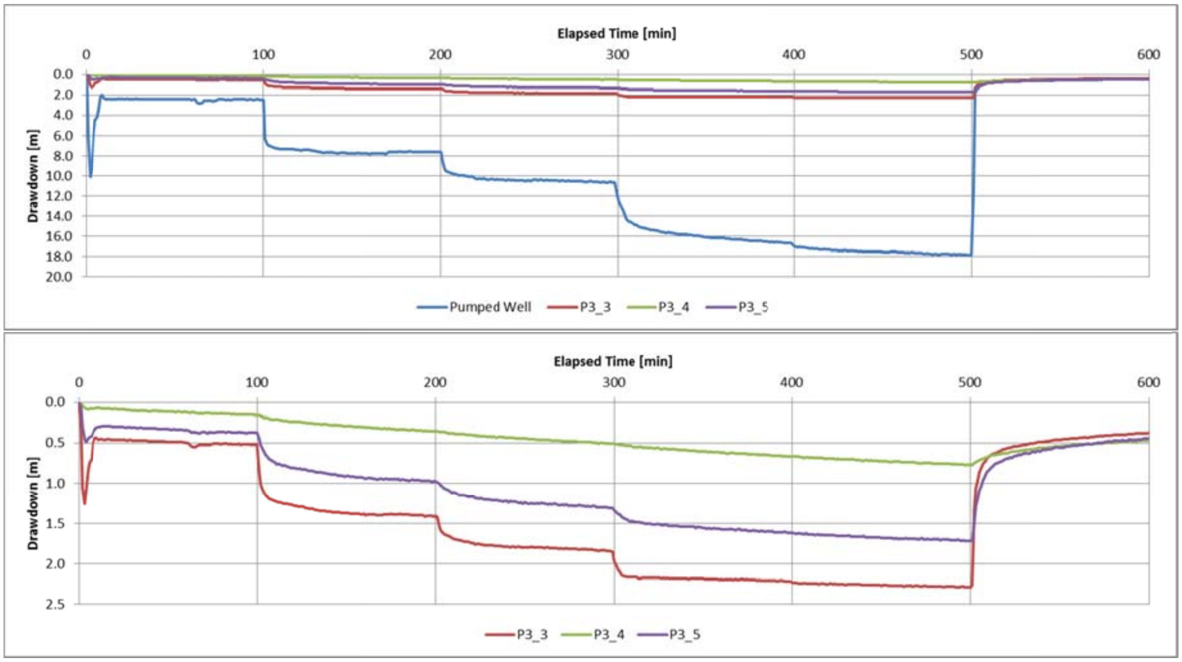

Figure 9: Drawdown during the step test as recorded by the data loggers at Makeni, P-3

The analysis of the step test yielded the following results:

Table 10: Results of step test at Makeni, P-3

Date of Test:	**18.03.2012**
No. and duration of steps	5 steps, 100 minutes each
Observed static water level, *SWL* at pumped well	11.81 m b.g.s.
Pumping rates Q_i:	Ranging from 4.29 L/s to 13.23 L/s
Observed maximum drawdown s_i at pumped well	Ranging from 2.47 m during the 1st step to 17.80 m during the last step
Observed specific capacity q_i at pumped well	Considerably dropping from 1.74 L/s/m during the 1st step to 0.74 L/s/m during the last step
Estimated parameters (Hantush-Bierschenk method):	B = 6.09 min/m^2 C = 13.86 min^2/m^5
Estimated parameters (Eden-Hazel method):	C = 13.21 min^2/m^5 T = 228 m^2/d

The drawdown during the last two steps with a pumping rate of 13.02 L/s and 13.29 L/s, respectively reached levels close to the pump intake. The rate could therefore not be further increased. The observed drawdown data for the last two steps could not be adequately fitted to the analytical approaches of Hantush-Bierschenk and Eden-Hazel (Annex 3-3). While the analytical method provided a good fit for the first three steps they failed to do so for the 4th and 5th step (Figure 10).

Besides, the results for the non-linear well coefficient *C* obtained from the Hantush-Bierschenk and the Eden-Hazel methods are very similar.

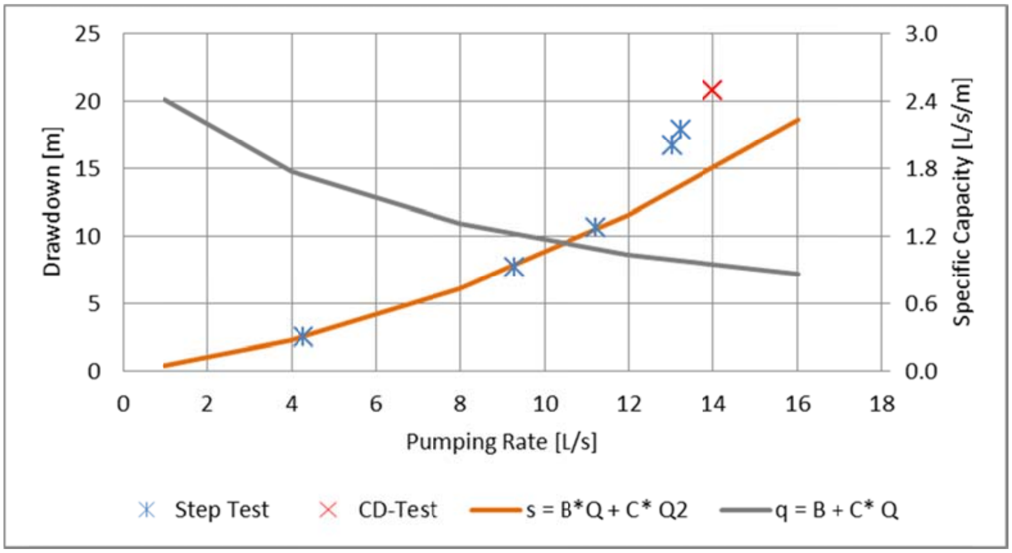

Figure 10: Drawdown and specific capacity for step test at site P3-1 (Makeni). Dotted symbols indicate observed drawdown. Orange curve shows drawdown, *s* and grey curve depicts specific capacity, *q* as a function of pumping rate, *Q* as predicted by Hantush-Bierschenk method.

The observed non-linear well loss at the pumped well is considerable but overall less prominent compared to sites P-1 and P-2.

3.3.2 Aquifer Test Analysis

Drawdown data at the pumped well and at the observation wells is shown in the graphs below (Figure 11):

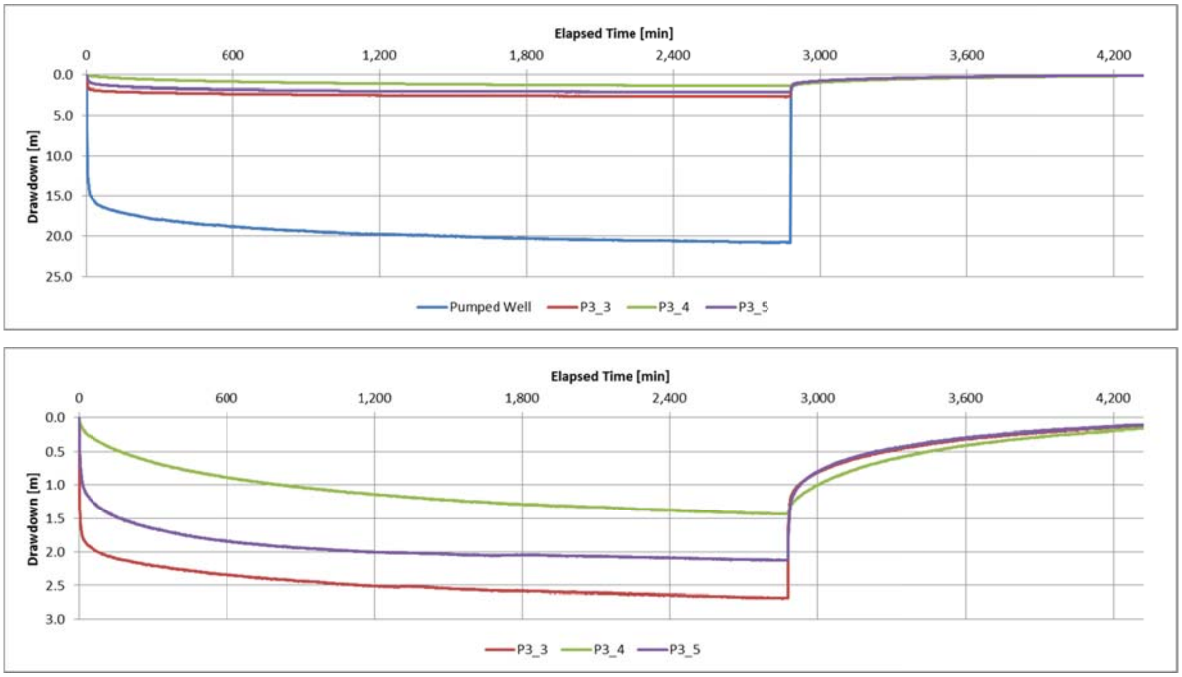

Figure 11: Drawdown during the aquifer test as recorded by the data loggers at Makeni, P-3

The analysis of the aquifer test yielded the following results:

Table 11: Results of main test at Makeni, P-3

Date of Test:	**19 - 22.03.2012**
Duration of test	Pumping 48 hours, Recovery 24 hours
Average pumping rate *Q*:	14.12 L/s
Static water level, *SWL* prior to test	P3-1: *SWL*= 12.24 m b.g.s. P3-3: *SWL* = 11.97 m b.g.s. P3-4: *SWL*= 12.72 m b.g.s. P3-5: *SWL*= 11.60 m b.g.s.
Observed maximum drawdown s_{max}	P3-1: s_{max} = 20.81m P3-3: s_{max} = 2.69 m P3-4: s_{max} = 1.43 m P3-5: s_{max} = 2.13 m
Residual water level, *RWL* after the test	P3-1: *RWL*= 0.15 m P3-3: *RWL* = 0.12 m P3-4: *RWL*= 0.16 m P3-5: *RWL*= 0.12 m
Observed specific capacity *q* at pumped well	0.67 L/s/m
Estimated parameters:	Pumped well, P3-1: *Theis Recovery Method* *T* = 262 m^2/d P3-3: *Theis Confined Aquifer Model* *T* = 455 m^2/d *S* = 3.7 10^{-5} P3-4: *There appears to be flow pattern controlled by a single vertical fracture corresponding to the Gringarten- solution (early-time data). A tentative value for permeability of fracture zone, K of 8.4 m/d was obtained.* *Theis Confined Aquifer Model* *T* = 280 m^2/d *S* = 0.018 P3-5: *Jacob Confined Aquifer Model (Straight-line method)* *T* = 430 m^2/d *S* = 0.00031

The drilling results can be interpreted in a way that a productive aquifer is developed within a brecciated productive fault zone or karstified limestone extending from the pumped well (P3-1) to borehole P3-4 to the south and abandoned borehole P3-2 to the southwest. Observation holes P3-3 and P3-5 located in north/northeast directions hit less productive layers of schist and quartzite. Drawdown observations confirm this finding as drawn water levels are smallest at P3-4 even though this borehole is furthest from the pumped well.

Locally, the aquifer is probably confined due to the occurrence of layers of presumably low permeable schist and clayey material within the scapolite.

Test pumping analysis for P3-3 and P3-5 results in a moderate to high transmissivity of around 450 m^2/d and varying and relatively low storativity in the order of 10^{-4} to 10^{-5} (Annex 4-3).

Early drawdown data observed at P3-4 suggests a linear flow pattern along a major vertical fault zone (Figure 12) in correspondence to the geological description in the drilling report. Late time-data shows a pseudo-radial pattern towards the well. The transmissivity obtained for this section is 280 m^2/d with a storativity of 0.018. A similar transmissivity was obtained for the pumped well from step and aquifer test analysis.

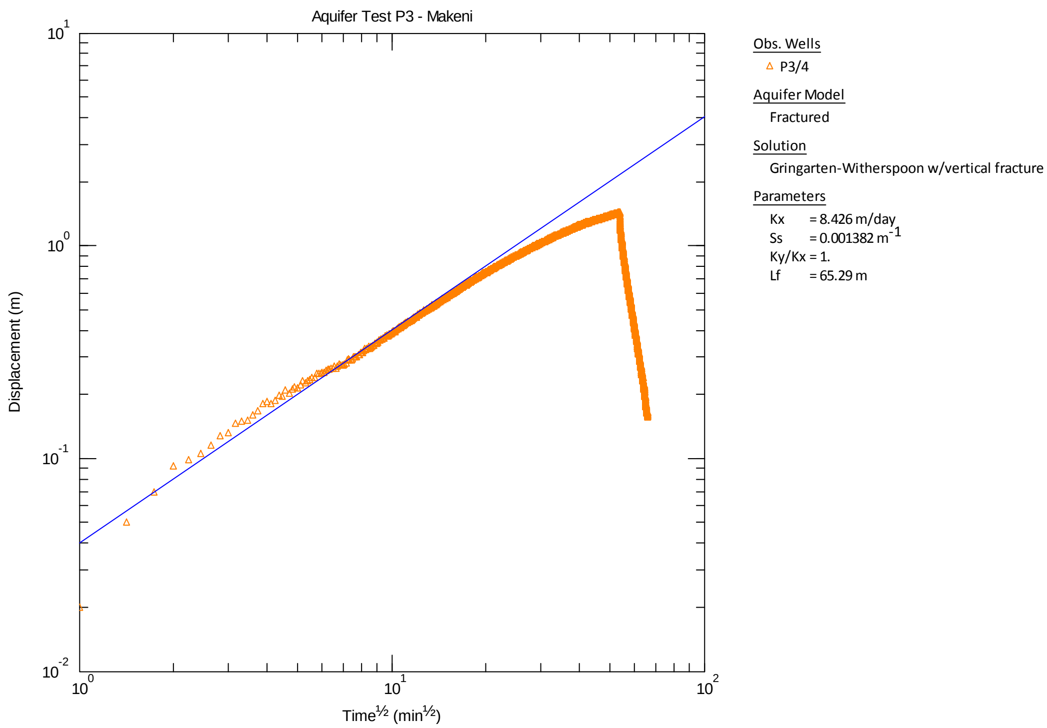

Figure 12: Linear flow pattern observed at well P3-4 indicated by a straight-line section in the plot of drawdown vs. $\sqrt{t}$

4 Summary of Major Findings

1. The test pumping analysis provided valuable additional information on the hydraulic characteristics of the Lusaka Dolomite and Cheta formations in the Lusaka region. The results are summarised in Table 12 below.
2. **Yields:** From drilling records, high yielding boreholes (≥12 L/s) were reported at all three investigation sites. The highest expected yields with presumably over 20 L/s (!) were attributed to borehole P1-4 at Katete within the Cheta Limestone Formation and P2-2 at Kasanova within cavernous rock of the Lusaka Dolomite Formation. During test pumping, however, discharge at comparable rates could only be achieved at Makeni (14 L/s from P1-3) whereas pumped yields at Katete and Kasanova remained well below expectations. The low yields are explained by high well losses. It is assumed that hydraulic active fracture or cavernous zones could not be appropriately connected to the well.

Table 12: Summary of test pumping analysis results

	P-1 Katete	**P-2 Kasanova**	**P-3 Makeni**
Geology:	Interlayered/adjacent micaceous schist and crystalline limestone	Fractured and/or karstic dolomitic limestone	Interlayered calcareous mica schist, crystalline limestone and quartzitic psammite
Formation:	Cheta	Lusaka Dolomite	Cheta
Highest yield [1)]	> 20 L/s at P1-4	> 20 L/s at P2-2	15 L/s at P2-2
Step Test Results:	B = 28.5 min/m^2 C = 309 min^2/m^5 T = 147 m^2/d	B = 5.05 min/m^2 C = 44.15 min^2/m^5 T = 558 m^2/d	B = 6.09 min/m^2 C = 13.86 min^2/m^5 T = 228 m^2/d
Aquifer Test Results:	Q = 2.7 L/s q = 0.27 L/s/m (23 m^2/d) 80 m^2/d < T < 88 m^2/d 0.0010 < S < 0.0057	Q = 3.27 L/s q = 1.02 L/s/m (88 m^2/d) Cavernous section: T = 1,174 m^2/d S = 0.029 Fractured section T = 600 m^2/d S = 0.0028	Q = 14.1 L/s q = 0.67 L/s/m (58 m^2/d) Limestone section: 262 m^2/d < T < 280 m^2/d S = 0.018 Schist section: 430 m^2/d < T < 455 m^2/d 3.7 10^{-5} < S < 0.00031

[1)] as reported from drilling records

3. The geological setup at all three investigated sites is extremely heterogeneous with respect to lithology (schist/limestone) and degree of fracturing and karstification. As a consequence, groundwater flow conditions were equally complex.
4. **Transmissivity:** Values for transmissivity of the aquifers tested are to be considered "moderate to high" or "high". The lowest values of around 90 m^2/d were characteristic

for the Cheta Limestone Formation at Katete. The crystalline limestone in this area however was interspersed with carbonaceous schist. At the other two sites the transmissivity for carbonate rock varied between 260 m^2/d and >1000 m^2/d with the highest values attributed to karst features within the Lusaka Dolomite Formation.

5. The results obtained for the Makeni site seem to confirm that the area mapped as “Cheta schist” in the geological maps is much more pervious than the geological description would suggest. The area is part of an agricultural belt highly dependent on groundwater for irrigation purposes.

6. The test pumping results are comparable with a statistical analysis of test pumping data in the area (Bäumle 2011). The median value of transmissivity for 56 tests carried out in carbonate rock aquifers amounted to 332 m^2/d according to this study. The regional study also exhibited the large variability of hydraulic rock properties. Maximum obtained transmissivities exceeding 3000 m^2/d as for some wells in Lusaka West and South (e.g. Mumbwa Roadside, Quarries, U8-D northwest of Mt. Makulu) could not be found at the three sites investigated in this report.

7. **Storativity:** The test pumping results at P-2 and P-3 suggest that storativity of well fractured crystalline limestone is in the order of 0.02 to 0.03. Previous test results from e.g. the Mass Media and NRDC areas yielded higher values between 0.05 and 0.16. It was however mentioned that the analysis results were partially questionable due to poor quality of data or interferences from adjacent wells (Bäumle 2011).

5 References

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PART D

Water Quality Analysis

Prepared by
Andrea Nick

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Abbreviations

avg	average
BGR	Federal Institute for Geosciences and Natural Resources
DWA	Department of Water Affairs
E. coli	Escherichia coli
EC	electrical conductivity
Eh	oxidation reduction potential recalculated to standard hydrogen electrode
m bgl	Meters below ground level
m btc	Meters below top of casing
mpn	most probable number
pH	negative logarithmic value of proton concentration
T	temperature
TC	total coliforms
UNZA	University of Zambia
WHO	World Health Organisation
ZDWS	Zambian Drinking Water Standard

1 Introduction

The analysis of groundwater quality comprises the in-situ measurements and water samples taken at the three sites Katete, Kasanova and Makeni (see Figure 1) and their chemical analysis in three water laboratories according to their respective capacities.

The main purpose of the analysis is to generate an understanding of the water quality in the three aquifers after an extended period of pumping, and to compare analysis results from the laboratories involved.

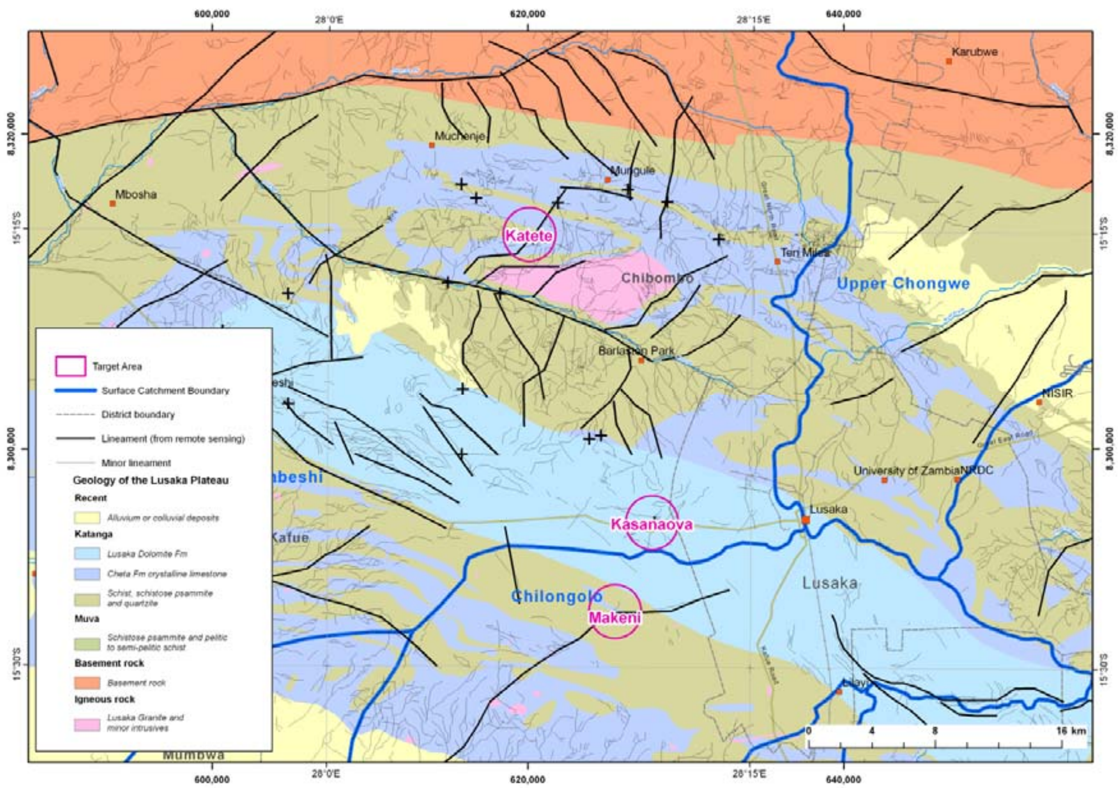


Figure 1: Sampling locations on the geological overview map of the area

2 Sampling

The supervising consultant and his field team were briefed in in-situ measurements which were taken once per hour throughout the pumping tests and in water sampling for cations, anions and microbiology. For the set-up of the flow cell and the in-situ-probes, see chapter 10 in Part B.

Water quality samples were taken at all three sites at the end of each constant discharge test. The collection of water samples was scheduled at 30 minutes before shut-down of the pump.

The sampling was oriented towards a comparison of the UNZA Water Laboratory and BGR Water Lab in Hannover, also considering the Department of Water Affairs Laboratory that was capable to test for the individual parameters microbiology, alkalinity and nitrates.

The samples taken at each site comprised

a) one 100 ml microbiology sampling bottle for analysis at Department of Water Affairs Laboratory with IDEXX methodology
b) three 250 ml bottles for anion analysis in all three laboratories
c) two 100 ml pre-acidified bottles for cation analysis at UNZA Water Laboratory and BGR

The microbiology samples were stored in a cooling box before delivery to DWA which was within 10 hours after sampling for sites P1 and P3, but was delivered and analyzed only after exceeded recommended storage time for site P2 due to public holidays. Same applies to the anion samples for analysis at DWA regarding nitrates and alkalinity.

The samples for UNZA were delivered to the laboratory within 48 hours after sampling while the samples for BGR were stored in the refrigerator for up to 5 weeks before being shipped to Hannover.

In-situ measurements

Before sampling the in-situ probes were read separately from the continuous readings that took place throughout the test. The results of the readings prior to sampling are given in Table 1 while the first 3 and the last set of values of the constant discharge test as well as average values for the complete test pumping period are given in Table 2.

Table 1: In-situ reading at time of sampling

Site ID	TH2O (°C)	EC (µS/cm)	pH	Eh (mV)	O_2 (mg/L)	Water level (m btc)
P1/3	25.6	786	7.05	-16.3	1.4	7.10
P2/2	25.1	734	7.08	-24.2	0.96	1.10
P3/1	24.4	532	6.93	-15.9	1.04	33.11

Table 2: In-situ reading at beginning and end of constant discharge tests and averages

Site ID	min	T H_2O (^oC)	EC (µS/cm)	pH	Eh (mV)	O_2 (mg/L)	Water level (m btc)
P1/3	0	24.7	850	7.16	-25.9	1.4	7.10
	30	25.6	816	6.99	-12.7	1.4	16.50
	60	25.6	798	7.03	-15.00	1.4	16.75
	2880	25.6	786	7.05	-16.30	1.4	17.28
	avg	25.7	785	7.05	-16.29	1.4	-
P2/2	0	24.4	731	7.08	-23.6	-	1.1
	30	25.1	728	7.02	-21.1	-	3.85
	60	25.1	732	7.06	-23.0	-	3.9
	2880	25.1	734	7.08	-24.1	0.96	4.3
	avg	25.1	732	7.08	-24.2	0.96	-
P3/1	0	-	-	-	-	-	12.22
	30	24.3	528	6.93	-16.4	1.1	27.84
	60	24.3	512	6.93	-16.1	1.05	28.56
	2880	24.2	536	6.92	-15.7	1.05	33.1
	avg	24.05	517.05	6.91	-15.20	0.95	-

Electrical conductivity values do not suggest urban pollution. At the Makeni site P3/1 groundwater seems to be low in mineralization with values below 550 µS/cm. PH values are around 7 (neutral) at all sites, with Makeni being a bit lower in pH than the other two sites. All tested groundwaters show slightly negative Eh-values (i.e. indicator for redox potential, possibly pointing to reducing conditions in the groundwater) and also low oxygen concentrations (saturation around 15%). However, this does not necessarily draw the interpretation of actual reducing conditions, especially as groundwater levels are between 1-4 m below ground level at the Kasanova site and manganese concentrations are low (see chapter 3).

3 Results of water quality analysis and comparison of laboratories

Results for microbiology, major ions and trace metals are given in the following. The limits stated by the Zambian Drinking Water Standard (ZDWS) or WHO guidelines are also indicated.

Microbiology

The results for the three sites on total coliforms (T.C.) and E. coli are given in most probable number (mpn) and are presented in Table 3.

Table 3: Results of microbiological analysis for total coliforms and E. coli

DATE	Site ID	Name	T.C. (mpn)	E. coli (mpn)
21/03/2012	P3/1	Makeni	1.0	<1
09/04/2012	P2/2	Kasanova	*70.3*	<1
11/04/2012	P1/3	Katete	50.4	<1
ZDWS limit			10	<1

The analysis of the sample from Kasanova has to be regarded invalid, as storage exceeded the recommended time which allowed coliforms to multiply. The high value for total coliforms at Katete cannot be explained by extended storage time prior to analysis, but might have been contaminated during sampling. As the site in Katete is similarly far from settlement areas the cause for the high total coliforms is unclear.

As the most probable number of E. coli is <1 for all sites, it can be assumed that no faecal coliform contamination existed by the time of sampling.

There is no comparison of the DWA lab with other laboratories for analysis in microbiology.

Major ions

The analysis from the BGR laboratory for the major ions (and NO_2^-) is shown in Table 4.

Table 4: Results of major ions from BGR laboratory

Site ID		P1/3	P2/2	P3/1	ZDWS limit
Name		Katete	Kasanova	Makeni	(mg/L)
K	mg/L	1.60	0.70	0.70	
Na	mg/L	40.50	17.30	12.60	
Mg	mg/L	35.80	26.50	26.90	150
Ca	mg/L	82.00	100.00	101.00	200
Cl	mg/L	1.16	36.60	21.60	250
SO4	mg/L	20.80	23.90	8.59	400
HCO3	mg/L	516.00	375.00	428.00	
NO3	mg/L	7.22	25.00	18.10	44
NO2	mg/L	0.016	0.012	<0.003	1

The piper diagram in Figure 2 classifies all three samples as calcium-magnesium-bicarbonate waters.

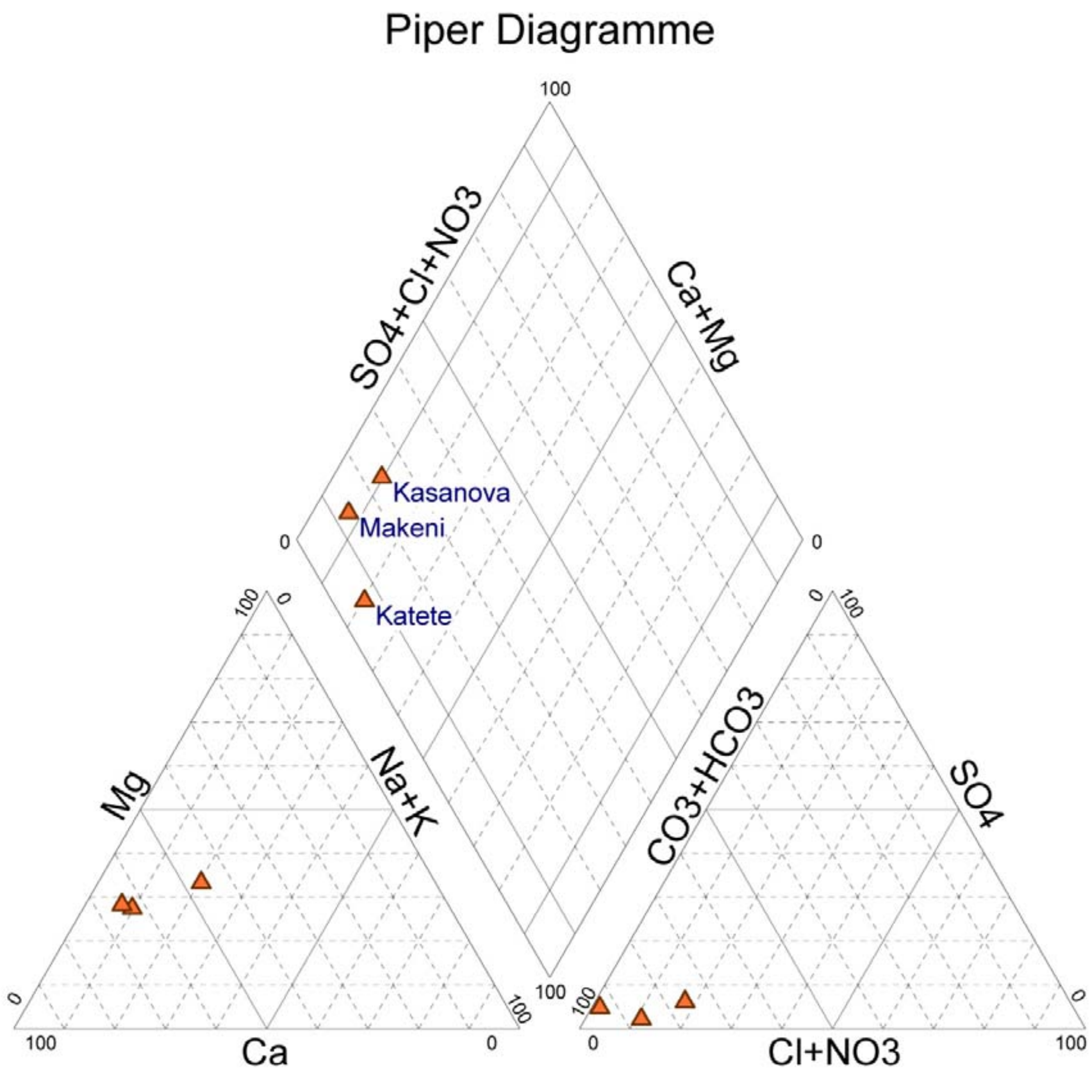


Figure 2: Piper diagramme of samples from test pumping

In general water quality is good and potable. Nitrate levels are well below the limit of the Zambian Drinking Water Standard (as are all other values). EC values below 800 µS/cm at all sites reconfirm the assumption that influence from urban pollution does not exist yet. The sample from Katete – although situated in the Cheta Formation and thus expected to have lower dolomite content – shows the highest Mg/Ca ratio among the three (Katete: 0.4, Kasanova: 0.3, Makeni: 0.3).

Nitrates and alkalinity have been processed by all three laboratories allowing for a comparison of analytics, although extended storage time and resulting degradation of nitrate has to be considered for the BGR laboratory results. Other major and minor ions were analyzed by BGR and UNZA only and are compared in Table 5.

Table 5: Comparison of laboratory results for major and minor ions and trace elements

Site ID		P1/3			P2/2			P3/1		
Name		Katete			Kasanova			Makeni		
		BGR	UNZA	DWA	BGR	UNZA	DWA	BGR	UNZA	DWA
NO_3-N*	mg/L	1.64	3.57	-	5.68	5.43	1.09	4.11	2.50	-
$CaCO_3$+	mg/L	423	300	-	307	300	1.75	351	205	5.90
K	mg/L	1.60	6.71	-	0.70	6.73	-	0.70	15.9	-
Na	mg/L	40.50	19.4	-	17.30	19.8	-	12.60	31	-
Mg	mg/L	35.80	25.92	-	26.50	28.8	-	26.90	10.32	-
Ca	mg/L	82.00	78.4	-	100.00	76.8	-	101.00	64.8	-
Cl	mg/L	1.16	30	-	36.60	30	-	21.60	18	-
SO4	mg/L	20.80	33.75	-	23.90	35.7	-	8.59	20.5	-
Fe(II)	mg/L	0.034	0.07	-	0.033	0.06	-	0.009	<0.01	-
F	mg/L	0.733	0.15	-	0.14	0.16	-	0.336	0.1	-
PO4	mg/L	<0.03	0.03	-	<0.03	<0.01	-	<0.03	<0.01	-
Cd	mg/L	<0.002	<0.0002	-	<0.002	<0.0002	-	<0.002	<0.0002	-
Pb	mg/L	<0.02	<0.01	-	<0.02	<0.01	-	<0.02	<0.01	-

* *Nitrate given as mg/L NO_3-N. ZDWS limit: 10 mg/L*
+*alkalinity given as mg/L $CaCO_3$. ZDWS limit: 500 mg/L*

The comparison shows that DWA laboratory faces strong challenges in reliable conductance of analysis on the one hand (three out of six results missing) and in the quality of their analysis results on the other hand. The UNZA lab establishes a rather close result for the P2/2 sample for some parameters while the other two sample analyses divert widely from BGR results for almost all the parameters. Ion balances for BGR results are between -2% and +1%, for UNZA they range from 5% to 18%.

Trace elements

Further analysis of trace elements was only done by BGR; results are shown in Table 6. There is no indication of heavy metal contamination; none of the values is above the limit of the Drinking Water Standard.

Table 6: Results for trace elements from BGR laboratory

Site ID		P1/3	P2/2	P3/1	ZDWS limit
Name		Katete	Kasanova	Makeni	(mg/L)
NH_4	mg/L	<0.01	<0.01	<0.01	0.1
Mn	mg/L	0.009	0.004	0.001	0.1
Br	mg/L	0.003	0.025	0.015	
Al	mg/L	<0.003	<0.003	<0.003	0.2
As	mg/L	<0.02	<0.02	<0.02	0.05
BO_2	mg/L	0.02	0.01	0.02	
Ba	mg/L	0.048	0.017	0.025	
Be	mg/L	<0.0005	<0.0005	<0.0005	
Co	mg/L	<0.003	<0.003	<0.003	
Cr	mg/L	<0.003	<0.003	<0.003	0.05
Cu	mg/L	<0.003	<0.003	<0.003	1
Li	mg/L	<0.003	<0.003	<0.003	
Ni	mg/L	<0.003	<0.003	<0.003	
Sc	mg/L	<0.001	<0.001	<0.001	
SiO_2	mg/L	21.1	5.5	17.3	
Sr	mg/L	0.43	0.103	0.214	
Ti	mg/L	0.001	0.001	0.001	
V	mg/L	<0.003	0.003	<0.003	
Zn	mg/L	0.017	0.011	0.188	5

4 Discussion of results

The water quality in all three sites is fit for consumption with the exception of coliforms which makes it necessary to chlorinate, boil or otherwise treat the water before consumption.

The water quality results indicate that the types of groundwater found in Makeni and Kasanova (P3 and P2) are similar to each other while the sample from Katete (P1) shows the highest carbonate hardness (>375 mg/L $CaCO_3$, “very hard”) as well as the highest Mg/Ca ratio. All samples show a HCO3:SiO2 ratio between 24:1 and 60:1, as most of the carbonate waters in Lusaka do (Museteka & Bäumle 2009).

The farming that takes place around the sites in Makeni and Kasanova does not seem to have a large influence on the deeper groundwater in terms of excess fertilizer infiltrating. Further studies would be needed looking at pesticides to confirm this statement.

5 References

Museteka L. & R. Bäumle (2009): Groundwater Chemistry of Springs and Water Supply Wells in Lusaka: Results of the sampling campaigns conducted in 2008. Report No. 1 - Department of Water Affairs, Zambia & Federal Institute for Geosciences and Natural Resources, Germany; Unpublished Report; 54 pages, Lusaka.

Annex 1

Geophysical Profiles and Soundings

Table of Contents:

Appendix A1 Target Area P-1 (Katete)

GReSP
Geophysical Investigation of the Crystalline Limestone aquifer Katete Target Area (P-1)

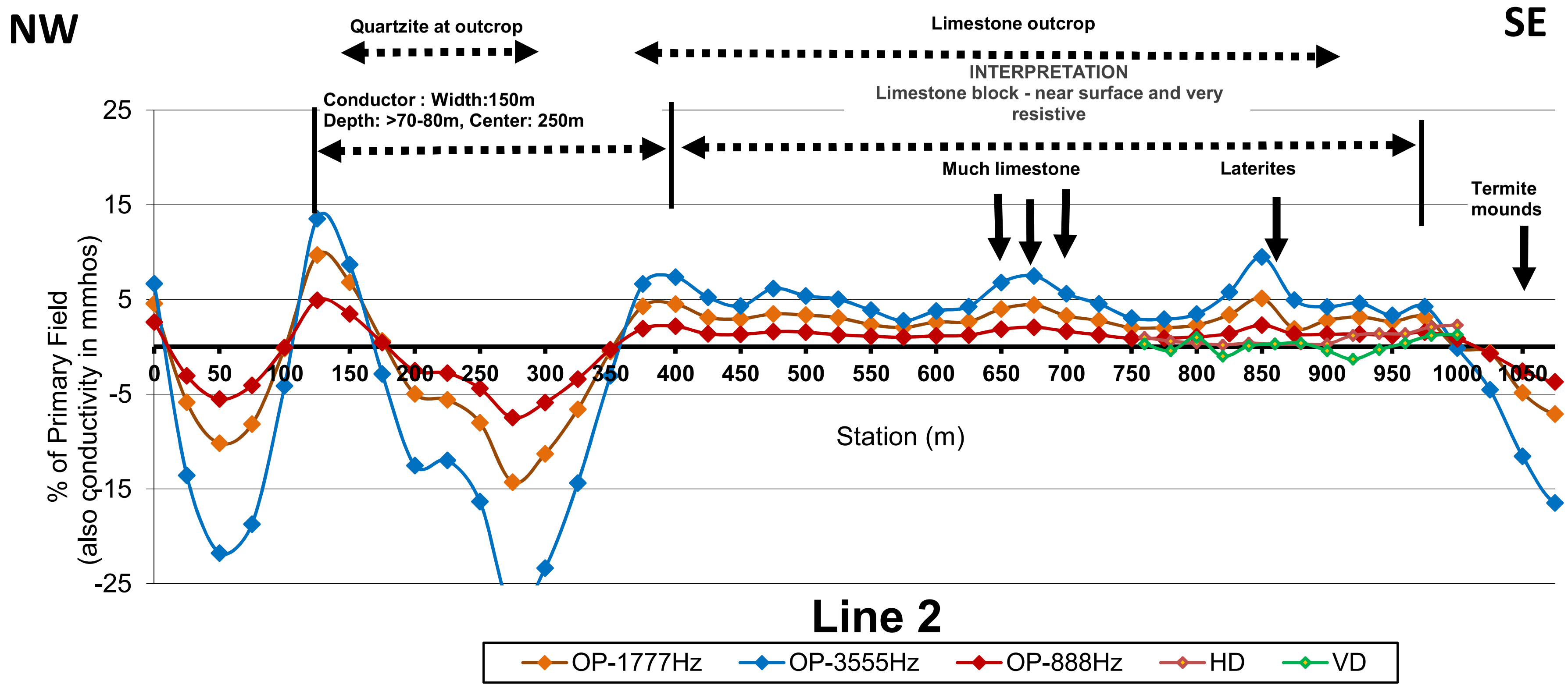


Figure 1.1 Max Min profile: Line 2

CODE: P-2 | **NAME: Kasanova** | **DATE: 19/07/2011**

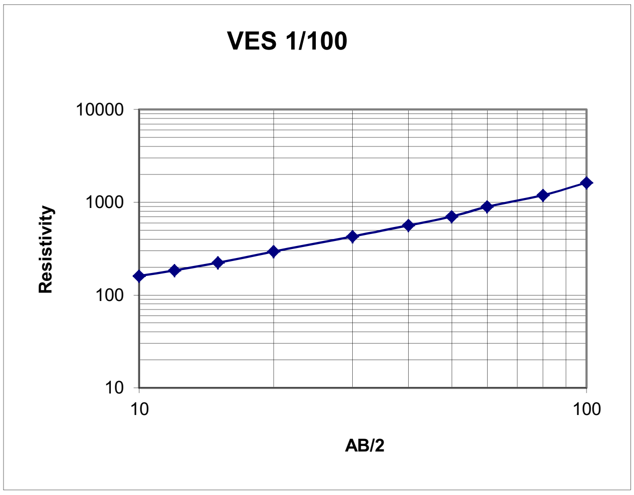
SURVEYOR: Jim | **DISTRICT: Kafue** | **Ward:**

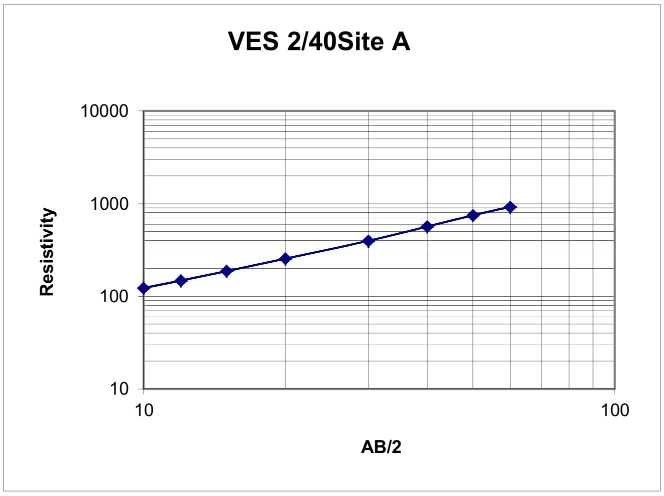
VES 1/100

AB/2	GC	SD	mV	MN=2	MN=10	Graph
10	0.5k	0		160		160
12	0.5k	0		185		185
15	0.4k	0		223		223
20	0.3k	0		295		295
30	0.3k	0		428	664	428
40	0.3k	0			800	564
50	0.4k	0			938	702
60	0.3k	0			1132	896
80	0.3k	0			1431	1195
100	0.3k	0			1862	1626
S			**15.41913**			
E			**28.19132**			

VES 2/40

AB/2	GC	SD	mV	MN=2	MN=10	Graph
10	0.3k	0		123		123
12	0.3k	0		148		148
15	0.3k	0		187		187
20	0.3k	0		255		255
30	0.5k	0.1		397	425	397
40	0.3k	0			595	567
50	0.5k	0			777	749
60	0.5k	0			948	920
80						
100						
S			**15.41835**			
E			**28.19169**			





Interpretation

From	To	Resisitivity Ohm-m	Interpretation
0	4	150	Soil, wet
6	13	250	Weathered dolomite
13	70+	5000	Dolomite

From	To	Resisitivity Ohm-m	Interpretation
0	2	100	Soil, wet
2	17	250	Weathered dolomite
13	70+	5000	Dolomite

Comment

Ground contact very good. Data integrity good.
All observations point to a 100% dolomite intersection
Weathering layers in dolomite supressed - making interpretation subjective
Air percussion drilling method suitable

Figure 2.2: VES Data and Interpretation, P-2 (Kasanova) target.

GReSP
Geophysical Investigation of the Crystalline Limestone aquifer Katete Target Area (P-1)

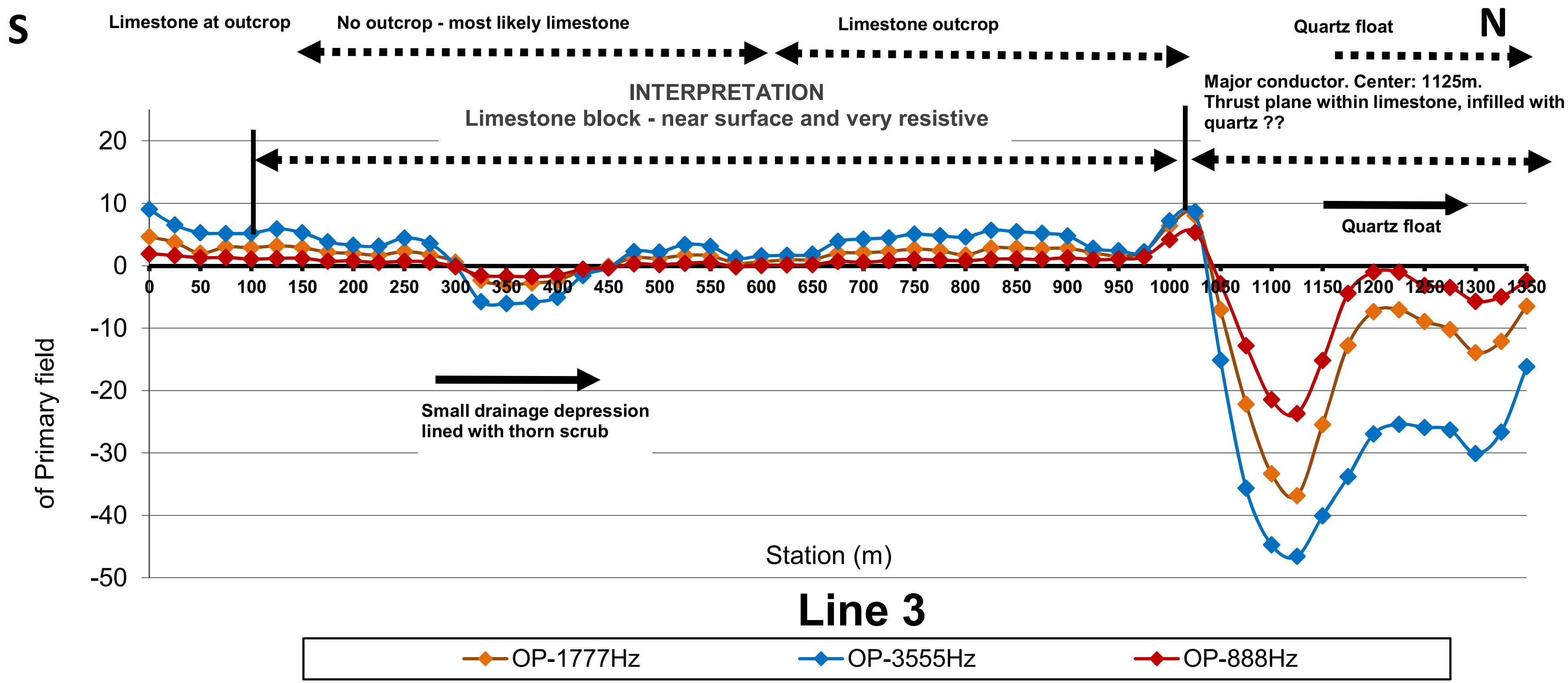


Figure 1.2 **Max Min profile: Line 3**

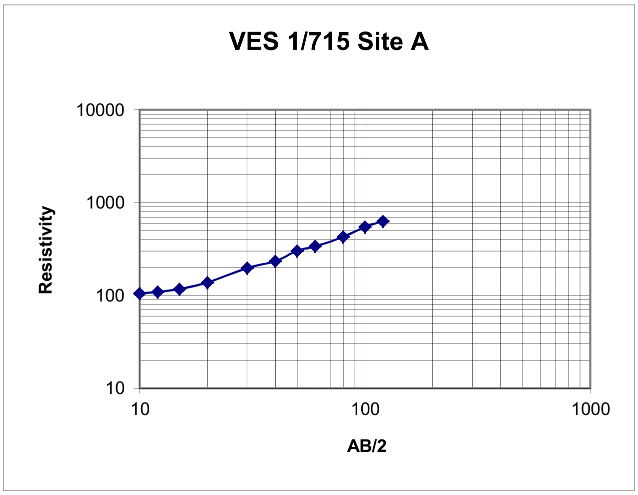
CODE: P-1	NAME: Katete	DATE: 22/07/2011
SURVEYOR: Jim	DISTRICT: Chibombo	Ward:

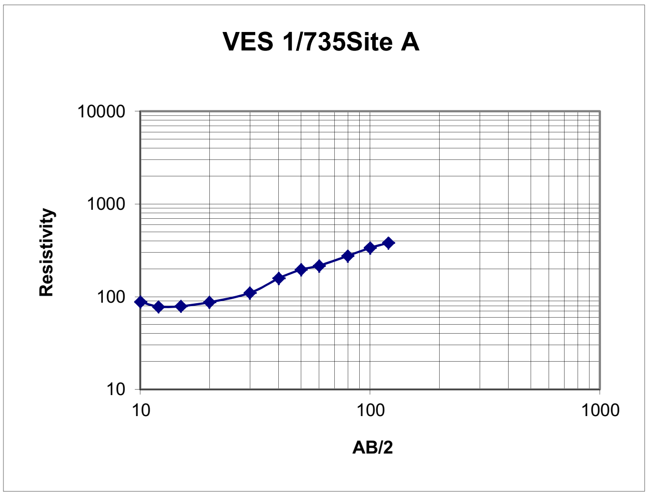
VES 1/715

AB/2	GC	SD	mV	MN=2	MN=10	Graph
10	2k			105		105
12	2k			109		109
15	2k			117		117
20	2k			138		138
30	1.5k			197	130	197
40	2k				167	234
50	1.5k				235	302
60	1.5k				271	338
80	1.5k				360	427
100	1k				481	548
120	2k				563	630
S				15.46948		
E				28.16573		

VES 1/735

AB/2	GC	SD	mV	MN=2	MN=10	Graph
10	2k			88		88
12	2k			78		78
15	2k			79		79
20	2.5k			87		87
30	2k			110	118	110
40	2k				150	158
50	1.5k				188	196
60	1.5k				208	216
80	2k				268	276
100	1k				328	336
120	2k				372	380
S				15.46824		
E				28.17053		





Interpretation

From	To	Resisitivity Ohm-m	Interpretation
0	3	100	Soil, dry
3	12	130	Weathered rock, dry
12	25	250	Weathered rock, wet
25	75+		

From	To	Resisitivity Ohm-m	Interpretation
0	1	120	Soil, dry
1	9	70	Clayey soil, dry
9	40	220	Weathered rock, wet
40	75+	450	Fractured bedrock, wet

Comment Ground contact good. Data integrity good.
Upswing of sounding curve is not steep in righthand VES - indicating weathering and fracturing
Air percussion drilling method suitable

Figure 1.3: VES Data and Interpretation, P-1 (Katete) target.

GReSP
Geophysical Investigation of the Crystalline Limestone aquifer Katete Target Area (P-1)

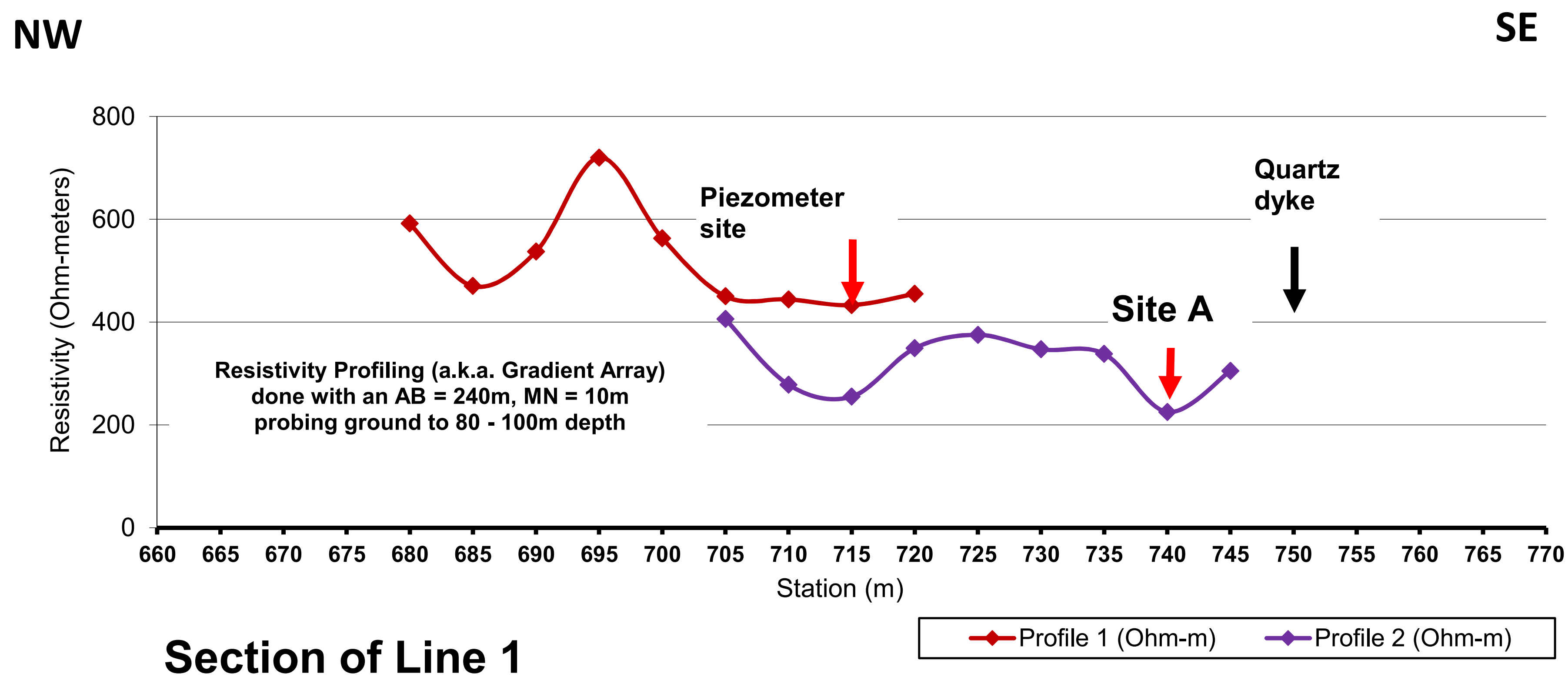


Figure 1.4 **Resistivity Profiling to Generate Site A**

Appendix A2 Target Area P-2 (Kasanova)

Figure 2.1	**EM Profiles**
Figure 2.2	**VES data and interpretation**

GReSP
Geophysical Investigation of the Lusaka Dolomite aquifer Kasanova Target Area (P-2)

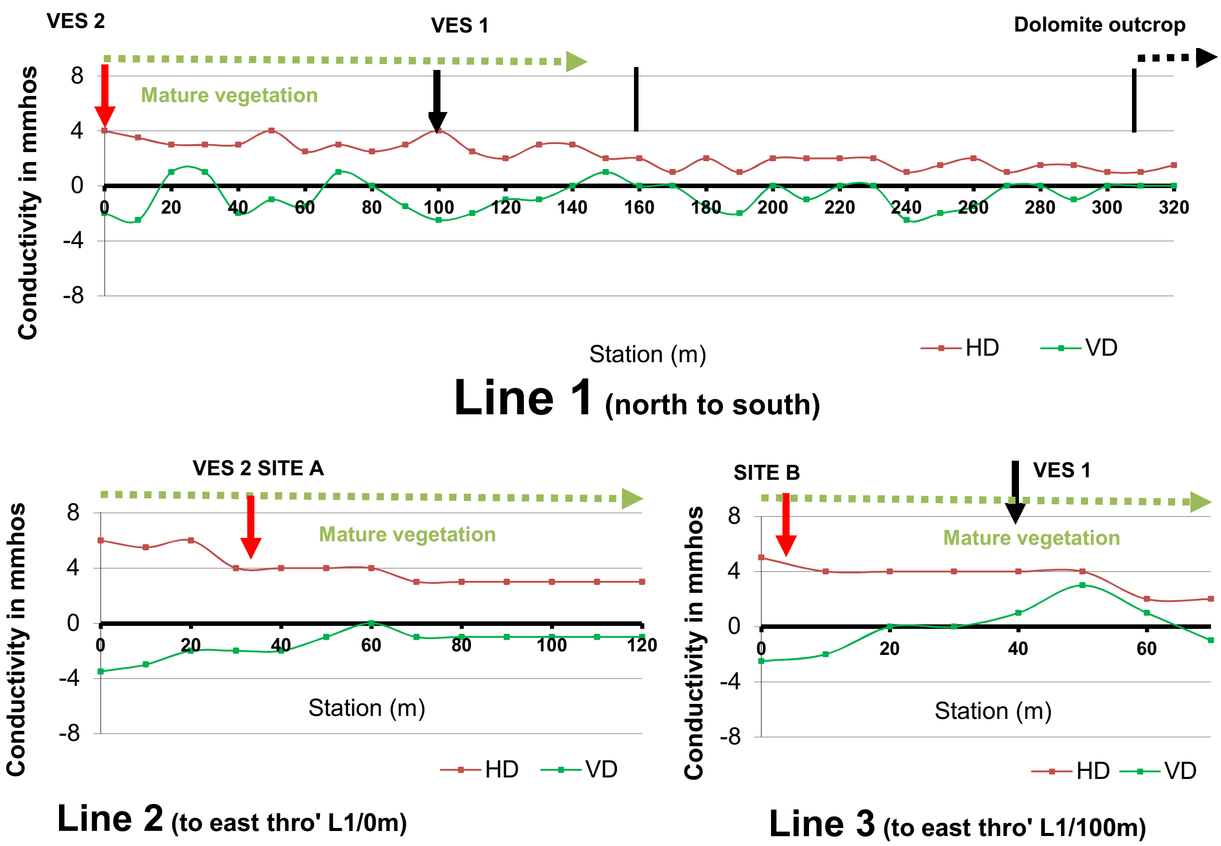
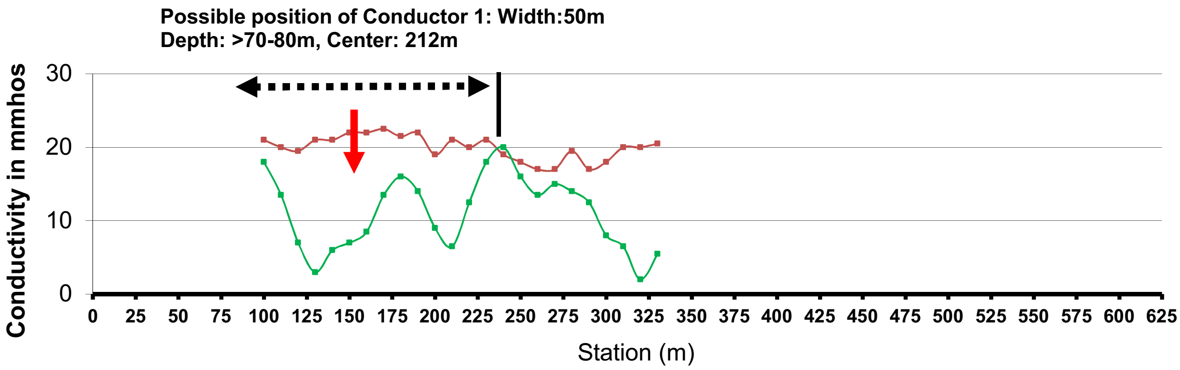


Figure 2.1 EM34 Conductivity profiles

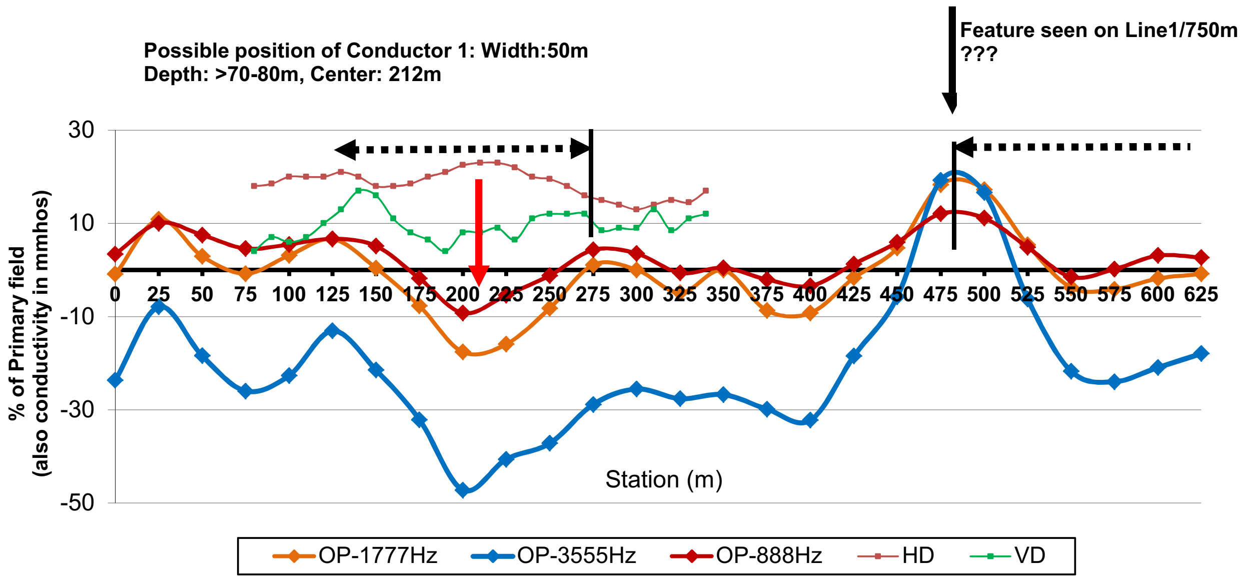
Appendix A3 Target Area P-3 (Makeni)

Figure 3.1 - 3.2	**EM Profiles**
Figure 3.3	**VES data and interpretation**

GReSP
Geophysical Investigation of the Schist - Psammite - Quartz aquifer Makeni Target Area (P-3)



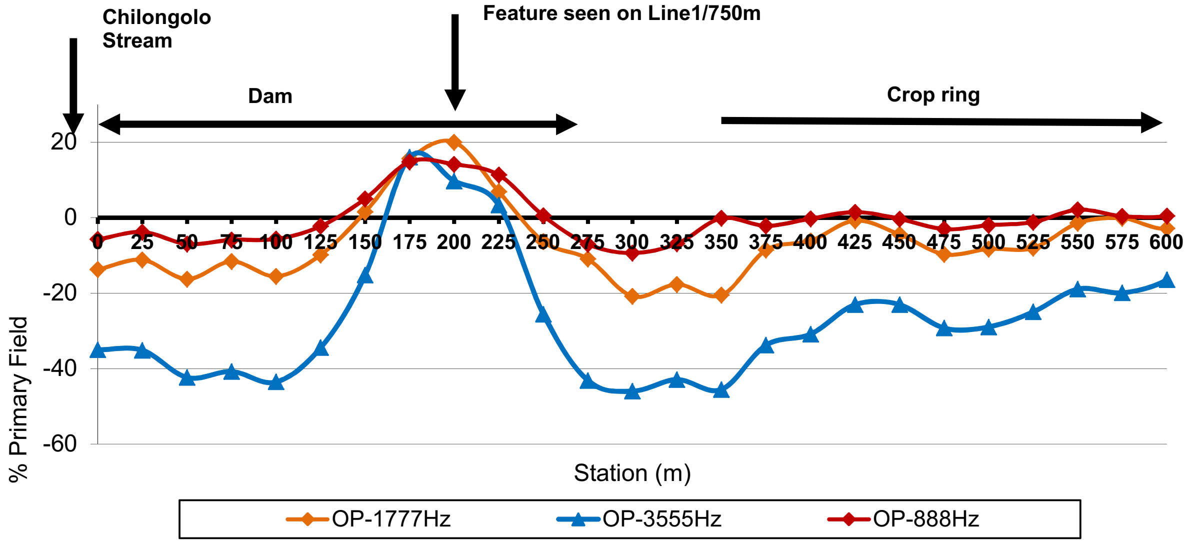
Line 4 (line parallel and between lines 1 and 3)



Line 3

Figure 3.1 **Max Min and EM34 EM profile lines**

GReSP
Geophysical Investigation of the Schist - Psammite - Quartz aquifer Makeni Target Area (P-3)



Line 2 (perpendicular to line 1, east end

Figure 3.2 **Max Min EM profile line**

CODE: P-3	NAME: Makeni	DATE: 21/07/2011
SURVEYOR: Jim	DISTRICT: Kafue	Ward:

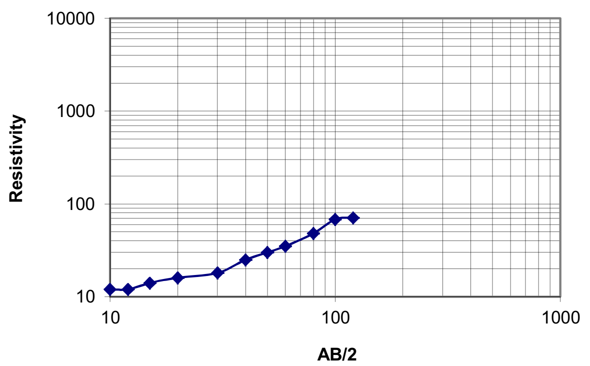
VES 1/230

AB/2	GC	SD	mV	MN=2	MN=10	Graph
10	0.5k			12		12
12	0.5k			12		12
15	0.5k			14		14
20	0.4k			16		16
30	0.5k			18	15	18
40	0.5k				22	25
50	0.6k				27	30
60	0.6k				32	35
80	0.5k				45	48
100	0.5k				65	68
120	0.7k				68	71
S	15.46948					
E	28.16573					

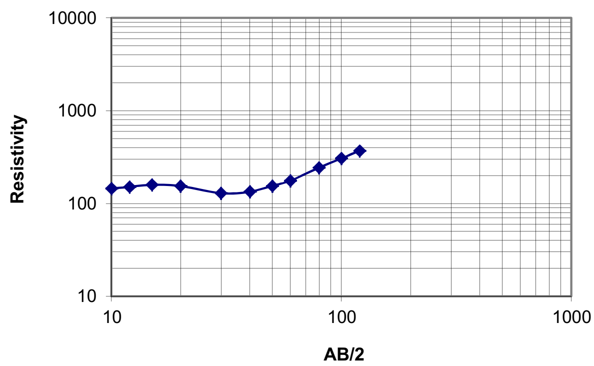
VES 1/760

AB/2	GC	SD	mV	MN=2	MN=10	Graph
10	0.7k			145		145
12	0.6k			151		151
15	0.5k			159		159
20	0.6k			154		154
30	1k			129	118	129
40	0.6k				123	134
50	0.6k				144	155
60	1k				165	176
80	0.7k				233	244
100	2k				295	306
120	0.6k				360	371
S	15.46824					
E	28.17053					

VES 1/230 Site A



VES 1/760Site B



Interpretation

From	To	Resisitivity	Interpretation
0	1	Ohm-m	12 Clay soil
1	18		30 Clayey, weathered rock
18	75+		130 Weathered rock, wet

From	To	Resisitivity	Interpretation
0	1	Ohm-m	135 Clay soil
1	10		160 Sandy, weathered rock
10	20		100 Weathered rock, wet
20	75+		400 Fractured bedrock, wet

Comment Ground contact very good. Data integrity good.
Upswing of sounding curve is not steep in both instances - indicating weathering and fracturing
Air percussion drilling method suitable

Figure 3.3: VES Data and Interpretation, P-3 (Makeni) target.

Annex 2

BOREHOLE GRAPHICS

Table of Contents:

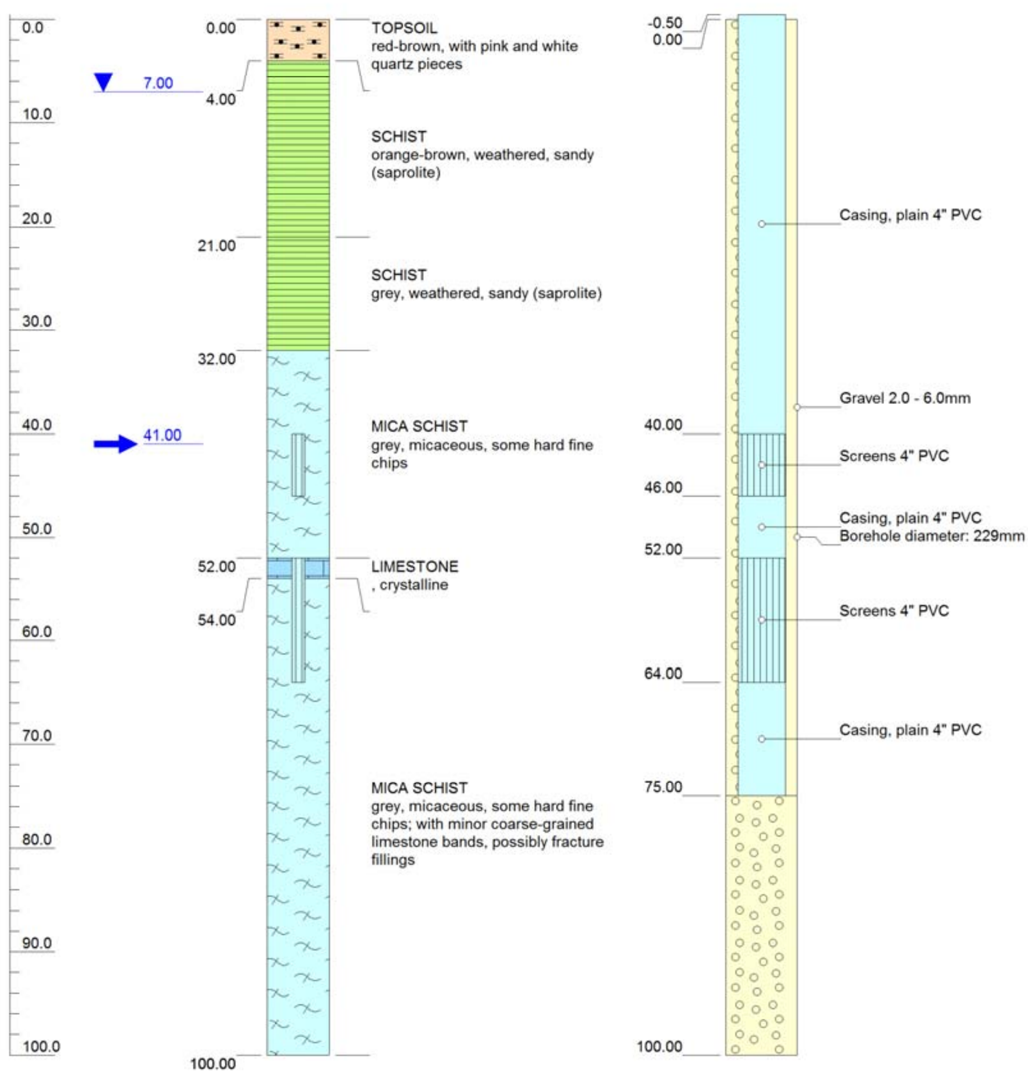
Annex 2-1

Borehole Graphics, P-1 Katete

P-1/1

Katete 1 (Piezometer)

m below ground surface (0.00 m)

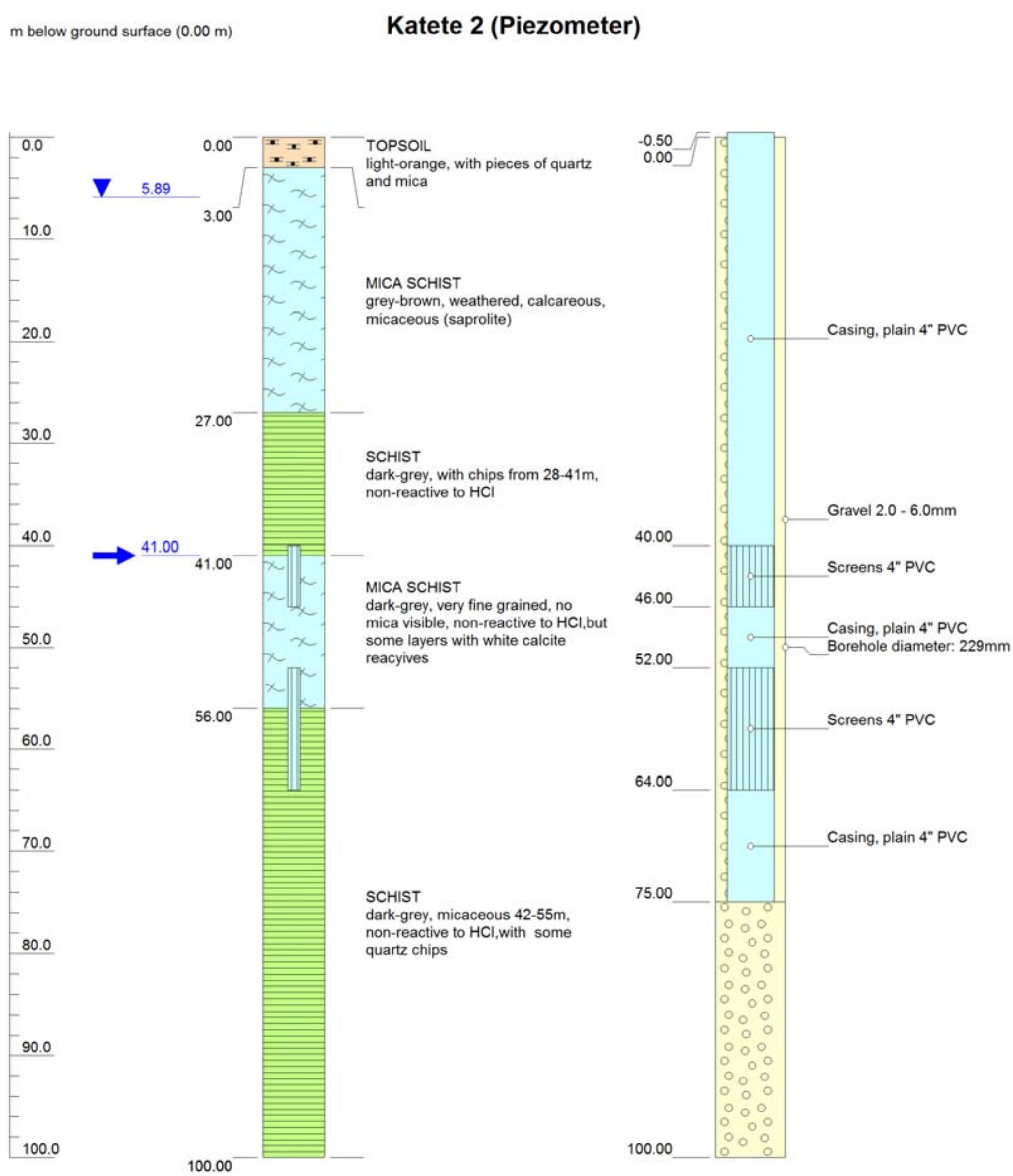


Vertical scale: 1:600 Horizontal scale: 1:20

Water point number: 1010858

Water point funded by BGR		**Data Source: GReSP**	
Locality:	Katete	East:	28.12106
Ward:		South:	-15.25984
District:	Chibombo	Altitude:	0.00 m
Province:	Central	Total depth of borehole:	100.0 m

P-1/2



Vertical scale: 1:600 Horizontal scale: 1:20

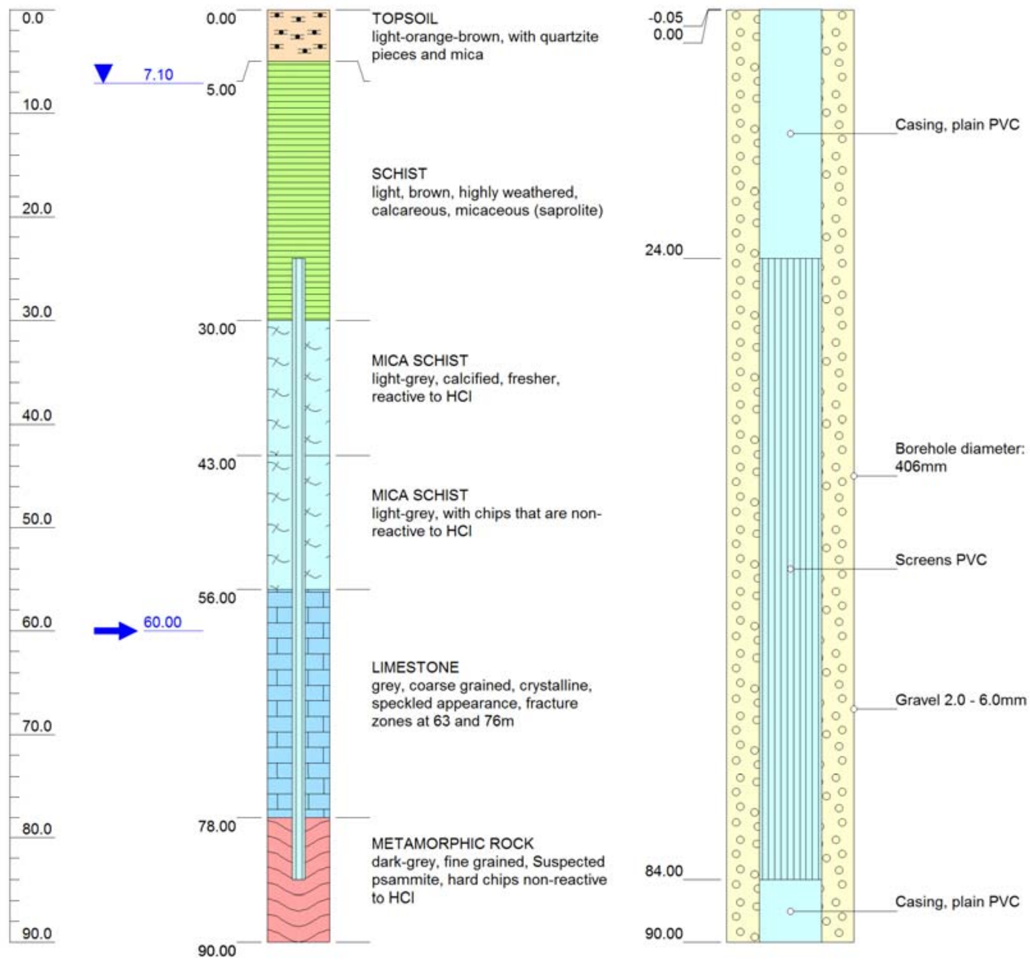
Page 1 of 1

Water point number:	**1010859**		
Water point funded by BGR		**Data Source: GReSP**	
Locality:	Katete	East:	28.12099
Ward:		South:	-15.25969
District:	Chibombo	Altitude:	0.00 m
Province:	Central	Total depth of borehole:	100.0 m

P-1/3

m below ground surface (0.00 m)

Katete 3 (Main Borehole)



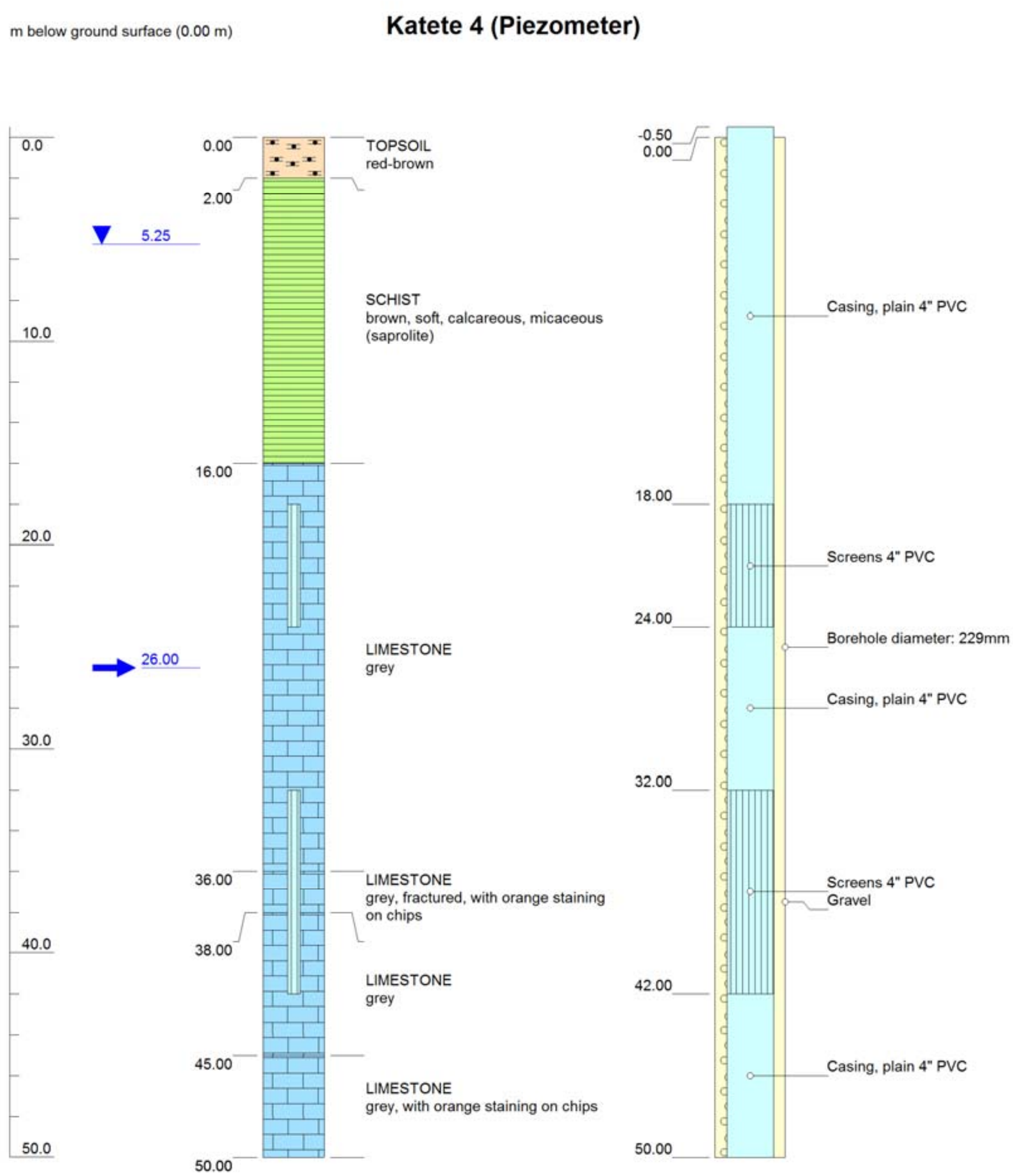
Vertical scale: 1:600   Horizontal scale: 1:20

Page 1 of 1

Water point number: **1010860**

Water point funded by BGR		**Data Source: GReSP**	
Locality:	Katete	East:	28.12116
Ward:		South:	-15.25992
District:	Chibombo	Altitude:	0.00 m
Province:	Central	Total depth of borehole:	90.0 m

P-1/4



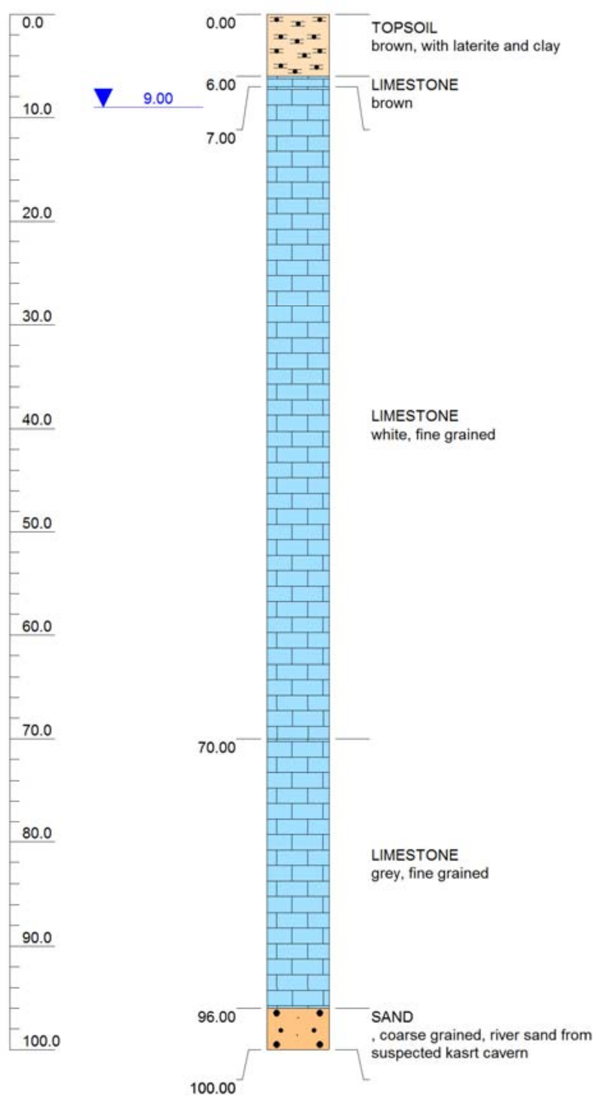
Vertical scale: 1:300 Horizontal scale: 1:20 *Page 1 of 1*

Water point number:	**1010861**		
Water point funded by BGR		**Data Source: GReSP**	
Locality:	Katete	East:	28.12104
Ward:		South:	-15.26008
District:	Chibombo	Altitude:	0.00 m
Province:	Central	Total depth of borehole:	50.0 m

P-1B-1

m below ground surface (0.00 m)

Katete 5 (Not Installed)



Vertical scale: 1:600 Horizontal scale: 1:20

Water point number: 1010862

Water point funded byBGR		**Data Source: GReSP**	
Locality:	Katete	East:	28.12370
Ward:		South:	-15.25538
District:	Chibombo	Altitude:	0.00 m
Province:	Central	Total depth of borehole:	100.0 m

P1/1 (Piezometer)

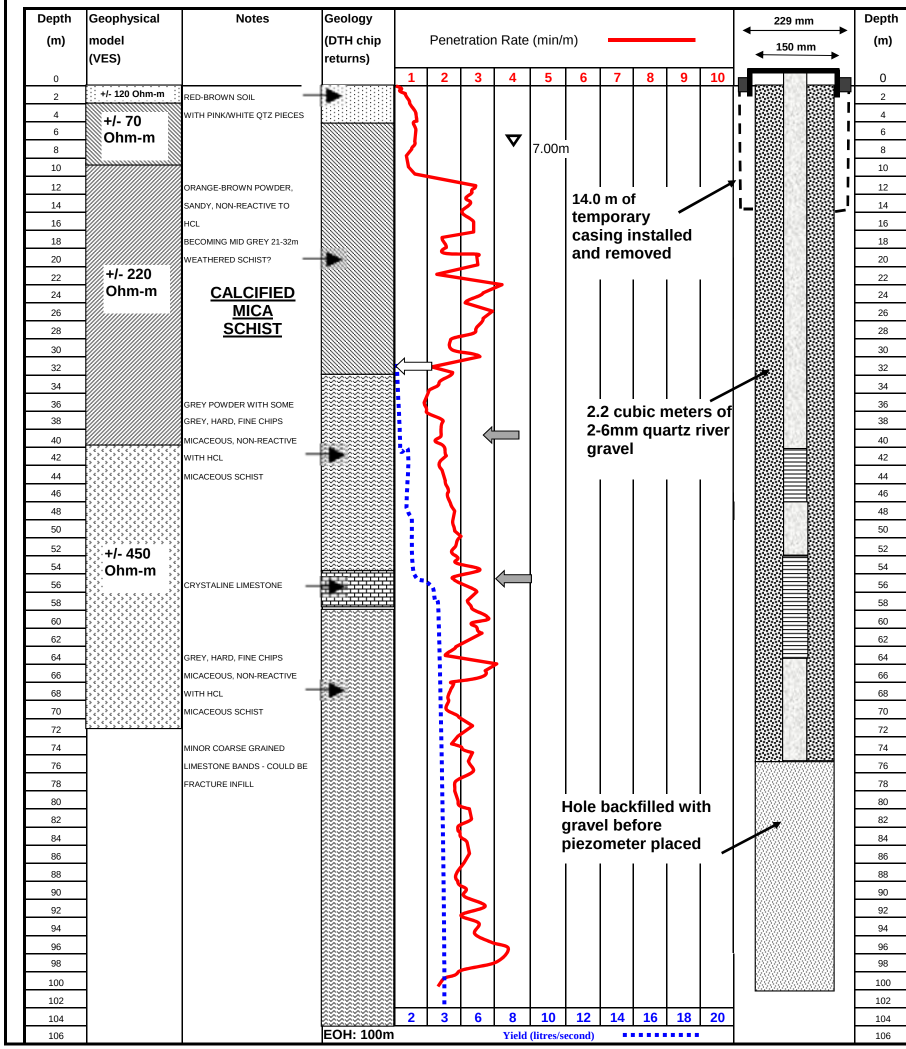
Well Completion Graphic

District:	**Chibombo**
Location:	**Katete**
Borehole ID:	**P1/1**
Drilling method:	**Air-Percussion**
Depth drilled (m):	**100**
Depth cased (m):	**75.3**
Pilot diameter (mm):	**150**
Final EOH diameter (mm):	**150**
Drilling completion date:	**28-Nov-11**
Coords (WGS84):	**15.25984S, 28.12106E**

Soil (laterite, sand)
Saprolite (regolith)
Saprock (regolith)
Dolomite
Limestone
Quartzite
Psammite
Schist
Bedrock (undifferentiated)

8"PVC plain casing (incl.centralizers)
3" PVC piezometer casing
8"PVC slotted casing (1mm slots, 8% OA)
3"PVC piezometer casing (site slotted)
Cement sanitary seal
Formation stabiliser (gravel 2 - 6 mm)
Mixed collapse material

Penetration and flow **Well Design** **Aquifer and Well Data**



Parameter			Value
Yield zones	Aquifer	Depth	l/s
1st		31	0.2
2nd		41	+ 0.5
3rd		53-56	+ 2

Hydraulics (from pump test)

SWL (m)	7.00
Pump depth (m) (testing)	
DWL at 3hr CDT (m)	
Q (l/s) for CDT	
S avail. (m), (pump - DWL)	
S max (m), (SWL-DWL)	
S utilised (**S**m/**S**a).100%	
SC (Q/S max)	
Main inflow (from PT)	
Other inflow (from PT)	
Recovery (90% in minutes)	
Recovery (m in 1st five minutes)	
Recommended pump depth (m)	
Pump Test comment	

Hydrochemistry (from pump test)

Water quality (mg/l)	460
pH	

Geophysics	JA	MM/EM34 + Resistivity

EM: Positioned on Line 1/740m on center of double EM negative

VES: VES 1/740m. 200 Ohm-m to AB = 240m

Target: Fractured bedrock

Outcome

Looking at the overall results (P1/1 to P1/4) the choice of site was not optimal and should have targeted the EM -ve either to north or south.

Symbols

- First water (from drilling)
- Main water (from drilling)
- Static Water Level (from development)

P1/2 (Piezometer)

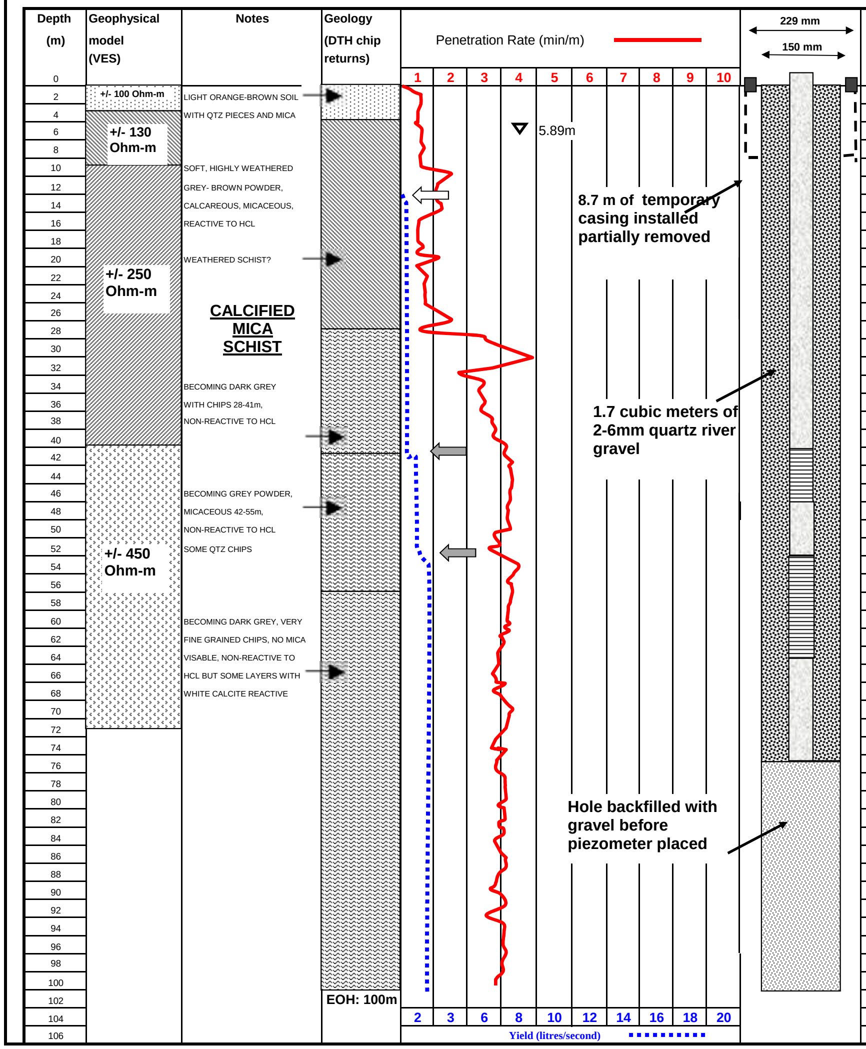
Well Completion Graphic

District:	Chibombo
Location:	Katete
Borehole ID:	P1/2
Drilling method:	Air-Percussion
Depth drilled (m):	100
Depth cased (m):	75.4
Pilot diameter (mm):	150
Final EOH diameter (mm):	150
Drilling completion date:	28-Nov-11
Coords (WGS84):	15.25969S, 28.12099E

Soil (laterite, sand)
Saprolite (regolith)
Saprock (regolith)
Dolomite
Limestone
Quartzite
Psammite
Schist
Bedrock (undifferentiated)

8"PVC plain casing (incl.centralizers)
3" PVC piezometer casing
8"PVC slotted casing (1mm slots, 8% OA)
3"PVC piezometer casing (site slotted)
Cement sanitary seal
Formation stabiliser (gravel 2 - 6 mm)
Mixed collapse material

Penetration and flow — Well Design — Aquifer and Well Data



Parameter			Value
Yield zones	Aquifer	Depth	l/s
1st		12	0.2
2nd		41	+ 0.8
3rd		51	+ 1

Hydraulics (from pump test)

SWL (m)	5.89
Pump depth (m) (testing)	
DWL at 3hr CDT (m)	
Q (l/s) for CDT	
S avail. (m), (pump - DWL)	
S max (m), (SWL-DWL)	
S utilised (Sm/Sa).100%	
SC (Q/S max)	
Main inflow (from PT)	
Other inflow (from PT)	
Recovery (90% in minutes)	
Recovery (m in 1st five minutes)	
Recommended pump depth (m)	
Pump Test comment	

Hydrochemistry (from pump test)

Water quality (mg/l)	450
pH	

Geophysics JA MM/EM34 + Resistivity

EM: Positioned on Line 1/715m on center of double EM negative

VES: VES 1/715m. 200 Ohm-m to AB = 240m

Target: Fractured bedrock

Outcome

Looking at the overall results (P1/1 to P1/4) the choice of site was not optimal and should have targeted the EM -ve either to north or south.

Symbols

First water (from drilling)
Main water (from drilling)
Static Water Level (from development)

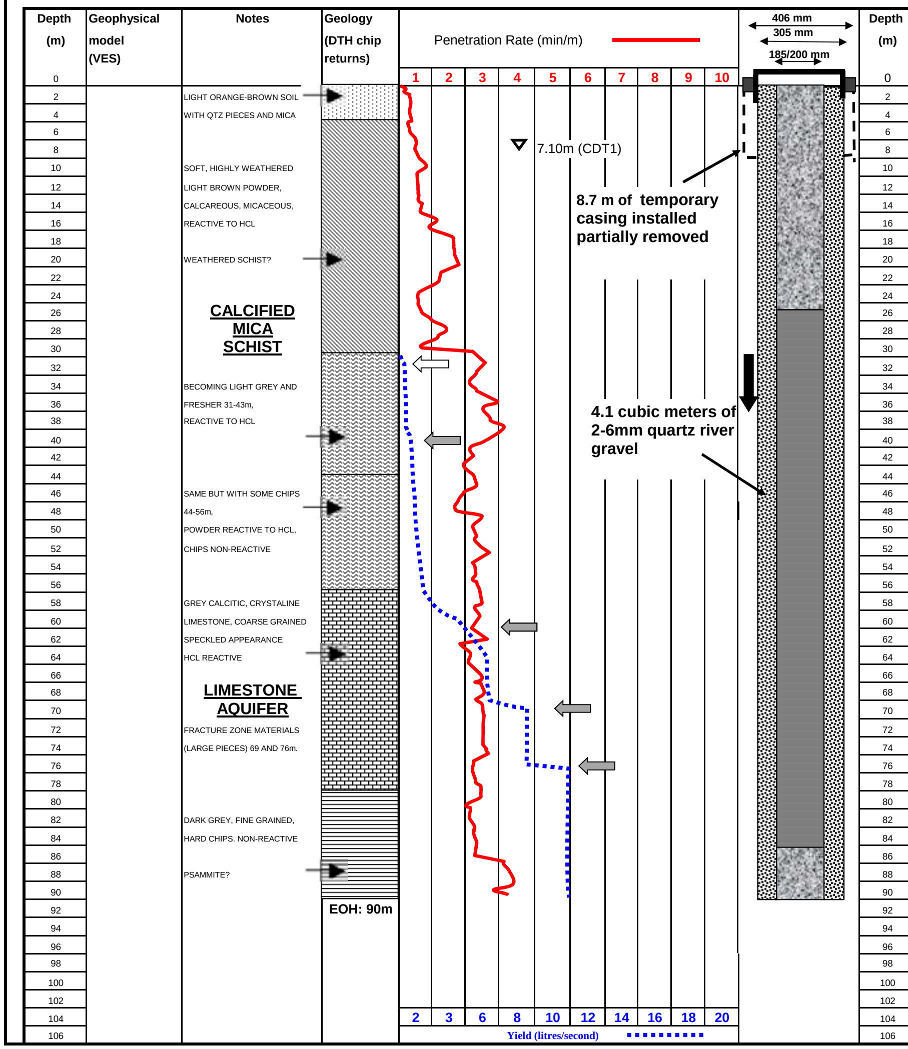
P1/3 (main borehole)

Well Completion Graphic

District:	Chibombo
Location:	Katete
Borehole ID:	P1/3
Drilling method:	Air-Percussion
Depth drilled (m):	90
Depth cased (m):	89.3
Pilot diameter (mm):	165
Final EOH diameter (mm):	305
Drilling completion date:	28-Nov-11
Coords (WGS84):	15.25992S, 28.12116E

Soil (laterite, sand)
Saprolite (regolith)
Saprock (regolith)
Dolomite
Limestone
Quartzite
Psammite
Schist
Bedrock (undifferentiated)

8"PVC plain casing (incl.centralizers)
3" PVC piezometer casing
8"PVC slotted casing (1mm slots, 8% OA)
3"PVC piezometer casing (site slotted)
Cement sanitary seal
Formation stabiliser (gravel 2 - 6 mm)
Mixed collapse material



Aquifer and Well Data

Parameter			Value
Yield zones	Aquifer	Depth	l/s
1st	Schist	30	0.8
2nd	Limestone	60	+ 3
3rd	Limestone	69	+ 4
4th	Limestone	76	+ 3

Hydraulics (from pump test)

SWL (m)	7.10
Pump depth (m) (testing)	72.50
DWL at 22hr CDT (m)	29.82
Q (l/s) for CDT	3.47
S avail. (m), (pump - SWL)	65.40
S max (m), (SWL-DWL)	22.72
S utilised (**S**m/**S**a).100%	35
SC (**Q/S** max) (m3/m/day)	13.20
Main inflow (from PT)	>30
Other inflow (from PT)	
Recovery (90% in minutes)	0.5
Recovery (m in 1st five minutes)	
Recommended pump depth (m)	
Pump Test comment	

Hydrochemistry (from pump test)

Water quality (mg/l)	380
pH	

Geophysics	JA	MM/EM34

EM: Positioned on Line 1/755m on northern edge of southern of double EM negative

VES: Not checked

Target: Fractured bedrock

Outcome

Looking at the overall results (P1/1 to P1/4) this target is better in that it was closer to the EM -ve and intersected some associated fracturing. Good outcome.

From pumping test the borehole has a maximum yield of 4.5-5 l/s. This is less than the 10l/s estimated by drilling. The conclusion is that the drilling yield was over-estimated

The peizometer P1/4 had by far the highest yield.

Symbols

First water (from drilling)
Main water (from drilling)
Static Water Level (from development)

P1/4 (Piezometer)

Well Completion Graphic

District:	Chibombo
Location:	Katete
Borehole ID:	P1/4
Drilling method:	Air-Percussion
Depth drilled (m):	50.3
Depth cased (m):	50.3
Pilot diameter (mm):	165
Final EOH diameter (mm):	165
Drilling completion date:	5-Dec-11
Coords (WGS84):	15.26008S, 28.12104E

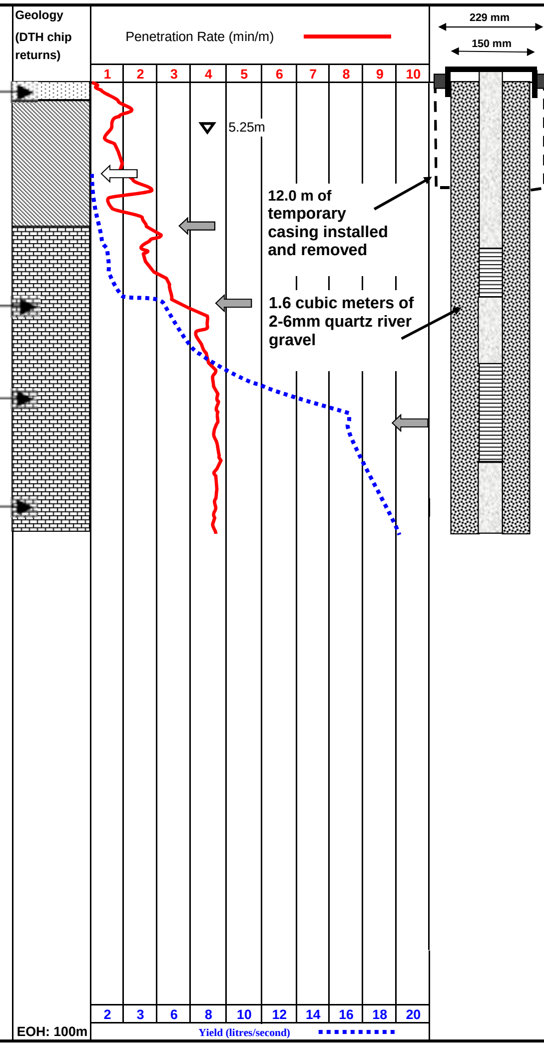
- Soil (laterite, sand)
- Saprolite (regolith)
- Saprock (regolith)
- Dolomite
- Limestone
- Quartzite
- Psammite
- Schist
- Bedrock (undifferentiated)

- 8"PVC plain casing (incl.centralizers)
- 3" PVC piezometer casing
- 8"PVC slotted casing (1mm slots, 8% OA)
- 3"PVC piezometer casing (site slotted)
- Cement sanitary seal
- Formation stabiliser (gravel 2 - 6 mm)
- Mixed collapse material

Penetration and flow | Well Design | Aquifer and Well Data

Depth (m)	Geophysical model (VES)	Notes
2		RED-BROWN SOIL WITH MICA
6		BROWN POWDER, SOFT
8		MICACEOUS, REACTIVE TO
10		HCL. CALCIFIED SCHIST
20		GREY POWDER , SOFT
22		PULVERISED LIMESONE
24		REACTIVE WITH HCL
26		SOME LARGER CHIPS
32		AS ABOVE BUT WITH ORANGE
34		STAINING ON CHIPS
36		FRACTURE ZONE 36-38m
44		AS ABOVE BUT WITH ORANGE
46		STAINING ON CHIPS
48		FRACTURE ZONE 45-50m

LIMESTONE AQUIFER



Parameter			Value
Yield zones	Aquifer	Depth	l/s
1st		10	0.5
2nd		16-26	+ 4
3rd		26-36	+ 10
4th		38-45	+ 5

Hydraulics (from pump test)

Parameter	Value
SWL (m)	5.25
Pump depth (m) (testing)	
DWL at 3hr CDT (m)	
Q (l/s) for CDT	
S avail. (m), (pump - DWL)	
S max (m), (SWL-DWL)	
S utilised (**S**m/**S**a).100%	
SC (**Q/S** max)	
Main inflow (from PT)	
Other inflow (from PT)	
Recovery (90% in minutes)	
Recovery (m in 1st five minutes)	
Recommended pump depth (m)	
Pump Test comment	

Hydrochemistry (from pump test)

Parameter	Value
Water quality (mg/l)	380
pH	

Geophysics JA MM/EM34

EM: Positioned on Line 1/775m on southern edge of double EM negative

VES: Not checked

Target: Fractured bedrock

Outcome

Looking at the overall results (P1/1 to P1/4) this site intersected limestone which is dipping north and must at subcrop 20-30 meters to south - marked by EM positive anomaly. Excellent aquifer.

Symbols

- First water (from drilling)
- Main water (from drilling)
- Static Water Level (from development)

P1B/1 (not installed)

Well Completion Graphic

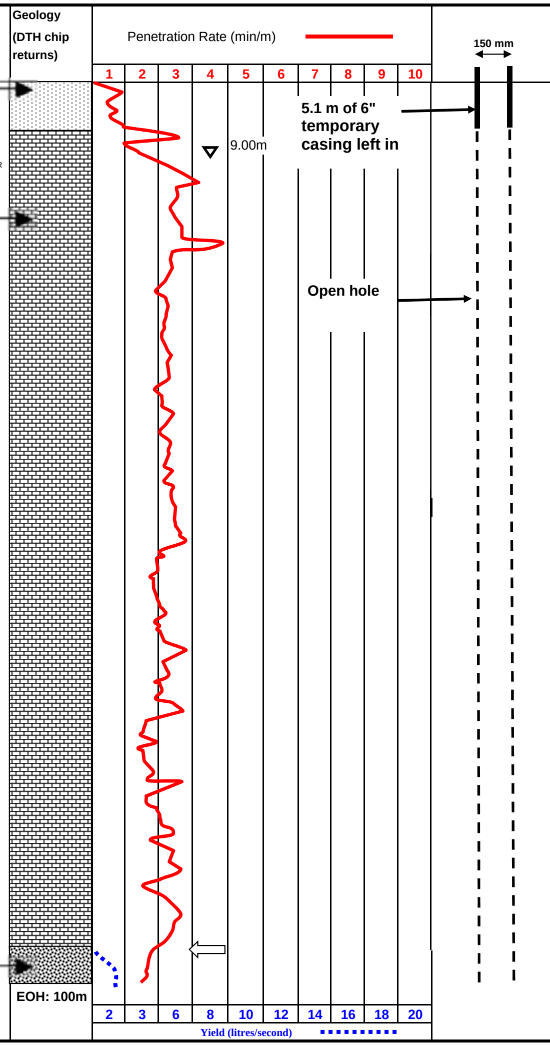
District:	Chibombo
Location:	Katete
Borehole ID:	P1B/1
Drilling method:	Air-Percussion
Depth drilled (m):	100
Depth cased (m):	-
Pilot diameter (mm):	150
Final EOH diameter (mm):	150
Drilling completion date:	1-Dec-11
Coords (WGS84):	15.25538, 28.1237E

Soil (laterite, sand)
Saprolite (regolith)
Saprock (regolith)
Dolomite
Limestone
Quartzite
Psammite
Schist

8"PVC plain casing (incl.centralizers)
3" PVC piezometer casing
8"PVC slotted casing (1mm slots, 8% OA)
3"PVC piezometer casing (site slotted)
Cement sanitary seal
Formation stabiliser (gravel 2 - 6 mm)
Mixed collapse material

Penetration and flow | Well Design | Aquifer and Well Data

Depth (m)	Geophysical model (VES)	Notes
0		
2		BROWN SOIL WITH
4		LATERITE AND CLAY
6		BROWN LIMESTONE AT 6-7m
8		
10		LIMESTONE CHIPS AND POWDER
12		FINE GRAINED, HCL REACTIVE
14		WHITE VARIETY 11-70m
16		GREY VARIETY 70-96m
18		
20		
22		
24		
26		
28		
30		
32		
34		
36		
38		
40		
42		
44		
46		
48		
50		
52		51-59 WHITE TO LIGHT ORANGE
54		
56		
58		
60		60-64 DARK PURPLE CHIPS
62		
64		
66		65-85 WHITE CHIPS
68		
70		
72		
74		
76		
78		
80		
82		
84		
86		86-100 LIGHT PURPLE CHIPS
88		
90		
92		
94		
96		
98		COARSE RIVER SAND FROM
100		SUSPECTED KARST
102		
104		
106		



Parameter			Value
Yield zones	Aquifer	Depth	l/s
1st	Karst	97	1

Hydraulics (from pump test)

SWL (m)	9.00
Pump depth (m) (testing)	
DWL at 3hr CDT (m)	
Q (l/s) for CDT	
S avail. (m), (pump - DWL)	
S max (m), (SWL-DWL)	
S utilised (**S**m/**S**a).100%	
SC (**Q**/**S** max)	
Main inflow (from PT)	
Other inflow (from PT)	
Recovery (90% in minutes)	
Recovery (m in 1st five minutes)	
Recommended pump depth (m)	
Pump Test comment	

Hydrochemistry (from pump test)

Water quality (mg/l)	380
pH	

Geophysics | JA | Max-Min

EM: Near line 2 - mid point. +/- 675m
VES: Not checked. Limestone at outcrop

Target: Kastified limestone. Visually picked amid much micro-karst and near a large termite mound

Outcome

Water strike within a suspected karst feature full of clean river sand at 96m!
Proves that karstic ground water pipework exists within the Cheta limestone
would have been interesting to extend the brehole to 120m. Casing left in place - to allow this possibility in future. Base of karst feature not intersected.

Symbols

- First water (from drilling)
- Main water (from drilling)
- Static Water Level (from development)

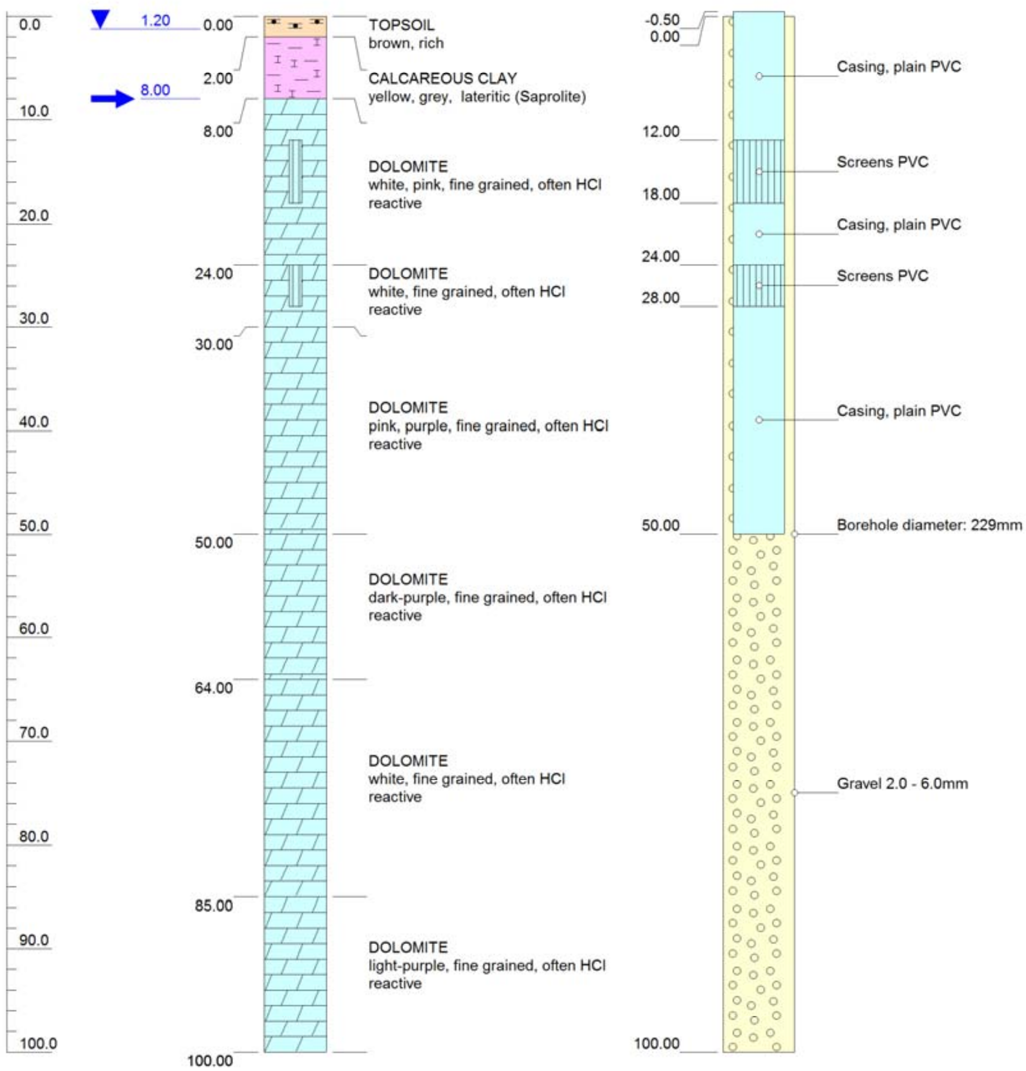
Annex 2-2

Borehole Graphics, P-2 Kasanova

P-2/1

m below ground surface (0.00 m)

Kasanova/Rosedale 1(Piezometer)



Vertical scale: 1:600 Horizontal scale: 1:20

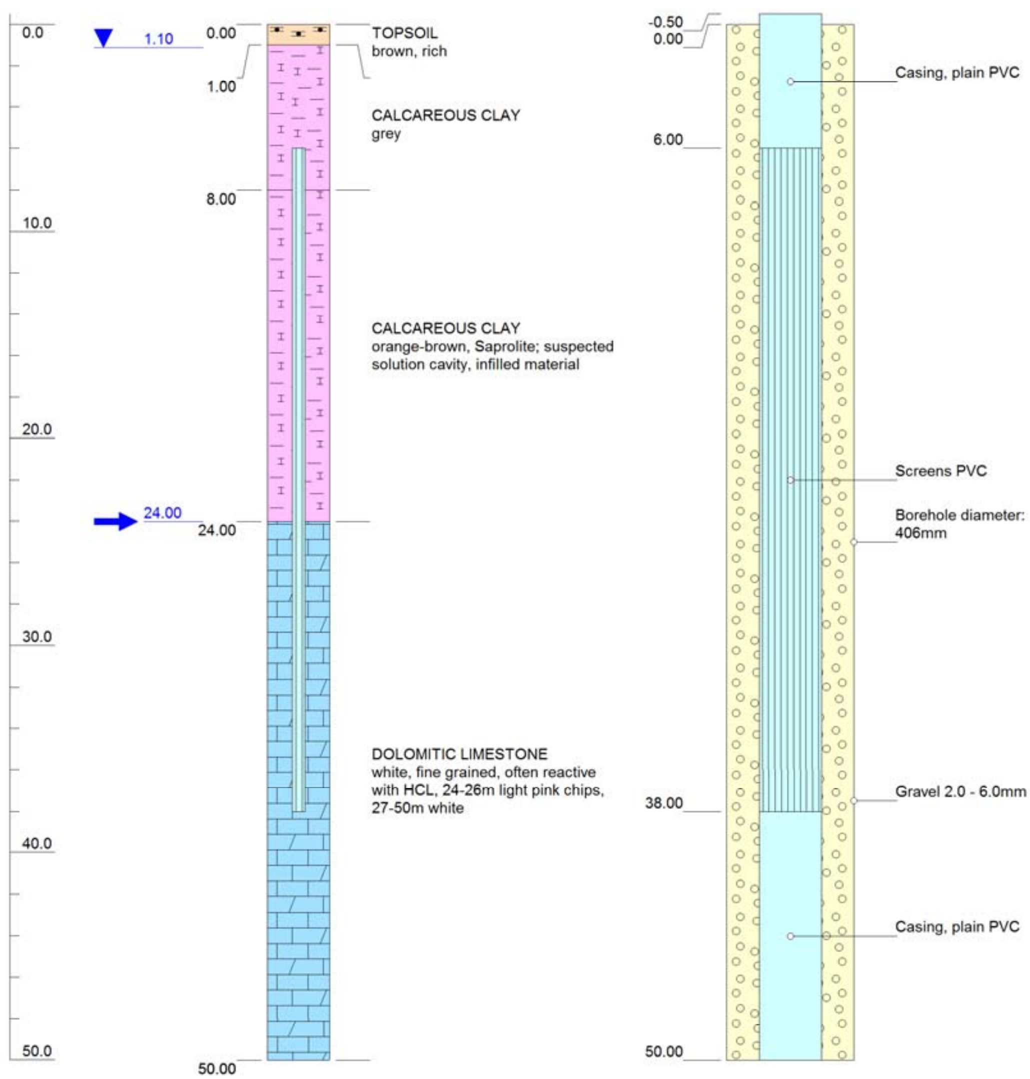
Water point number: 5020928

Water point funded byBGR		**Data Source: GReSP**	
Locality:	Rosedale	East:	28.19164
Ward:		South:	-15.41832
District:	Kafue	Altitude:	0.00 m
Province:	Lusaka	Total depth of borehole:	100.0 m

P-2/2

m below ground surface (0.00 m)

Kasanova/Rosedale 2 (Main Borehole)



Vertical scale: 1:300 Horizontal scale: 1:20

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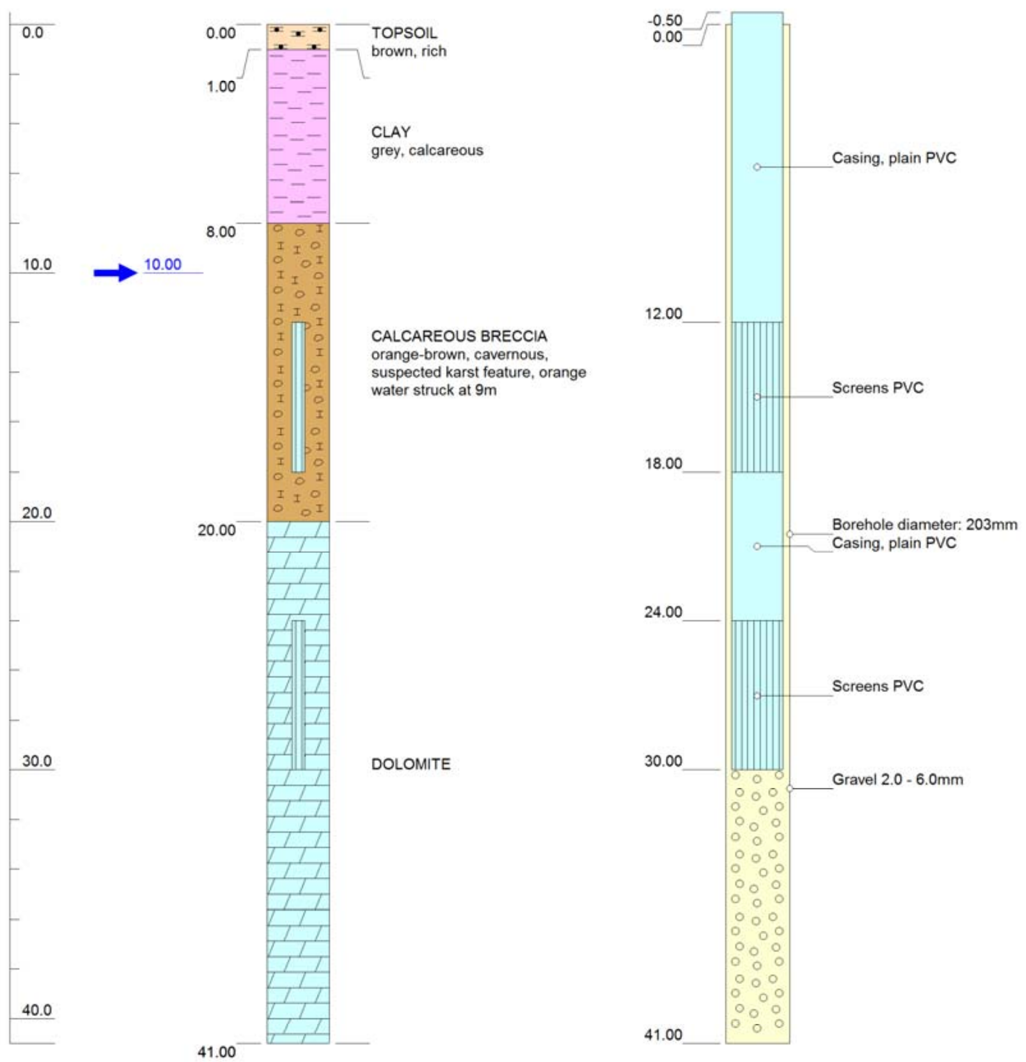
Water point number: 5020929

Water point funded by BGR		**Data Source: GReSP**	
Locality:	Rosedale	East:	28.19176
Ward:		South:	-15.41837
District:	Kafue	Altitude:	0.00 m
Province:	Lusaka	Total depth of borehole:	50.0 m

P-2/3

m below ground surface (0.00 m)

Kasanova/Rosedale 3 (Piezometer)



Vertical scale: 1:250   Horizontal scale: 1:20

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Water point number:	**5020930**		
Water point funded by BGR		**Data Source: GReSP**	
Locality:	Rosedale	East:	28.19185
Ward:		South:	-15.41858
District:	Kafue	Altitude:	0.00 m
Province:	Lusaka	Total depth of borehole:	41.0 m

P2/1 (Piezometer)

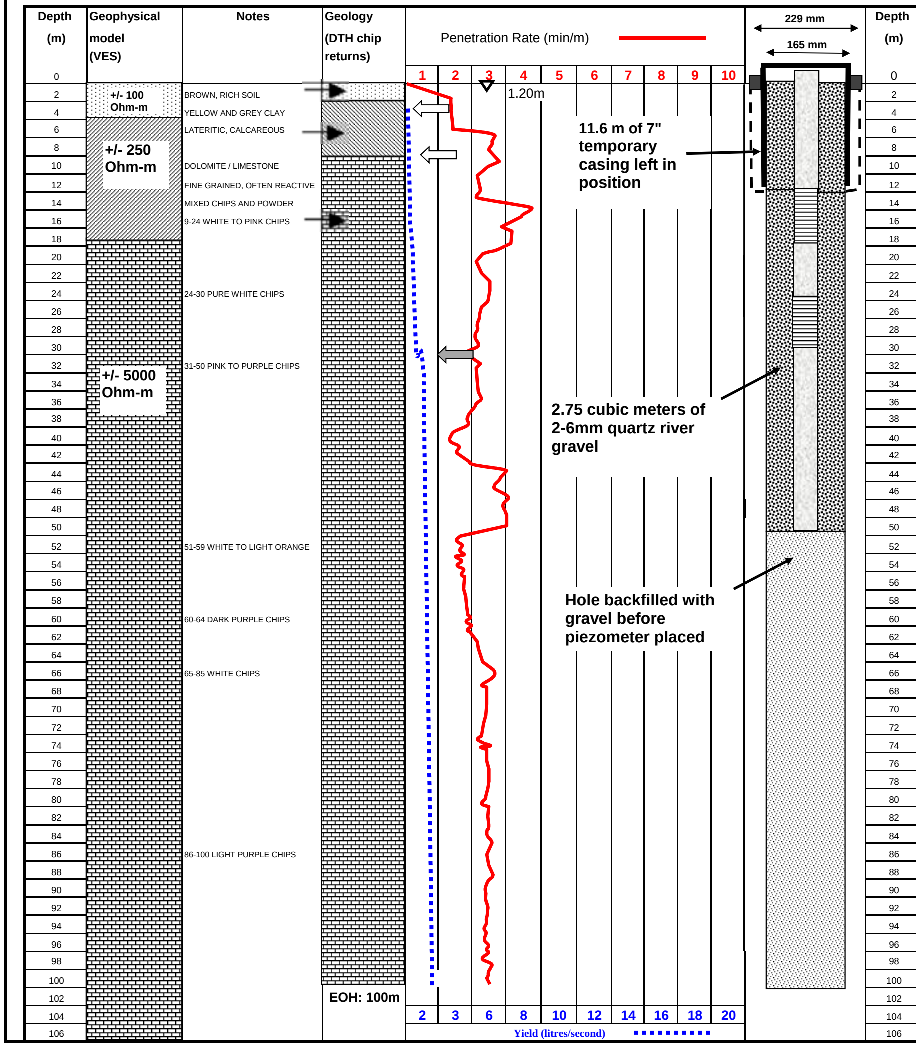
Well Completion Graphic

District:	Lusaka
Location:	Kasanova / Rosedale
Borehole ID:	P2/1
Drilling method:	Air-Percussion
Depth drilled (m):	100
Depth cased (m):	49.51
Pilot diameter (mm):	165
Final EOH diameter (mm):	165
Drilling completion date:	8-Nov-11
Coords (WGS84):	15.41832S, 28.19164E

Soil (laterite, sand)
Saprolite (regolith)
Saprock (regolith)
Dolomite
Limestone
Quartzite
Psammite
Schist

8"PVC plain casing (incl.centralizers)
3" PVC piezometer casing
8"PVC slotted casing (1mm slots, 8% OA)
3"PVC piezometer casing (site slotted)
Cement sanitary seal
Formation stabiliser (gravel 2 - 6 mm)
Mixed collapse material

Penetration and flow | Well Design | Aquifer and Well Data



Parameter			Value
Yield zones	Aquifer	Depth	l/s
1st	Soil	3	0.05
2nd	SR	8	+ 0.15
3rd	Dolomite	30-32	+ 1.5

Hydraulics (from pump test)	
SWL (m)	1.20
Pump depth (m) (testing)	
DWL at 3hr CDT (m)	
Q (l/s) for CDT	
S avail. (m), (pump - DWL)	
S max (m), (SWL-DWL)	
S utilised (**S**m/**S**a).100%	
SC (**Q**/**S** max)	
Main inflow (from PT)	
Other inflow (from PT)	
Recovery (90% in minutes)	
Recovery (m in 1st five minutes)	
Recommended pump depth (m)	
Pump Test comment	

Hydrochemistry (from pump test)	
Water quality (mg/l)	350
pH	

Geophysics | JA | EM34 + Resistivity

EM: Flat dolomite/resistive response (Line 2)
VES: VES 2/40m. Data indicates shallow dolomite (<17m)
Target: Point of thickest weathering - on EM Line 2

Outcome

Typical non-informative geophysics over dolomite Slightly north and east at P2/1 the weathering was much deeper - over karstic feature. This would probably have given a better VES profile - but was not checked. 60m north into thick vegegation a fenced sink-hole was observed.

Concluded that P2/1 intersects largely massive dolomite bordering an adjacent sink-hole / karstic feature.

Symbols

- First water (from drilling)
- Main water (from drilling)
- Static Water Level (from development)

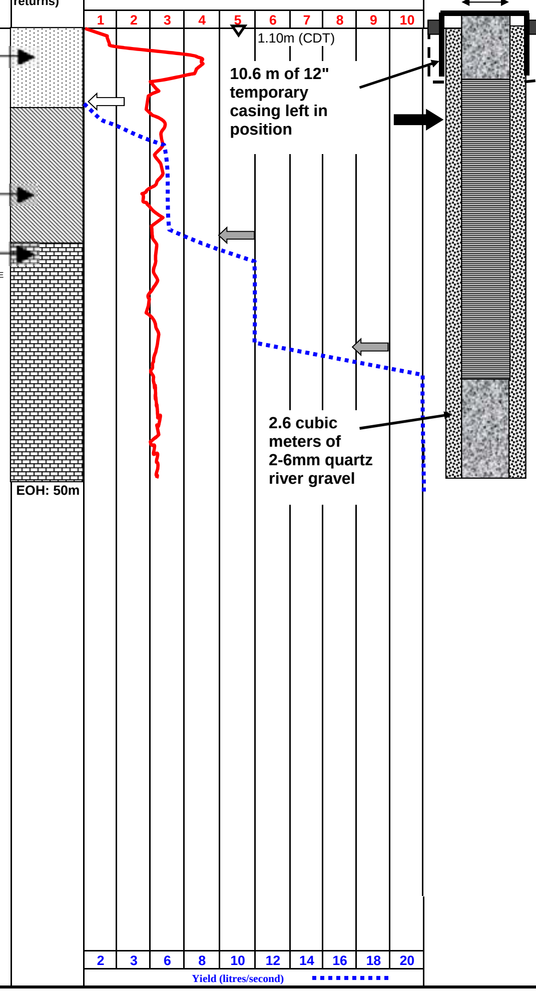
P2/2 (Main borehole)

Well Completion Graphic

District:	Lusaka
Location:	Kasanova / Rosedale
Borehole ID:	P2/2
Drilling method:	Air-Percussion
Depth drilled (m):	50
Depth cased (m):	50
Pilot diameter (mm):	165
Final EOH diameter (mm):	305
Drilling completion date:	10-Nov-11
Coords (WGS84):	15.41837S, 28.19176E

Legend:
- Soil (laterite, sand)
- Saprolite (regolith)
- Saprock (regolith)
- Dolomite
- Limestone
- Quartzite
- Psammite
- Schist
- 8"PVC plain casing (incl.centralizers)
- 3" PVC piezometer casing
- 8"PVC slotted casing (1mm slots, 8% OA)
- 3"PVC piezometer casing (site slotted)
- Cement sanitary seal
- Formation stabiliser (gravel 2 - 6 mm)
- Mixed collapse material

Depth (m)	Geophysical model (VES)	Notes
0		
2		BROWN, RICH SOIL 1m ON
4		GREY, CALCAREOUS CLAY
6		
8		
10		
12		
14		ORANGE-BROWN CLAY
16		CALCAREOUS.. SUSPECT SOLN
18		CAVITY - FULL OF MATERIAL
20		
22		
24		
26		DOLOMITE / LIMESTONE
28		FINE GRAINED, OFTEN REACTIVE
30		MIXED CHIPS AND POWDER
32		24-26 LIGHT PINK CHIPS
34		
36		27-50 WHITE CHIPS



Aquifer and Well Data

Parameter			Value
Yield zones	Aquifer	Depth	l/s
1st	Dolomite	9	5.00
2nd	Karst	23-24	+ 5.00
3rd	Dolomite	37-38	+ 10.00

Hydraulics (from pump test)

Parameter	Value
SWL (m)	1.10
Pump depth (m) (testing)	42.50
DWL at 48hr CDT (m)	4.30
Q (l/s) for CDT	3.27
S avail. (m), (pump - DWL)	41.40
S max (m), (SWL-DWL)	3.20
S utilised (**S**m/**S**a).100%	8
SC (**Q/S** max)	88.29
Main inflow (from PT)	10
Other inflow (from PT)	
Recovery (90% in minutes)	1
Recovery (m in 1st five minutes)	
Recommended pump depth (m)	
Pump Test comment	

Hydrochemistry (from pump test)

Water quality (mg/l)	340
pH	

Geophysics	JA	EM34 + Resistivity

EM: Positioned 18m east of EM Line 2
VES: Positioned 18m east of VES 2/40m (P2/1)
Target: Point of thickest weathering - on area where big trees are absent / fallen - unable to get roots to anchor due to shallow karstic feature

Outcome

Dolomite weathered to 20-25m - suspected intersection of

From pumping test the borehole has a maximum yield of 4.5-5 l/s. This is less than the 20l/s estimated by drilling. However the drilling yield was clear and thus the reduction is related to the screen or post-drilling collapse or infilling of surrounding karstic features. The latter is suspected as the screen has an open area of 8% and easily yielded 14l/s on the Makeni site. Problem compounded by a very shallow aquifer.

Recovery pin-pointed the main inflow zone at 10mbgl
Recovery pin-pointed the main inflow zone at 10mbgl
(point at which gushing water ceased)

Symbols
- First water (from drilling)
- Main water (from drilling)
- Static Water Level (from development)

P2/3 (Piezometer)

Well Completion Graphic

District:	Lusaka
Location:	Kasanova / Rosedale
Borehole ID:	P2/3
Drilling method:	Air-Percussion
Depth drilled (m):	41
Depth cased (m):	41
Pilot diameter (mm):	165
Final EOH diameter (mm):	165
Drilling completion date:	16-Nov-11
Coords (WGS84):	15.41858S, 28.19185E

Legend

- Soil (laterite, sand)
- Saprolite (regolith)
- Saprock (regolith)
- Dolomite
- Limestone
- Quartzite
- Psammite
- Schist
- 8"PVC plain casing (incl.centralizers)
- 3" PVC piezometer casing
- 8"PVC slotted casing (1mm slots, 8% OA)
- 3"PVC piezometer casing (site slotted)
- Cement sanitary seal
- Formation stabiliser (gravel 2 - 6 mm)
- Mixed collapse material

Penetration and flow | **Well Design** | **Aquifer and Well Data**

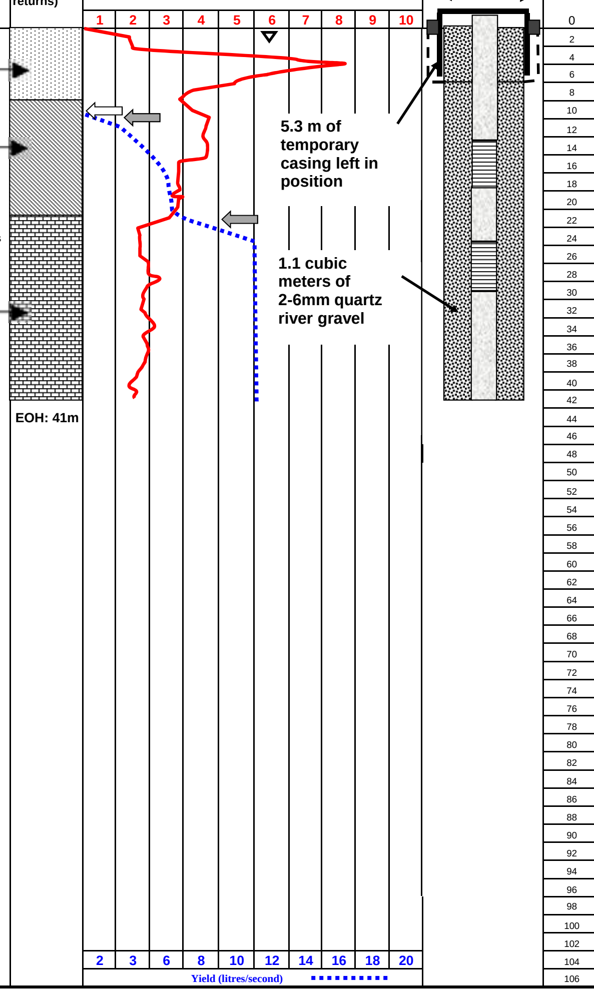
Depth (m) | **Geophysical model (VES)** | **Notes** | **Geology (DTH chip returns)**

Notes:

BROWN, RICH SOIL 1m ON
GREY, CALCAREOUS CLAY
HCL REACTIVE

LT TO DARK ORANGE-BROWN
CALCAREOUS BRECCIA
ORANGE WATER STRUCK AT 9m
BRECCIA HIGHLY HCL REACTIVE
SUSPECTED KARST FEATURE

AS ABOVE BUT DOLOMITE CHIPS
ALSO SEEN. SUSPECT THIS IS
DOLOMITE WITH MUCH
CONTAMINATION FROM ABOVE



Parameter			Value
Yield zones	Aquifer	Depth	l/s
1st	Dolomite	9	**0.25**
2nd	Karst	10	**+ 5.00**
3rd	Karst	31-22	**+ 5.00**

Hydraulics (from pump test)

SWL (m)	
Pump depth (m) (testing)	
DWL at 3hr CDT (m)	
Q (l/s) for CDT	
S avail. (m), (pump - DWL)	
S max (m), (SWL-DWL)	
S utilised (**S**m/**S**a).100%	
SC (**Q/S** max)	
Main inflow (from PT)	
Other inflow (from PT)	
Recovery (90% in minutes)	
Recovery (m in 1st five minutes)	
Recommended pump depth (m)	
Pump Test comment	

Hydrochemistry (from pump test)

Water quality (mg/l)	
pH	

Geophysics | JA

EM: Positioned 35m east of EM Line 2

VES: Positioned 35m east of VES 2/40m (P2/1)

Target: Attempting to intersect same karstic feature as seen in P2/2

Outcome

Suddeen change from white dolomite to red water and weathered material at 9-10m - supected saturated karst feature. Large pieces of water worn wall rock from 10-20m supports this

Symbols

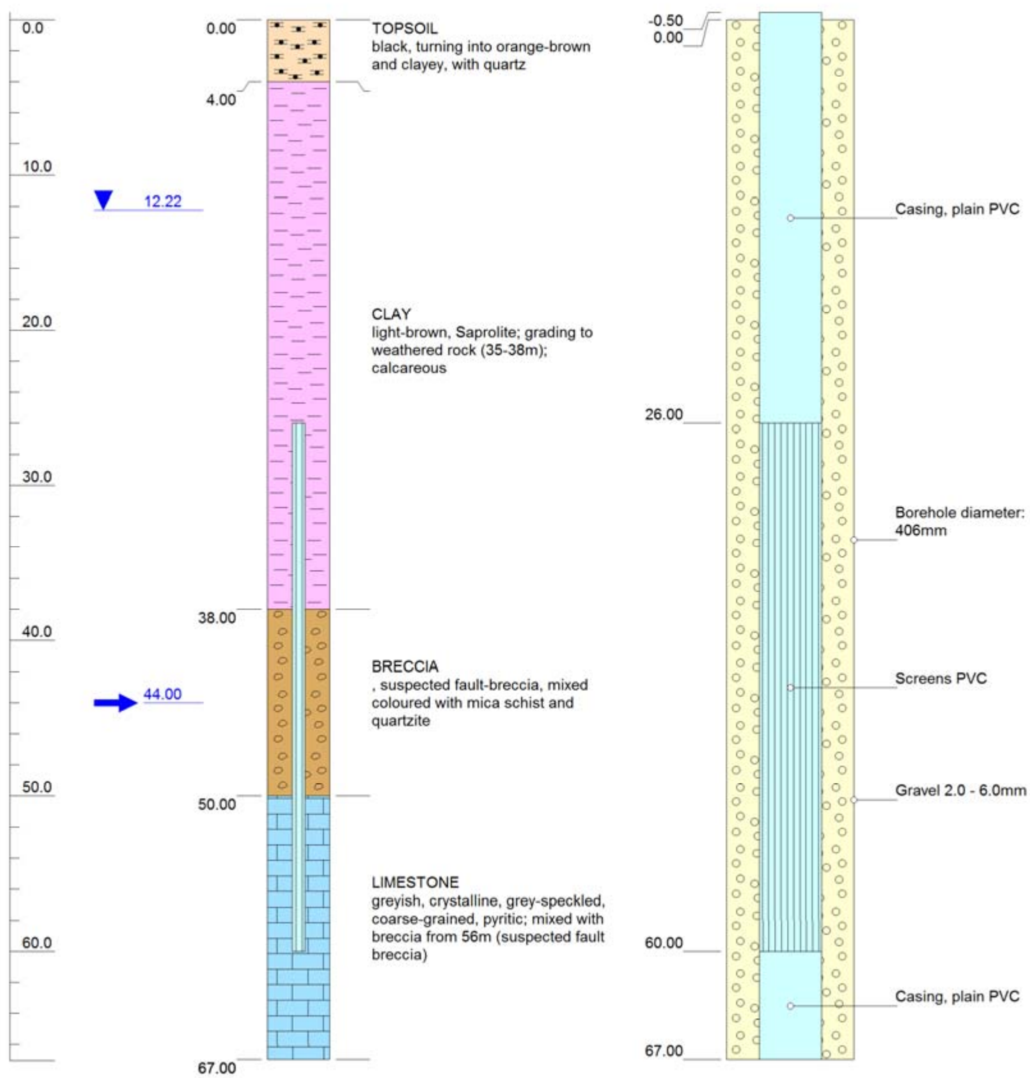
- First water (from drilling)
- Main water (from drilling)
- Static Water Level (from development)

Annex 2-3

Borehole Graphics, P-3 Makeni

P-3/1

Makeni/Sunrise 1 (Main Borehole)



Vertical scale: 1:400 Horizontal scale: 1:20

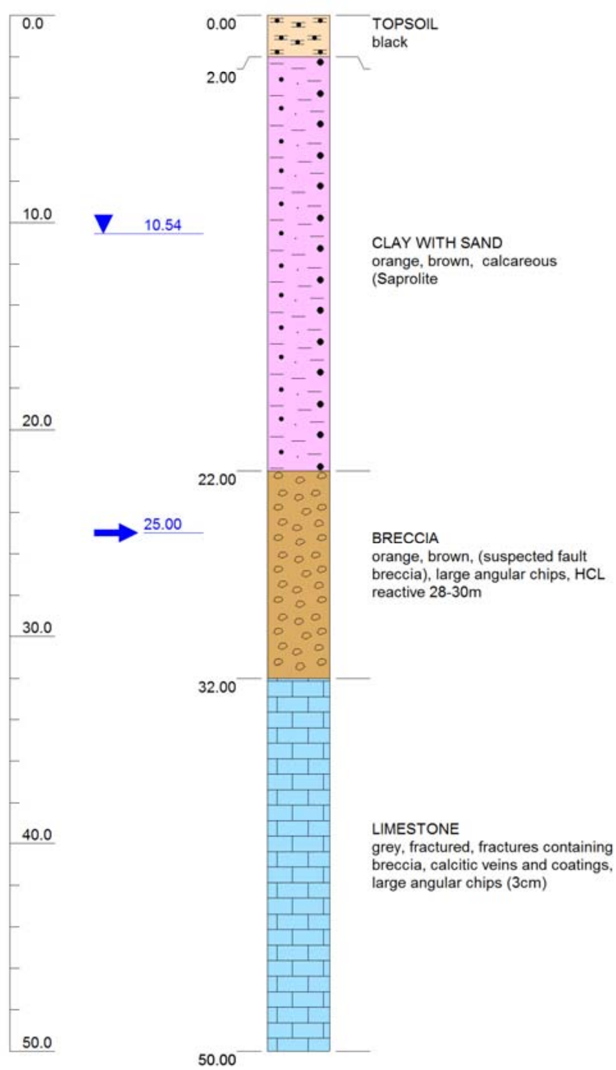
Water point number: 5020931

Water point funded by BGR		**Data Source: GReSP**	
Locality:	Sunrise Farm	East:	28.16550
Ward:		South:	-15.46960
District:	Kafue	Altitude:	0.00 m
Province:	Lusaka	Total depth of borehole:	67.0 m

P-3/2

m below ground surface (0.00 m)

Makeni/Sunrise 2 (Abandoned)



Vertical scale: 1:300 Horizontal scale: 1:20

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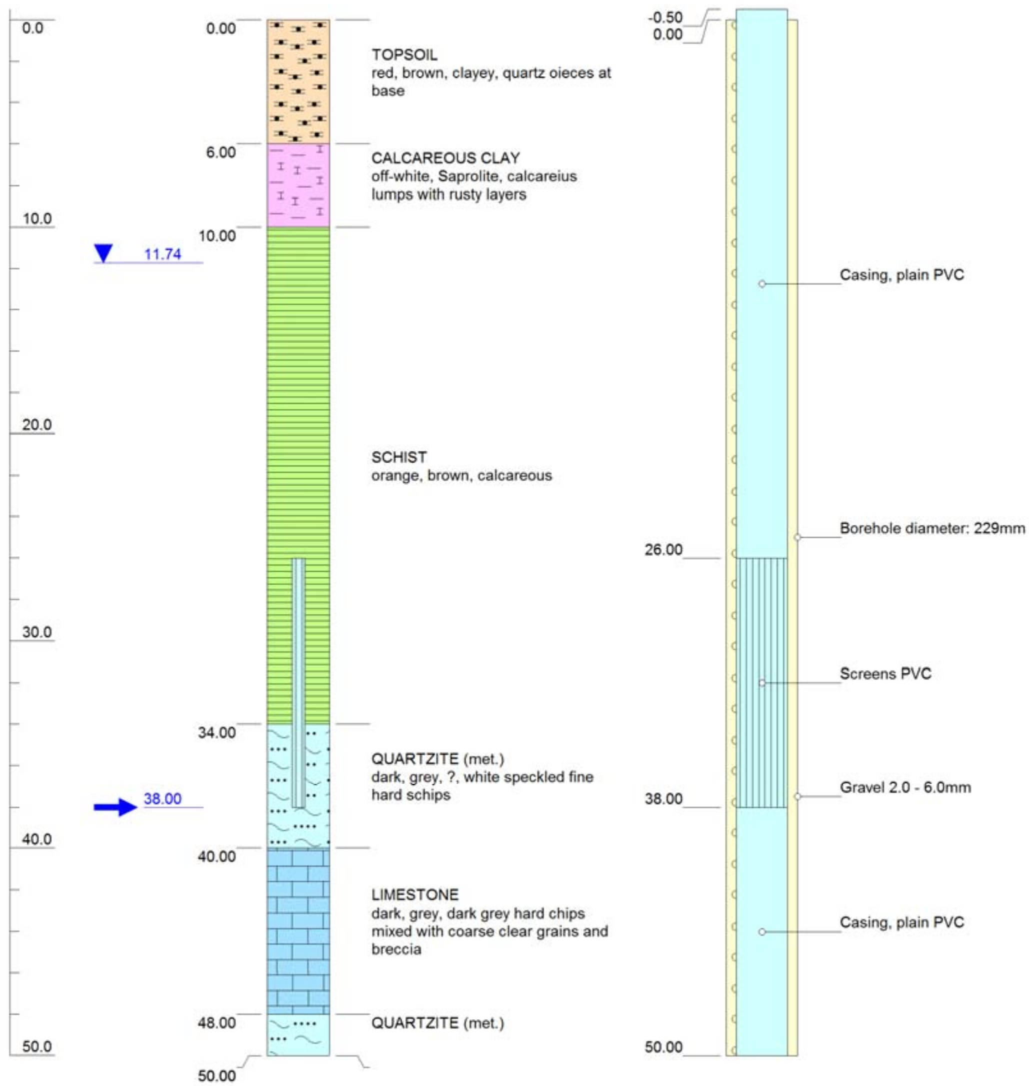
Water point number:	**5020932**		
Water point funded by BGR		**Data Source: GReSP**	
Locality:	Sunrise farm	East:	28.16550
Ward:		South:	-15.46960
District:	Kafue	Altitude:	0.00 m
Province:	Lusaka	Total depth of borehole:	50.0 m

P-3/3

Makeni/Sunrise 3 (Piezometer)

m below ground surface (0.00 m)



Vertical scale: 1:300 Horizontal scale: 1:20

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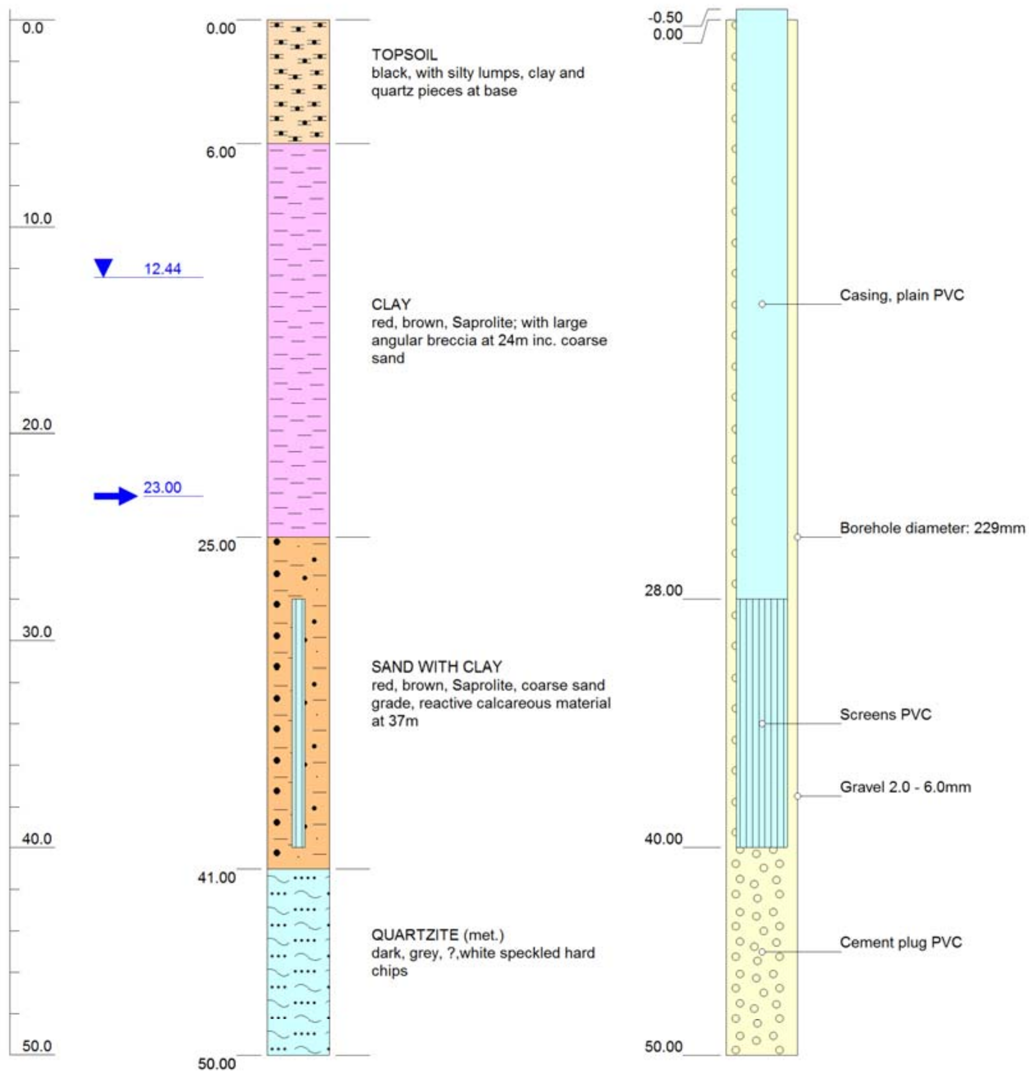
Water point number:	**5020933**		
Water point funded by BGR		**Data Source: GReSP**	
Locality:	Sunrise Farm	East:	28.16880
Ward:		South:	-15.46946
District:	Kafue	Altitude:	0.00 m
Province:	Lusaka	Total depth of borehole:	50.0 m

P-3/4

m below ground surface (0.00 m)

Makeni/Sunrise 4 (Piezometer)



Vertical scale: 1:300 Horizontal scale: 1:20

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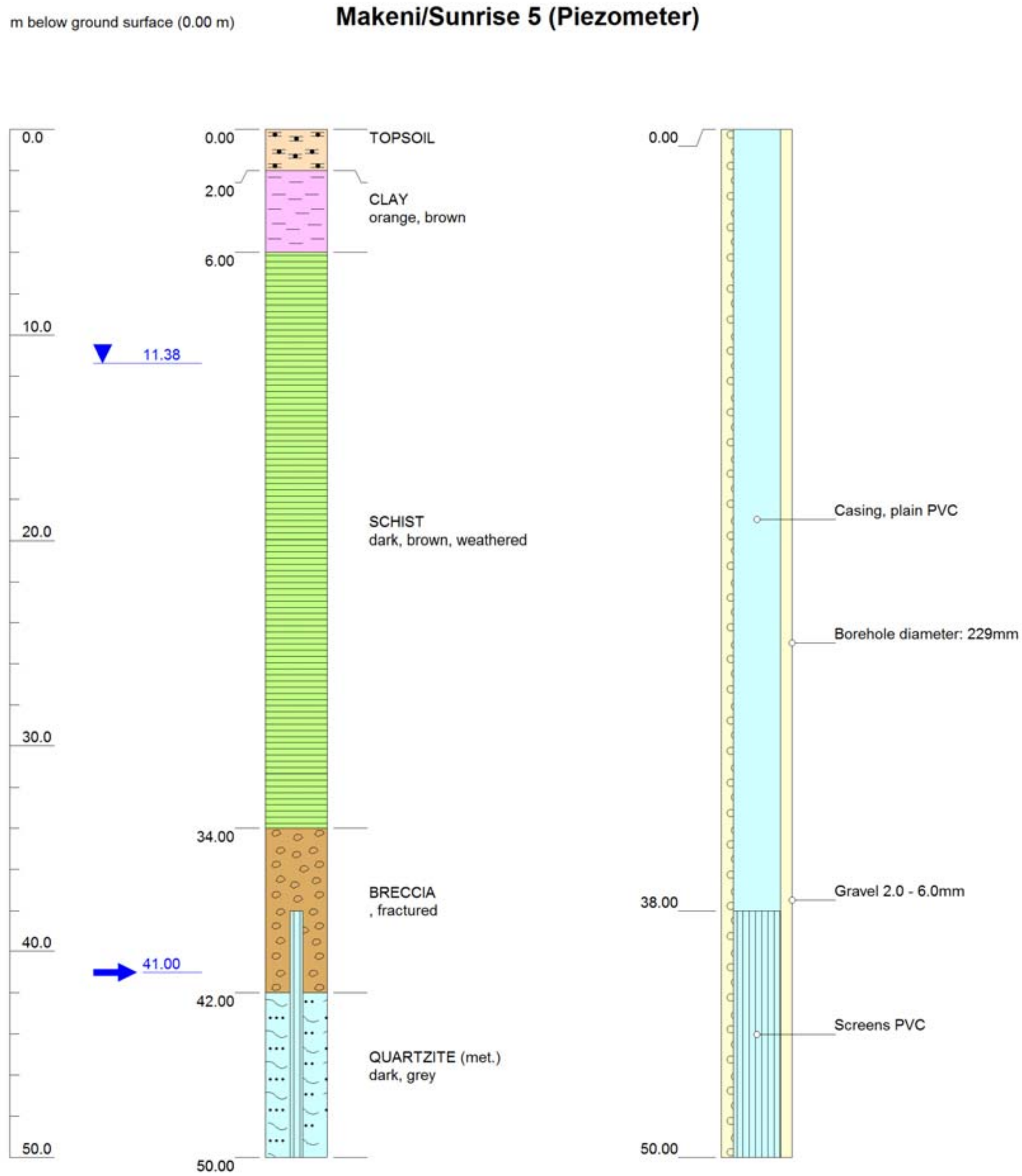
Water point number:	**5020934**		
Water point funded by BGR		**Data Source: GReSP**	
Locality:	Sunrise farm	East:	28.16576
Ward:		South:	-15.46982
District:	Kafue	Altitude:	0.00 m
Province:	Lusaka	Total depth of borehole:	50.0 m

P-3/5

Makeni/Sunrise 5 (Piezometer)



Vertical scale: 1:300 Horizontal scale: 1:20

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Water point number: 5020935

Water point funded by BGR		Data Source: GReSP	
Locality:	Sunrise	East:	28.16569
Ward:		South:	-15.46932
District:	Kafue	Altitude:	0.00 m
Province:	Lusaka	Total depth of borehole:	50.0 m

P3/1 (Main borehole)

Well Completion Graphic

District:	**Kafue**
Location:	**Makeni / Sunrise Farm**
Borehole ID:	**P3/1**
Drilling method:	**Air-Percussion**
Depth drilled (m):	**65**
Depth cased (m):	**67!**
Pilot diameter (mm):	**165**
Final EOH diameter (mm):	**305**
Drilling completion date:	**20-Nov-11**
Coords (WGS84):	**15.4696S, 28.1655E**

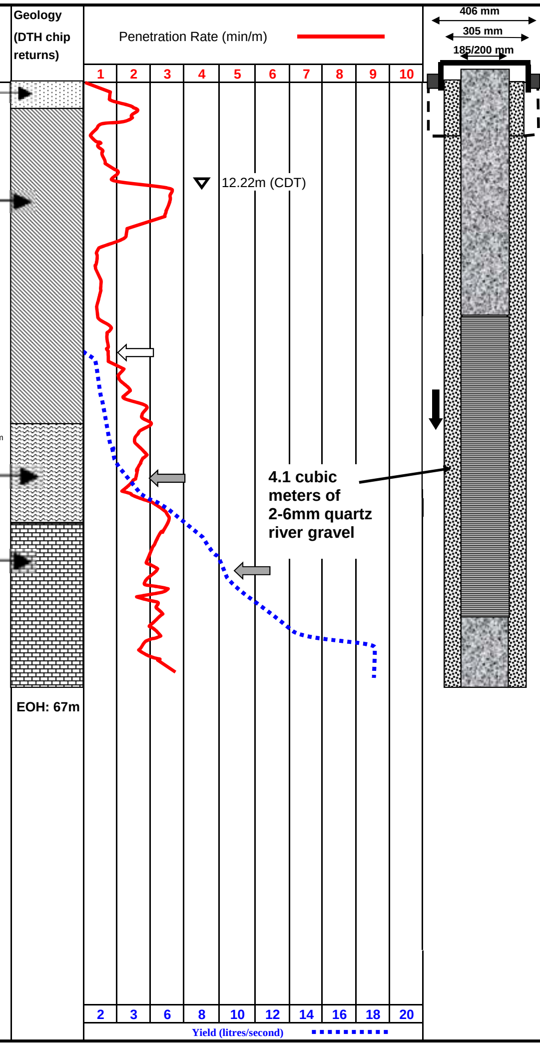
Legend:

- Soil (laterite, sand)
- Saprolite (regolith)
- Saprock (regolith)
- Dolomite
- Limestone
- Quartzite
- Psammite
- Schist
- Bedrock (undifferentiated)

- 8"PVC plain casing (incl.centralizers)
- 3" PVC piezometer casing
- 8"PVC slotted casing (1mm slots, 8% OA)
- 3"PVC piezometer casing (site slotted)
- Cement sanitary seal
- Formation stabiliser (gravel 2 - 6 mm)
- Mixed collapse material

Penetration and flow **Well Design** **Aquifer and Well Data**

Depth (m)	Geophysical model (VES)	Notes
0		
2	+/- 12 Ohm-m	BLACK, CLAY SOIL TURNING
4		ORANGE-BROWN AND CLAYEY
6		WITH QUARTZ
8	+/- 30 Ohm-m	
10		LIGHT BROWN CLAY,
12		GRADING TO WEATHERED
14		ROCK 35-38m
16		
18		CALCAREOUS AND HCL
20		REACTIVE
22–30		
32	+/- 130 Ohm-m	
34–38		
40		MIXED COLOURED CHIPS TO 3cm
42		INCL. QTZ, HARD MICA SCHIST
44		ETC. NON REACTIVE TO HCL
46		SUSPECTED FAULT BRECCIA
48		
50		GREY SPECKLED, CRYSTALINE
52		LIMESTONE, COARSE GRAINED
54		PYRITIC, HCL REACTIVE
56		
58		MIXED WITH MUCH BRECCIA
60		FROM 56m. SUSPECTED FAULT
62		BRECCIA
64–106		



Parameter			Value
Yield zones	Aquifer	Depth	**l/s**
1st	Schist	30	**1.50**
2nd	Breccia	44	**+ 5.00**
3rd	Breccia	54	**+ 10.00**

Hydraulics (from pump test)

SWL (m)	**12.22**
Pump depth (m) (testing)	**56.50**
DWL at 3hr CDT (m)	**33.10**
Q (l/s) for CDT	**14.12**
S avail. (m), (pump - DWL)	**44.28**
S max (m), (SWL-DWL)	**20.88**
S utilised (**S**m/**S**a).100%	**47**
SC (**Q/S** max)	**58.43**
Main inflow (from PT)	**>34**
Other inflow (from PT)	
Recovery (90% in minutes)	**2**
Recovery (m in 1st five minutes)	
Recommended pump depth (m)	
Pump Test comment	

Hydrochemistry (from pump test)

Water quality (mg/l)	**370**
pH	

Geophysics	**JA**	**MM/EM34 + Resistivity**

EM: Positioned on Line 1/230m on center EM -ve (seen on both Max-Min OP and EM34 V_D)

VES: <80 Ohm-m to AB = 240m or +/- 80 deep

Target: Excellent target on a suspected deep weathering zone - probably coincident with fault or fault zone

Outcome

Carbonate succession

Major inflows are with weathered fault zones

From pumping test the borehole has a maximum yield of 15-20 l/s. This appears similar to that estimated by drilling.

Symbols

- First water (from drilling)
- Main water (from drilling)
- Static Water Level (from development)

P3/2 (Abandoned)

Well Completion Graphic

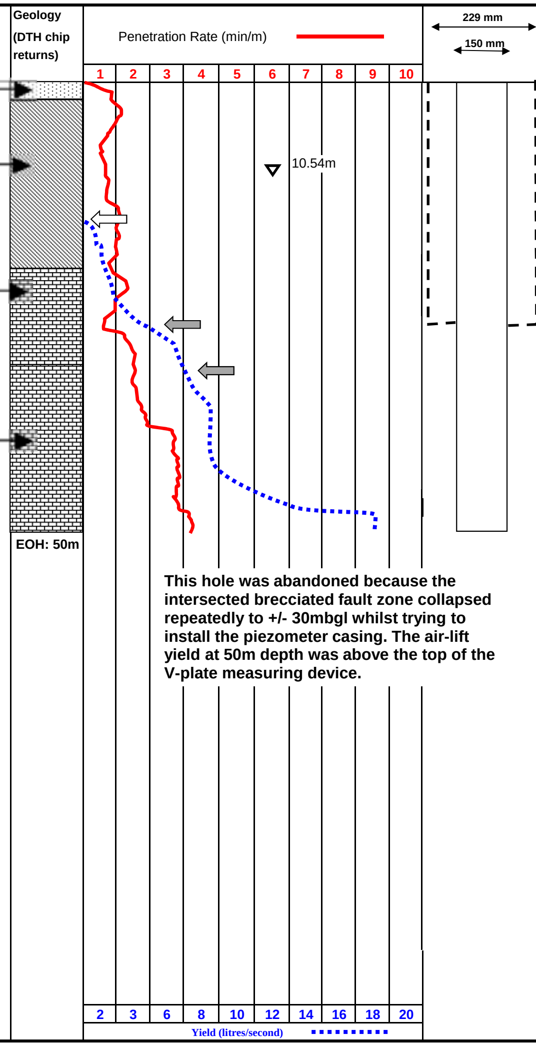
District:	Kafue
Location:	Makeni / Sunrise Farm
Borehole ID:	P3/2
Drilling method:	Air-Percussion
Depth drilled (m):	50
Depth cased (m):	-
Pilot diameter (mm):	165
Final EOH diameter (mm):	165
Drilling completion date:	22-Nov-11
Coords (WGS84):	15.4696S, 28.1655E

Soil (laterite, sand)
Saprolite (regolith)
Saprock (regolith)
Dolomite
Limestone
Quartzite
Psammite
Schist
Bedrock (undifferentiated)

8"PVC plain casing (incl.centralizers)
3" PVC piezometer casing
8"PVC slotted casing (1mm slots, 8% OA)
3"PVC piezometer casing (site slotted)
Cement sanitary seal
Formation stabiliser (gravel 2 - 6 mm)
Mixed collapse material

Penetration and flow | Well Design | Aquifer and Well Data

Depth (m)	Geophysical model (VES)	Notes
0		
2		BLACK SOIL
6		ORANGE-BROWN CLAY,
8		GRADING DOWN TO ORANGE-
10		BROWN SAND 28-30m
14		CALCAREOUS AND HCL
16		REACTIVE
24		ORANGE-BROWN, LARGE
26		ANGULAR CHIPS - SUSPECTED
28		FAULT BRECCIA.
30		HCL REACTIVE 28-30m
34		GREY CHIPS, CALCITIC VEINS
36		AND COATINGS.
38		LARGE ANGULAR CHIPS TO 3cm.
40		35-39m, HCL REACTIVE
42		SUSPECT LIMESTONE WITH
44		FRACTURES CONTAINING
46		BRECCIA



This hole was abandoned because the intersected brecciated fault zone collapsed repeatedly to +/- 30mbgl whilst trying to install the piezometer casing. The air-lift yield at 50m depth was above the top of the V-plate measuring device.

Yield zones	Aquifer	Depth	l/s
1st	Schist	15-16	1.5
2nd	Breccia	25-27	+ 4.00
3rd	Breccia	36+	+ 5.00

Parameter	Value
Hydraulics (from pump test)	
SWL (m)	10.54
Pump depth (m) (testing)	
DWL at 3hr CDT (m)	
Q (l/s) for CDT	
S avail. (m), (pump - DWL)	
S max (m), (SWL-DWL)	
S utilised (**S**m/**S**a).100%	
SC (**Q**/**S** max)	
Main inflow (from PT)	
Other inflow (from PT)	
Recovery (90% in minutes)	
Recovery (m in 1st five minutes)	
Recommended pump depth (m)	
Pump Test comment	
Hydrochemistry (from pump test)	
Water quality (mg/l)	370
pH	

Geophysics | JA | MM/EM34 + Resistivity

EM: Positioned on Line 1/200m on edge EM -ve (seen on both Max-Min OP and EM34 V_D)

VES: Not checked but conductive to depth (EM34)

Target: Excellent target on a suspected deep weathering zone - probably coincident with fault or fault zone

Outcome

Produced a lot of large angular rock fragments interpreted as a fault zone with breccia infill. There were a large variety of rock-types in the fault breccia The county rock appears to be a schist / carbonate succession. Extremely good result in terms of geophysics used

Symbols

- First water (from drilling)
- Main water (from drilling)
- Static Water Level (from development)

P3/3 (Piezometer)

Well Completion Graphic

District:	**Kafue**
Location:	**Makeni / Sunrise Farm**
Borehole ID:	**P3/3**
Drilling method:	**Air-Percussion**
Depth drilled (m):	**50**
Depth cased (m):	**50.19**
Pilot diameter (mm):	**165**
Final EOH diameter (mm):	**165**
Drilling completion date:	**24-Nov-11**
Coords (WGS84):	**15.46946S, 28.1688E**

Soil (laterite, sand)
Saprolite (regolith)
Saprock (regolith)
Dolomite
Limestone
Quartzite
Psammite
Schist
Bedrock (undifferentiated)

8"PVC plain casing (incl.centralizers)
3" PVC piezometer casing
8"PVC slotted casing (1mm slots, 8% OA)
3"PVC piezometer casing (site slotted)
Cement sanitary seal
Formation stabiliser (gravel 2 - 6 mm)
Mixed collapse material

Penetration and flow | **Well Design** | **Aquifer and Well Data**

Depth (m) | **Geophysical model (VES)** | **Notes** | **Geology (DTH chip returns)**

Notes:

RED-BROWN SOIL, CLAYEY
QUARTZ PIECES, 4-6m,

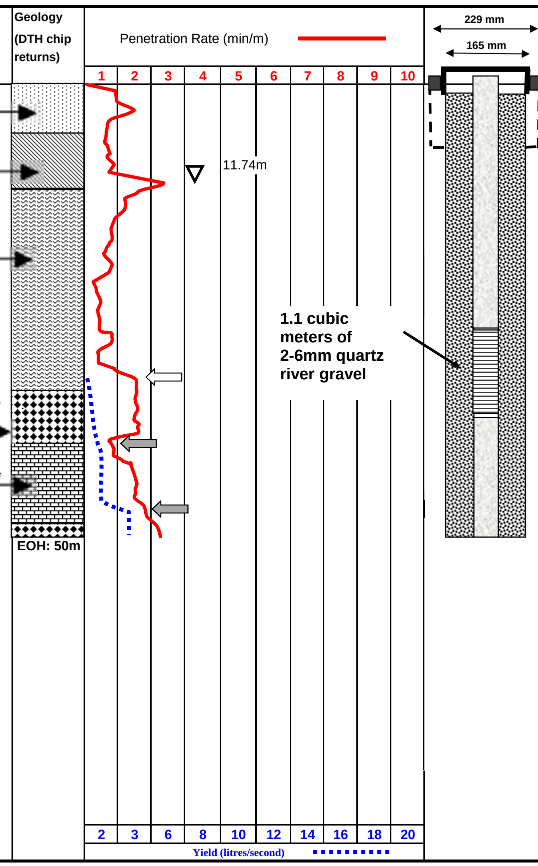
Off-WHITE, SOFT, CALCAREOUS
LUMPS SOME WITH RUSTY
LAYERS. HIGHLY REACTIVE

ORANGE-BROWN POWDER
CALCAREOUS
PULVERISED CALCITIC
SCHIST?

BECOMING BROWN 22-33m

DARK GREY. / WHITE SPECKLED
FINE, HARD CHIPS. HCL NON-
REACTIVE, QUARTZITE

DARK GREY, HARD CHIPS MIXED
COARSE CLEAR GRAINS AND
BRECCIA FROM 46-48m. HCL
REACTIVE. LIMESTONE



Depth (m): 0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32, 34, 36, 38, 40, 42, 44, 46, 48, 50, 52, 54, 56, 58, 60, 62, 64, 66, 68, 70, 72, 74, 76, 78, 80, 82, 84, 86

Parameter			Value
Yield zones	Aquifer	Depth	**l/s**
1st	Schist	33-34	**0.25**
2nd	Limestone	38-39	**+ 5.00**
3rd	Limestone	47-48	**+ 5.00**

Hydraulics (from pump test)	
SWL (m)	**11.74**
Pump depth (m) (testing)	
DWL at 3hr CDT (m)	
Q (l/s) for CDT	
S avail. (m), (pump - DWL)	
S max (m), (SWL-DWL)	
S utilised (**S**m/**S**a).100%	
SC (**Q**/**S** max)	
Main inflow (from PT)	
Other inflow (from PT)	
Recovery (90% in minutes)	
Recovery (m in 1st five minutes)	
Recommended pump depth (m)	
Pump Test comment	

Hydrochemistry (from pump test)	
Water quality (mg/l)	**370**
pH	

Geophysics | **JA** | **MM/EM34 + Resistivity**

EM: Positioned on Line 1/245m oFF center EM -ve (seen on both Max-Min OP and EM34 V_D)

VES: Not checked

Target: Piezometer position 12m from main borehole

Outcome

Did not penetrate the brecciated fracture zone encountered in P3/1, 2 and 4. Conclude that it is to the east of the main fracture

Symbols

- First water (from drilling)
- Main water (from drilling)
- Static Water Level (from development)

P3/4 (Piezometer)

Well Completion Graphic

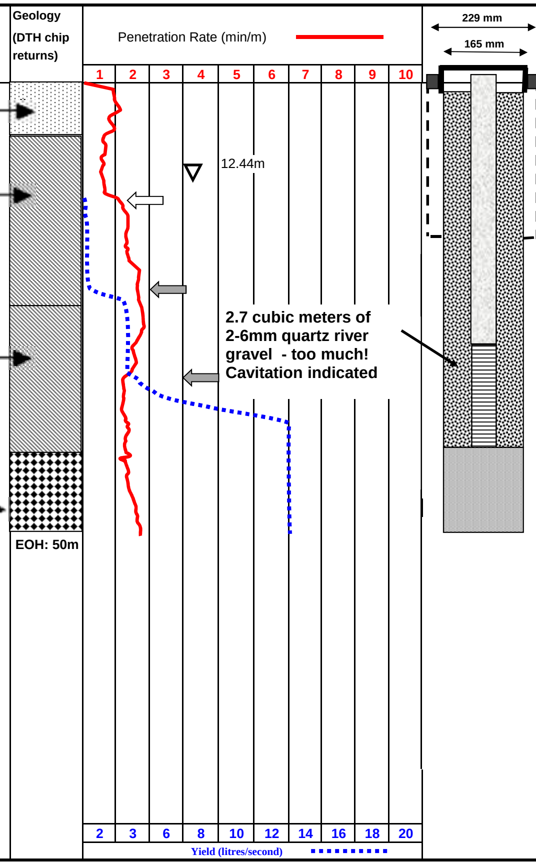
District:	**Kafue**
Location:	**Makeni / Sunrise Farm**
Borehole ID:	**P3/4**
Drilling method:	**Air-Percussion**
Depth drilled (m):	**50**
Depth cased (m):	**40.49**
Pilot diameter (mm):	**165**
Final EOH diameter (mm):	**165**
Drilling completion date:	**25-Nov-11**
Coords (WGS84):	**15.46982S, 28.16576E**

▨	Soil (laterite, sand)
▨	Saprolite (regolith)
▨	Saprock (regolith)
▨	Dolomite
▨	Limestone
▨	Quartzite
▨	Psammite
▨	Schist
▨	Bedrock (undifferentiated)

▨	8"PVC plain casing (incl.centralizers)
▨	3" PVC piezometer casing
▨	8"PVC slotted casing (1mm slots, 8% OA)
▨	3"PVC piezometer casing (site slotted)
▨	Cement sanitary seal
▨	Formation stabiliser (gravel 2 - 6 mm)
▨	Mixed collapse material

Penetration and flow **Well Design** **Aquifer and Well Data**

Depth (m)	Geophysical model (VES)	Notes
0		
2		BLACK SOIL WITH SILTY LUMPS
4		CLAY AND QUARTZ PIECES
6		AT 6-7m
8		
10		
12		RED-BROWN CLAY WITH LARGE
14		ANGULAR BRECCIA AT 24m
16		INCL. COARSE SAND
18		NON-REACTIVE WITH HCL
20		
22		
24		
26		
28		
30		RED-BROWN MIXTURE.
32		COARSE SAND GRADE.
34		NON-REACTIVE WITH HCL
36		REACTIVE CALCAREOUS
38		MATERIAL AT 37m
40		
42		
44		DARK GREY. / WHITE SPECKLED
46		FINE GRAINED, HARD CHIPS
48		HCL NON REACTIVE
50		QUARTZITE ?
52		
54		
56		
58		
60		
62		
64		
66		
68		
70		
72		
74		
76		
78		
80		
82		
84		
86		



Parameter			Value
Yield zones	Aquifer	Depth	**l/s**
1st	Breccia	13	**0.25**
2nd	Breccia	23	**+ 3.50**
3rd	Breccia	36	**+ 5.00**

Hydraulics (from pump test)	
SWL (m)	**12.44**
Pump depth (m) (testing)	
DWL at 3hr CDT (m)	
Q (l/s) for CDT	
S avail. (m), (pump - DWL)	
S max (m), (SWL-DWL)	
S utilised (**S**m/**S**a).100%	
SC (**Q/S** max)	
Main inflow (from PT) ➡	
Other inflow (from PT) ⇨	
Recovery (90% in minutes)	
Recovery (m in 1st five minutes)	
Recommended pump depth (m)	
Pump Test comment	

Hydrochemistry (from pump test)

Water quality (mg/l)	
pH	

Geophysics JA MM/EM34 + Resistivity

EM: Positioned on trend midway between EM Lines 1 and 3

VES: Not checked

Target: Piezometer position 12m from main borehole

Outcome

Produced a lot of large angular rock fragments interpreted as a fault zone with breccia infill. Same as P3/2. The county rock appears to be a schist / carbonate succession.

Symbols

⇦	First water (from drilling)
⇦	Main water (from drilling)
▽	Static Water Level (from development)

P3/5(Piezometer)

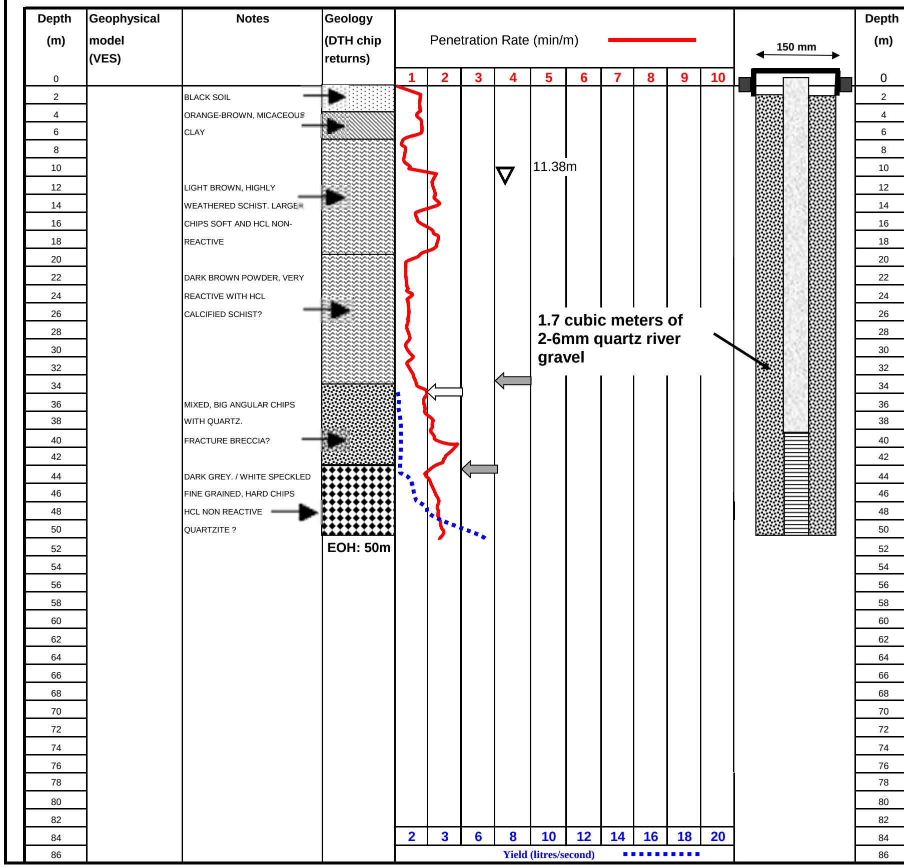
Well Completion Graphic

District:	**Kafue**
Location:	**Makeni / Sunrise Farm**
Borehole ID:	**P3/5**
Drilling method:	**Air-Percussion**
Depth drilled (m):	**50**
Depth cased (m):	**50.01**
Pilot diameter (mm):	**165**
Final EOH diameter (mm):	**165**
Drilling completion date:	**25-Nov-11**
Coords (WGS84):	**15.46932S, 28.16569E**

Soil (laterite, sand)
Saprolite (regolith)
Saprock (regolith)
Dolomite
Limestone
Quartzite
Psammite
Schist
Bedrock (undifferentiated)

8"PVC plain casing (incl.centralizers)
3" PVC piezometer casing
8"PVC slotted casing (1mm slots, 8% OA)
3"PVC piezometer casing (site slotted)
Cement sanitary seal
Formation stabiliser (gravel 2 - 6 mm)
Mixed collapse material

Penetration and flow **Well Design** **Aquifer and Well Data**



Parameter			Value
Yield zones	Aquifer	Depth	l/s
1st	Breccia	34	**0.05**
2nd	Breccia	41	**+ 0.60**
3rd	Quartzite	46-50	**+ 5.00**

Hydraulics (from pump test)

SWL (m)	**11.38**
Pump depth (m) (testing)	
DWL at 3hr CDT (m)	
Q (l/s) for CDT	
S avail. (m), (pump - DWL)	
S max (m), (SWL-DWL)	
S utilised (**S**m/**S**a).100%	
SC (**Q**/**S** max)	
Main inflow (from PT)	
Other inflow (from PT)	
Recovery (90% in minutes)	
Recovery (m in 1st five minutes)	
Recommended pump depth (m)	
Pump Test comment	

Hydrochemistry (from pump test)

Water quality (mg/l)	
pH	

Geophysics

EM: Few meters north of EM Line 1

VES: Not checked

Target: Piezometer position 22m from main borehole

Outcome

Similar to P3/1, 2 and 4. Water probably from fractures

Symbols

- First water (from drilling)
- Main water (from drilling)
- Static Water Level (from development)

Annex 3

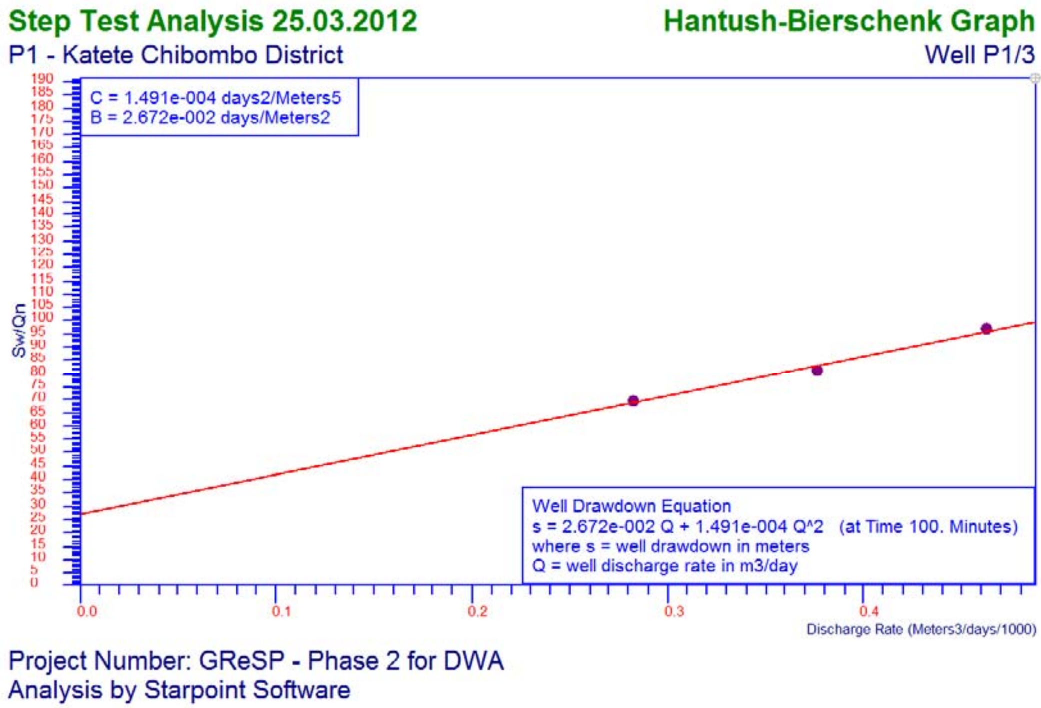
STEP TEST ANALYSIS

Table of Contents:

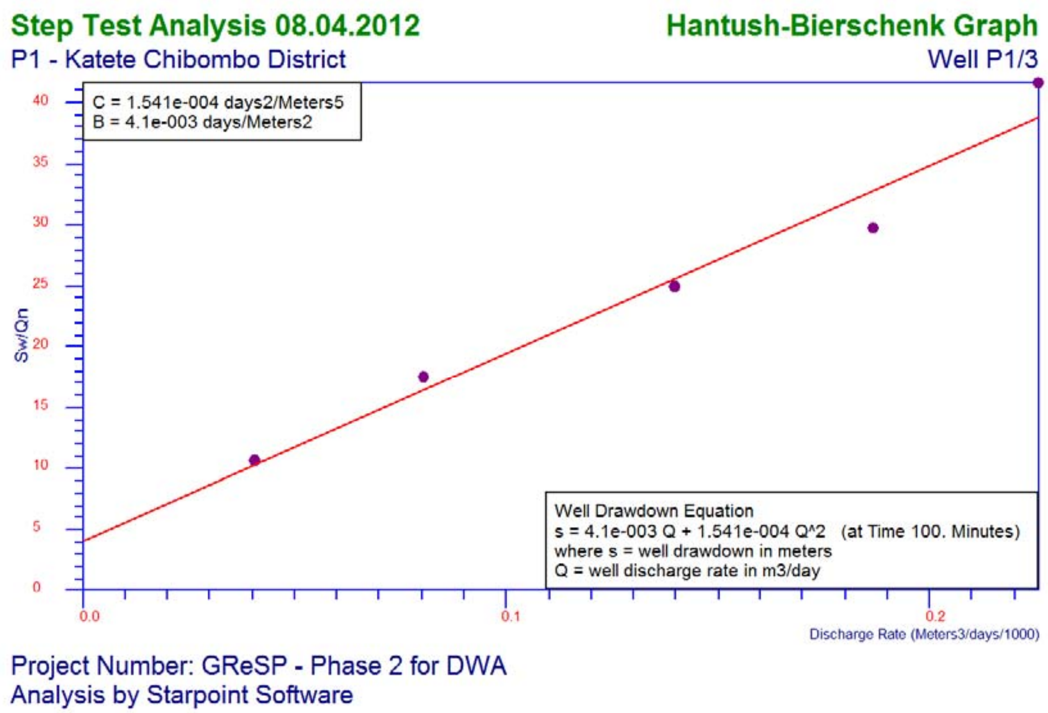
Annex 3-1

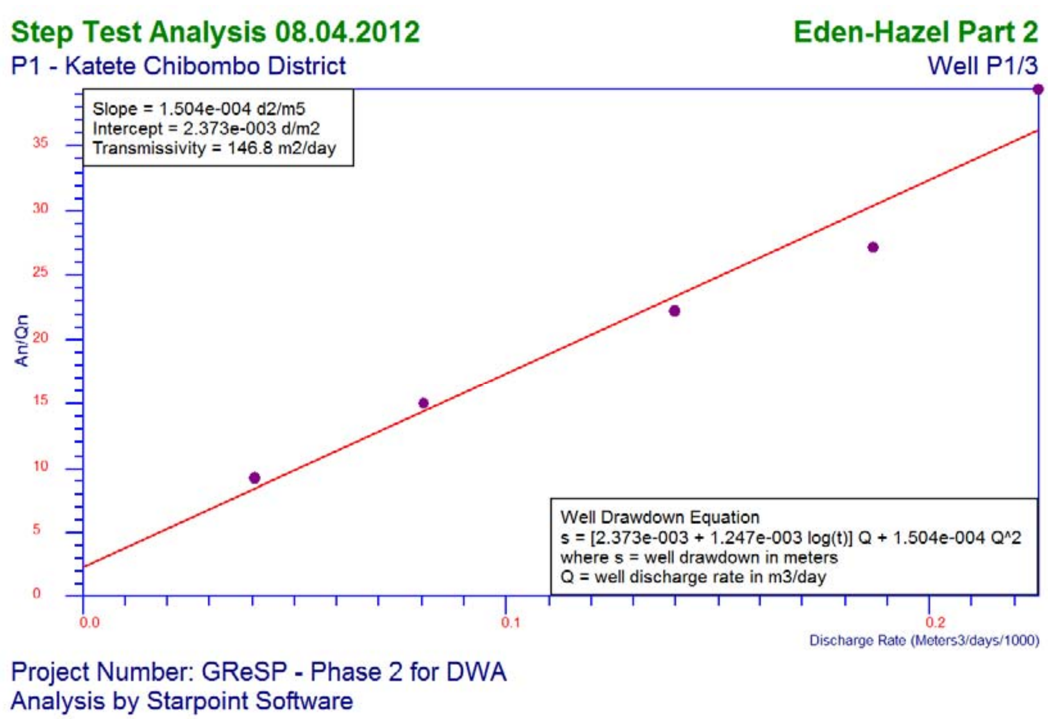
Step Test Analysis, P-1 Katete

P-1 Katete, Abandoned test 25.03.2012



P-1 Katete, Main test 08.04.2012

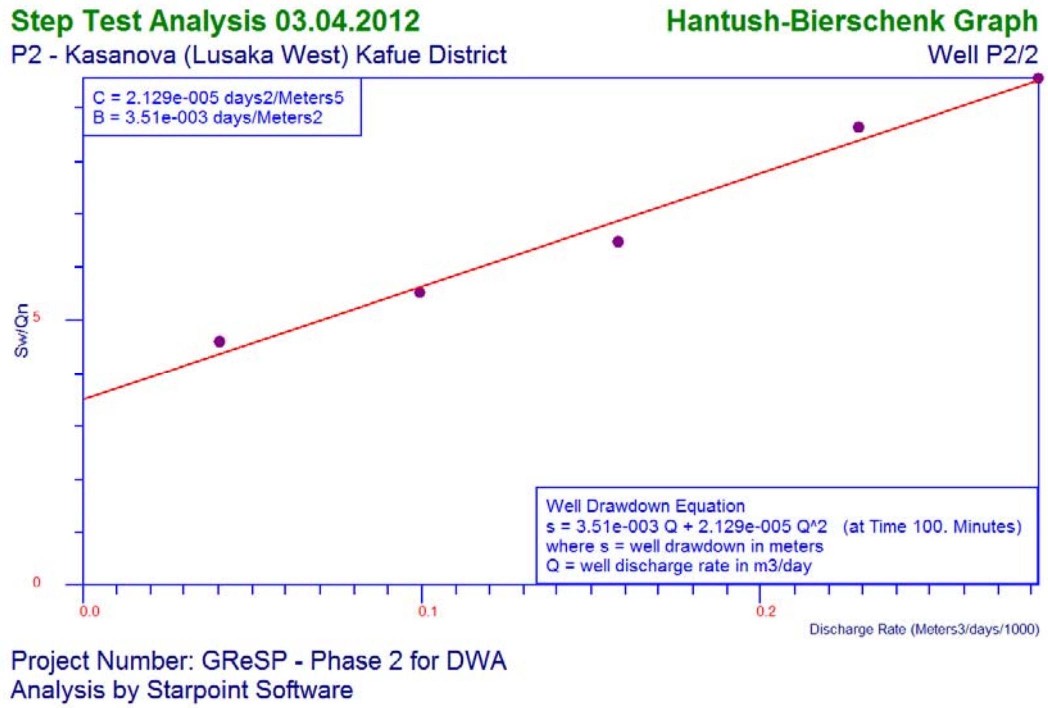


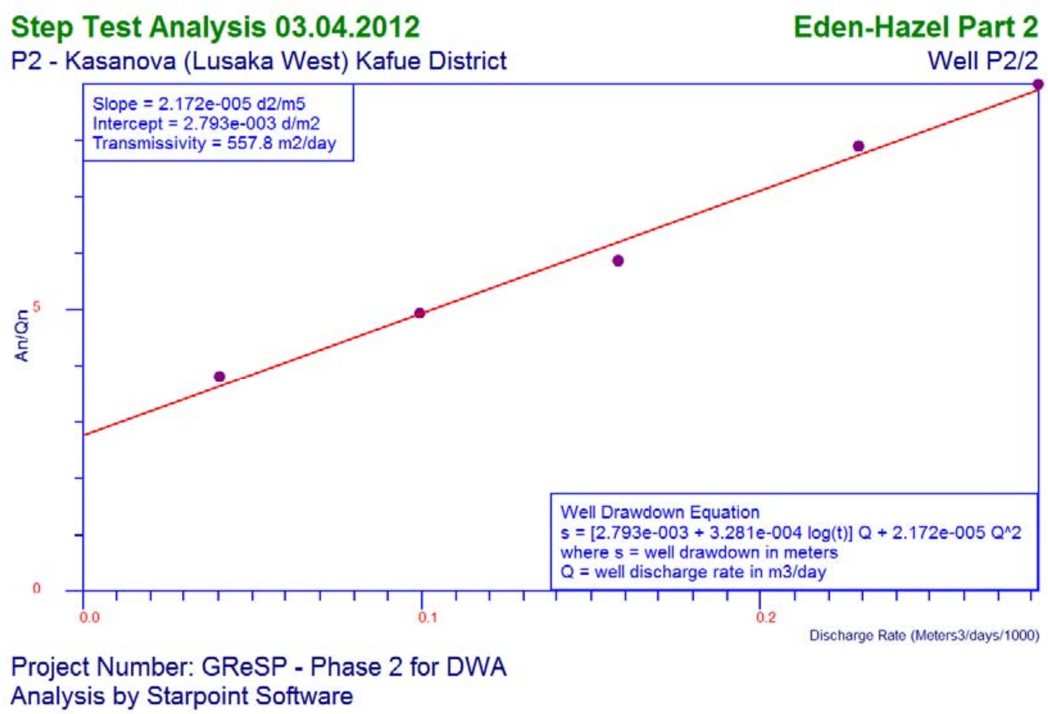


Annex 3-1

Step Test Analysis, P-2 Kasanova

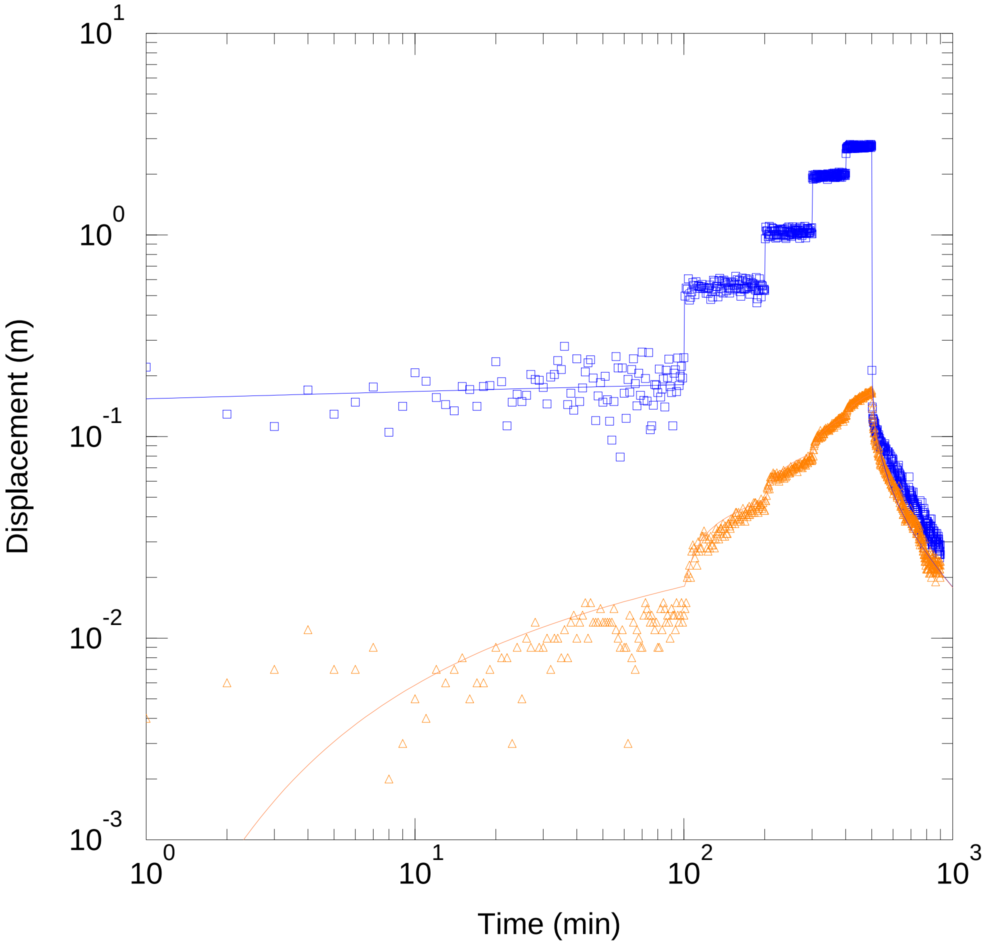
P-2 Kasanova, 03.04.2012





Step Test Kasanova P-2

Prepared By: GReSP	Prepared For: DWA
Project: GRESP - Phase 2	Location: Kasanova, Lusaka West



Data Set: Z:\GIS_DWA\Lusaka Province\tables\pumptesting\Pumping Test Kasanova\AQUIFER DATA\Kasanova.aqt
Date: 05/11/12 Time: 15:00:37

SOLUTION

Aquifer Model: Confined
Solution Method: Theis (Step Test)

T = 550. m^2/day
S = 0.004727
Sw = 5.607
C = 44. min^2/m^5
P = 2.

Step Test Model: Jacob-Rorabaugh
Time (t) = 1. min Rate (Q) in cu. m/min
$s(t) = 4.211Q + 44.Q^{2.}$
W.E. = 14.62% (Q from last step)

Saturated Thickness: 30. m Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (m)	Y (m)
P2/2	0	0

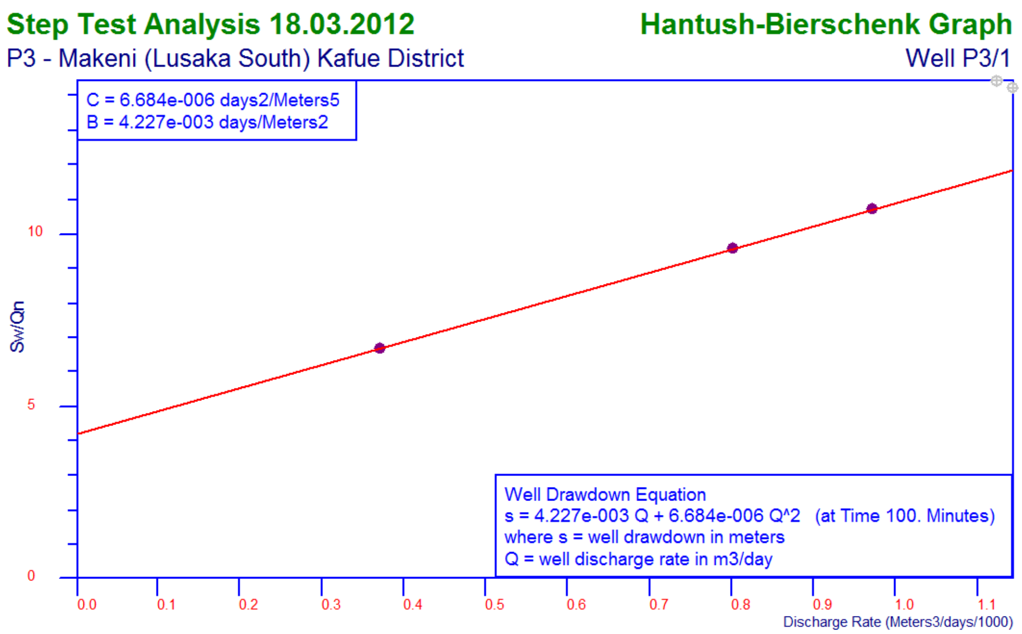
Observation Wells

Well Name	X (m)	Y (m)
□ P2/2	0	0
△ P2/3	29.35	0

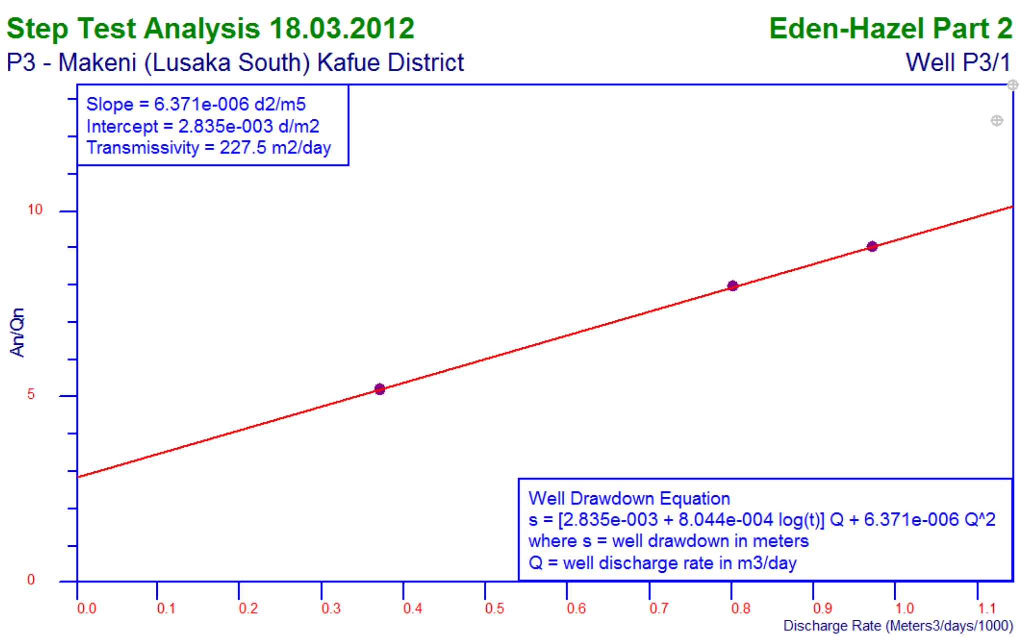
Annex 3-1

Step Test Analysis, P-3 Makeni

P-3 Makeni, 18.03.2012



Project Number: GReSP - Phase 2 for DWA
Analysis by Starpoint Software



Project Number: GReSP - Phase 2 for DWA
Analysis by Starpoint Software

Annex 4

A Q U I F E R T E S T A N A L Y S I S

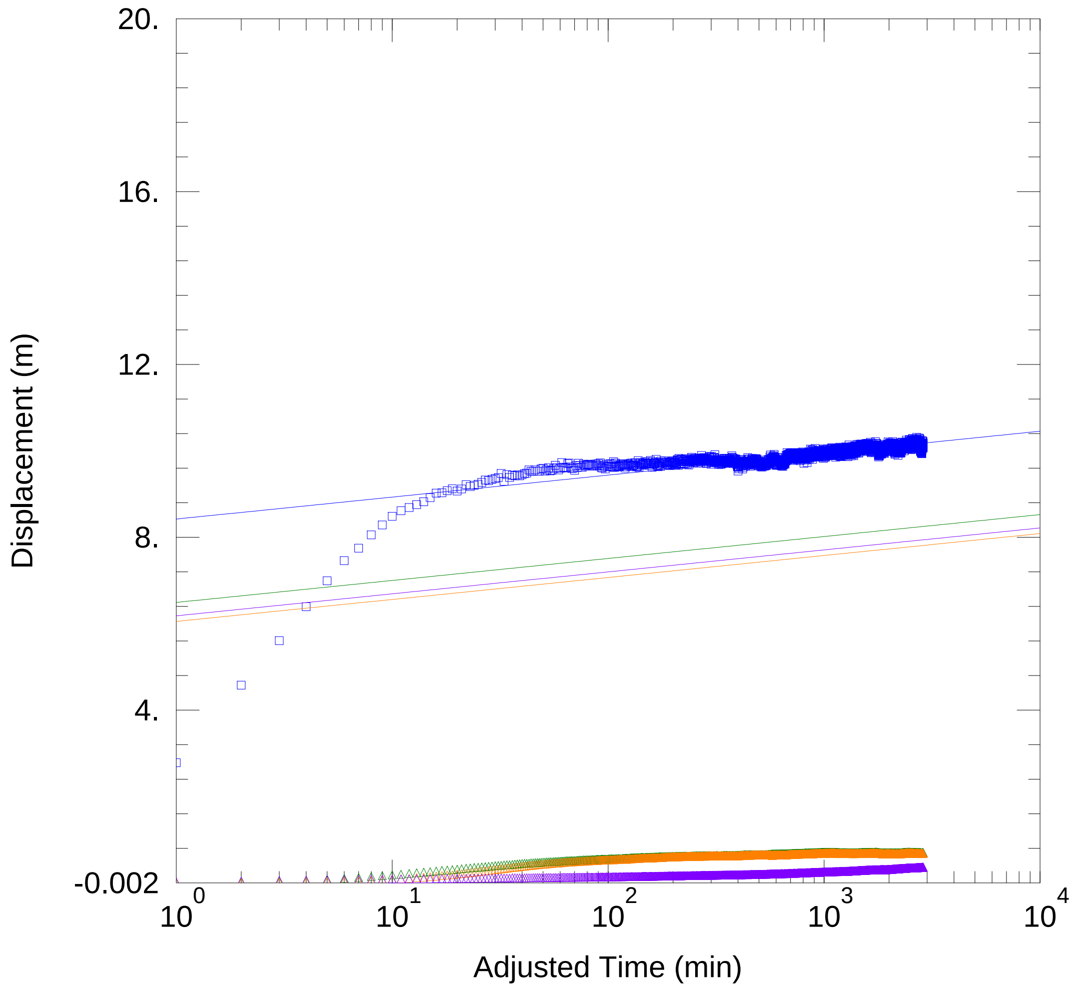
Table of Contents:

Annex 4-1

Aquifer Test Analysis, P-1 Katete

Aquifer Test P1 - Katete (Chibombo District)

Prepared By: GReSP	Prepared For: DWA
Project: GRESP - Phase 2	Location: Chibombo-Katete



Data Set: Z:\GIS_DWA\Lusaka Province\tables\pumptesting\Pumping Test KatAQUIFER DATAt\CDT2_Katete.aqt

Date: 05/22/12 Time: 08:48:12

SOLUTION

Aquifer Model: Confined

Solution Method: Cooper-Jacob

T = 84.06 m^2/day S = 1.623E-16

Saturated Thickness: 30. m Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

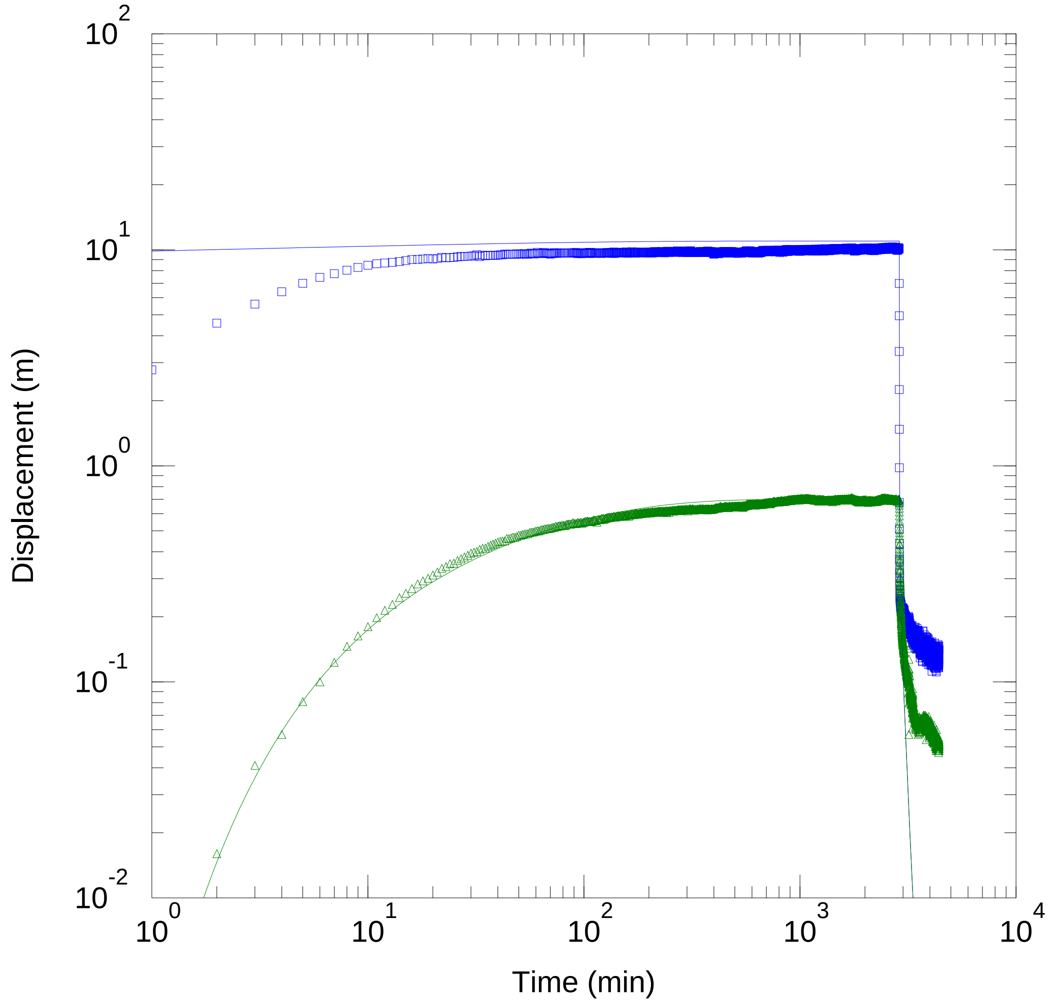
Well Name	X (m)	Y (m)
P1/3	0	0

Observation Wells

Well Name	X (m)	Y (m)
□ P1/3	0	0
△ P1/1	11.85	0
△ P1/2	32.1	0
△ P1/4	23.9	0

Aquifer Test P1 - Katete (Chibombo District)

Prepared By: GReSP	Prepared For: DWA
Project: GRESP - Phase 2	Location: Chibombo-Katete



Data Set: Z:\...\CDT2_Katete_P1-1.aqt
Date: 05/14/12 Time: 15:36:54

SOLUTION

Aquifer Model: Leaky
Solution Method: Hantush-Jacob

T = 80. m^2/day S = 0.005741
1/B = 0.02183 m^{-1} Sw = 0.
C = 315. min^2/m^5 P = 2.

Step Test Model: Jacob-Rorabaugh
Time (t) = 1. min Rate (Q) in cu. m/min
s(t) = 9.839Q + 315.$Q^{2.}$
W.E. = 16.16% (Q from last step)

AQUIFER DATA

Saturated Thickness: 30. m Anisotropy Ratio (Kz/Kr): 1.
Aquitard Thickness (b'): 1. m Aquitard Thickness (b"): 1. m

WELL DATA

Pumping Wells

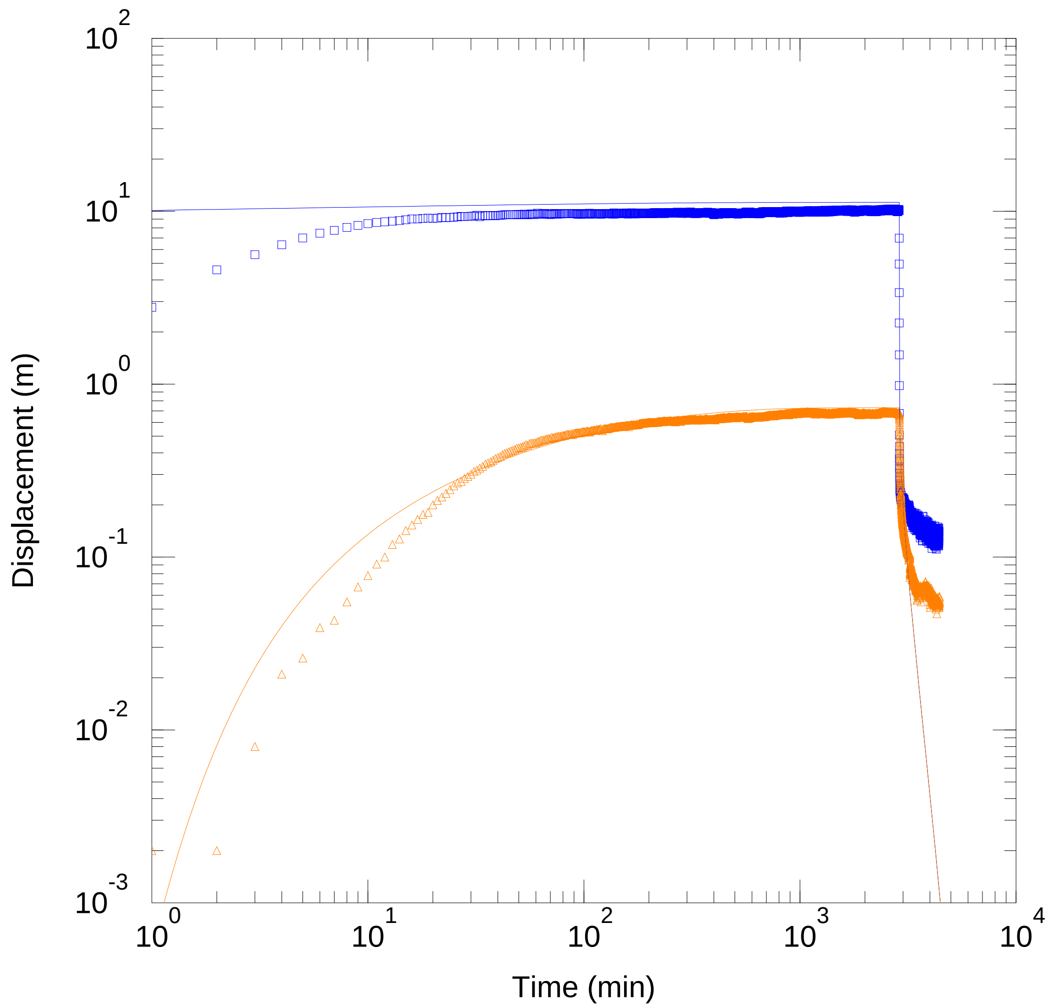
Well Name	X (m)	Y (m)
P1/3	0	0

Observation Wells

Well Name	X (m)	Y (m)
□ P1/3	0	0
△ P1/1	11.85	0

Aquifer Test P1 - Katete (Chibombo District)

Prepared By: GReSP	Prepared For: DWA
Project: GRESP - Phase 2	Location: Chibombo-Katete



Data Set: Z:\...\CDT2_Katete_P1-2.aqt
Date: 05/14/12 Time: 15:46:13

SOLUTION

Aquifer Model: Leaky
Solution Method: Hantush-Jacob

T = 88.16 m^2/day	S = 0.001032
1/B = 0.006354 m^{-1}	Sw = 0.
C = 315. min^2/m^5	P = 2.

Step Test Model: Jacob-Rorabaugh
Time (t) = 1. min Rate (Q) in cu. m/min
s(t) = 11.29Q + 315.$Q^{2.}$
W.E. = 18.11% (Q from last step)

AQUIFER DATA

Saturated Thickness: 30. m Anisotropy Ratio (Kz/Kr): 1.
Aquitard Thickness (b'): 1. m Aquitard Thickness (b"): 1. m

WELL DATA

Pumping Wells

Well Name	X (m)	Y (m)
P1/3	0	0

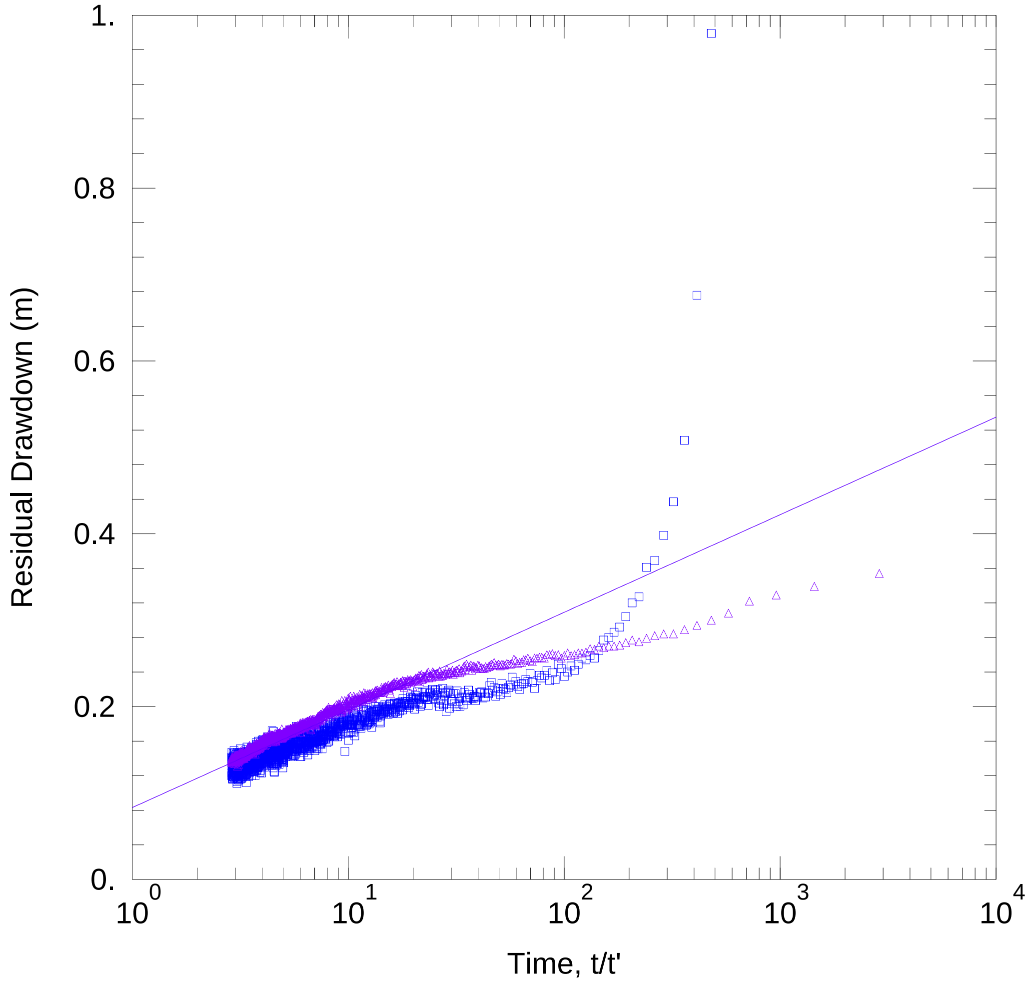
Observation Wells

Well Name	X (m)	Y (m)
□ P1/3	0	0
△ P1/2	32.1	0

BGR

Aquifer Test P1 - Katete (Chibombo District)

Prepared By: GReSP	Prepared For: DWA
Project: GRESP - Phase 2	Location: Chibombo-Katete



Data Set: Z:\...\CDT2_Katete_P1-4.aqt
Date: 05/21/12 Time: 16:43:01

SOLUTION

Aquifer Model: Confined
Solution Method: Theis (Recovery)

T = 378.4 m^2/day S/S' = 0.1843

AQUIFER DATA

Saturated Thickness: 30. m Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (m)	Y (m)
P1/3	0	0

Observation Wells

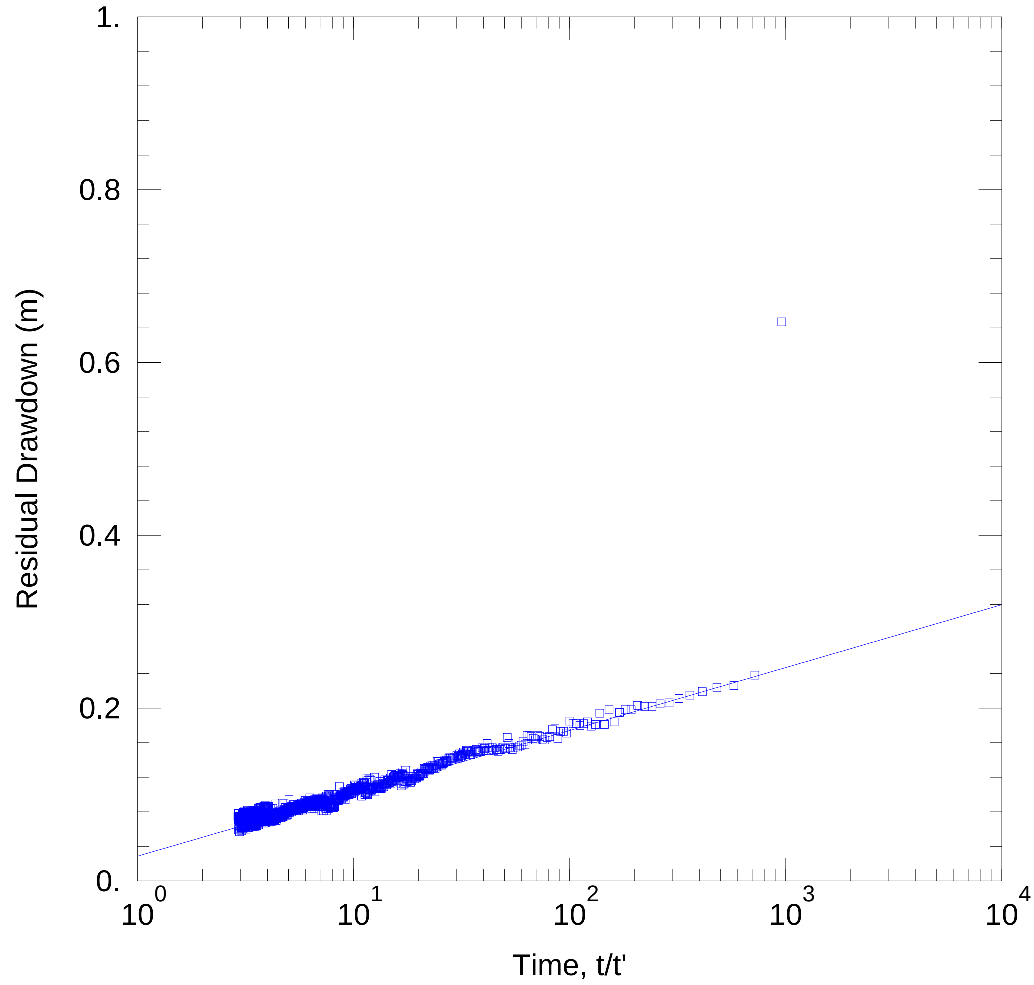
Well Name	X (m)	Y (m)
□ P1/3	0	0
△ P1/4	23.9	0

Annex 4-2

Aquifer Test Analysis, P-2 Kasanova

Aquifer Test P2 - Kasanova

Prepared By: GReSP	Prepared For: DWA
Project: GRESP - Phase 2	Location: Kasanova, Lusaka West



Data Set: Z:\...\CDT_Kasanova_P2-2.aqt
Date: 05/24/12 Time: 10:17:47

SOLUTION

Aquifer Model: Confined
Solution Method: Theis (Recovery)

T = 718.1 m^2/day S/S' = 0.4054

AQUIFER DATA

Saturated Thickness: 30. Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

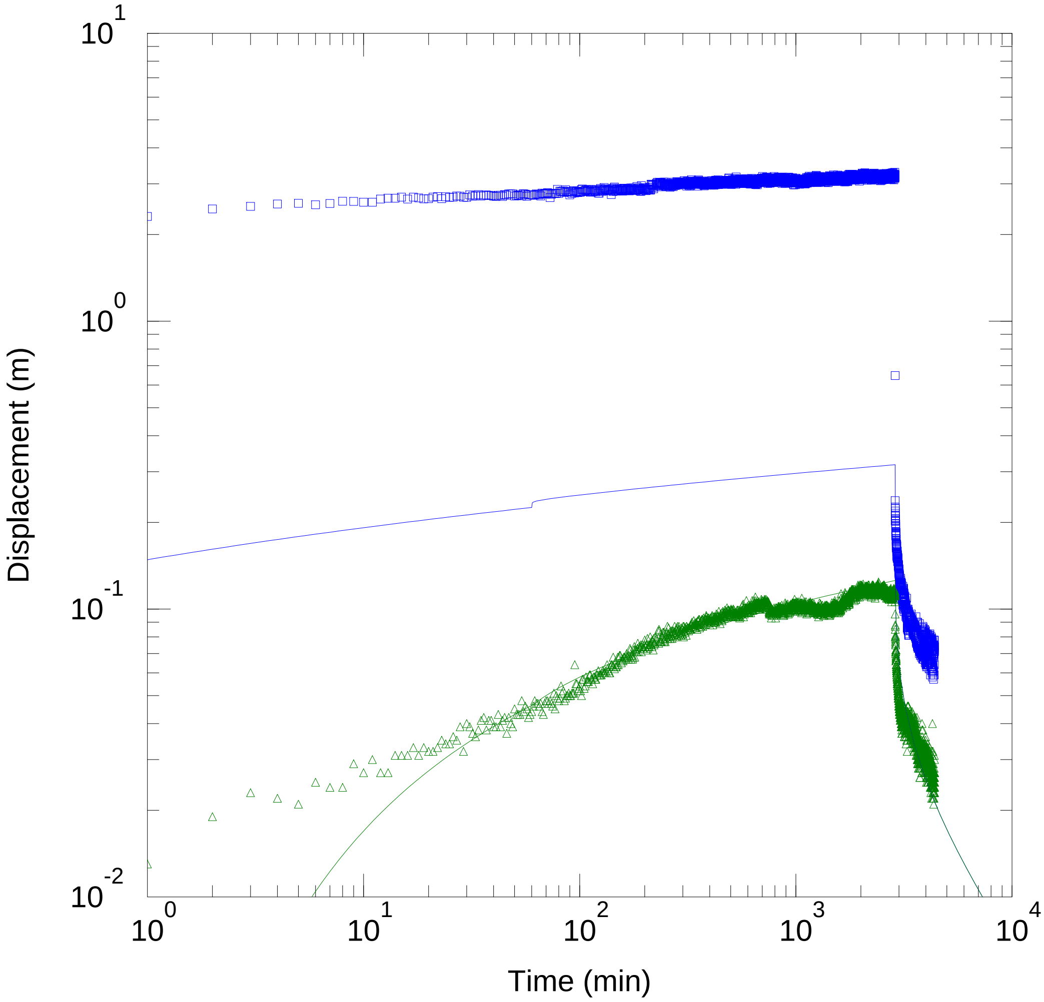
Well Name	X (m)	Y (m)
P2/2	0	0

Observation Wells

Well Name	X (m)	Y (m)
P2/2	0	0

Aquifer Test P2 - Kasanova

Prepared By: GReSP	Prepared For: DWA
Project: GRESP - Phase 2	Location: Kasanova, Lusaka West



Data Set: Z:\...\CDT_Kasanova_P2-1.aqt
Date: 05/22/12 Time: 14:54:54

SOLUTION

Aquifer Model: Confined
Solution Method: Theis

T = 1135. m^2/day S = 0.02922
Kz/Kr = 1. b = 30. m

WELL DATA

Pumping Wells

Well Name	X (m)	Y (m)
P2/2	0	0

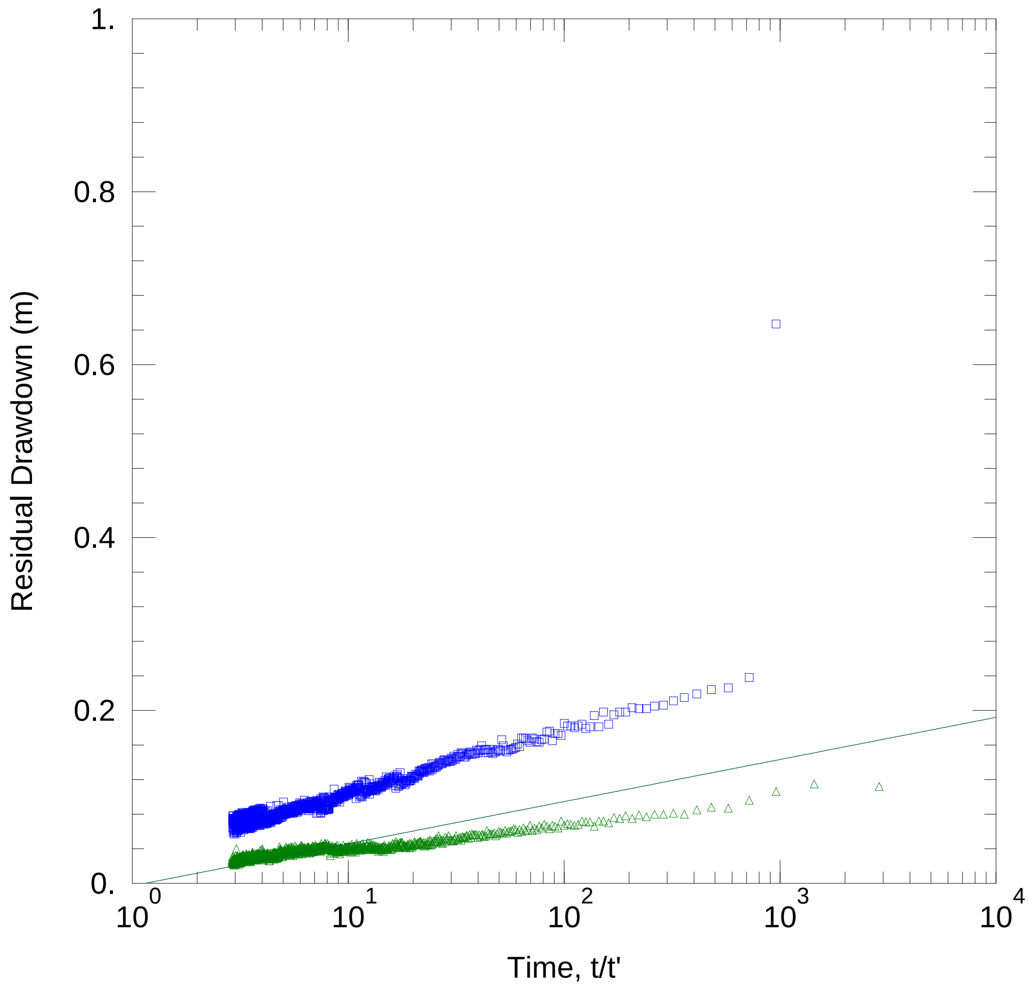
Observation Wells

Well Name	X (m)	Y (m)
□ P2/2	0	0
△ P2/1	18.05	0

BGR

Aquifer Test P2 - Kasanova

Prepared By: GReSP	Prepared For: DWA
Project: GRESP - Phase 2	Location: Kasanova, Lusaka West



Data Set: Z:\...\CDT_Kasanova_P2-3.aqt
Date: 05/22/12 Time: 14:47:31

SOLUTION

Aquifer Model: Confined
Solution Method: Theis (Recovery)

T = 1072.1 m^2/day S/S' = 1.153

AQUIFER DATA

Saturated Thickness: 30. m Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

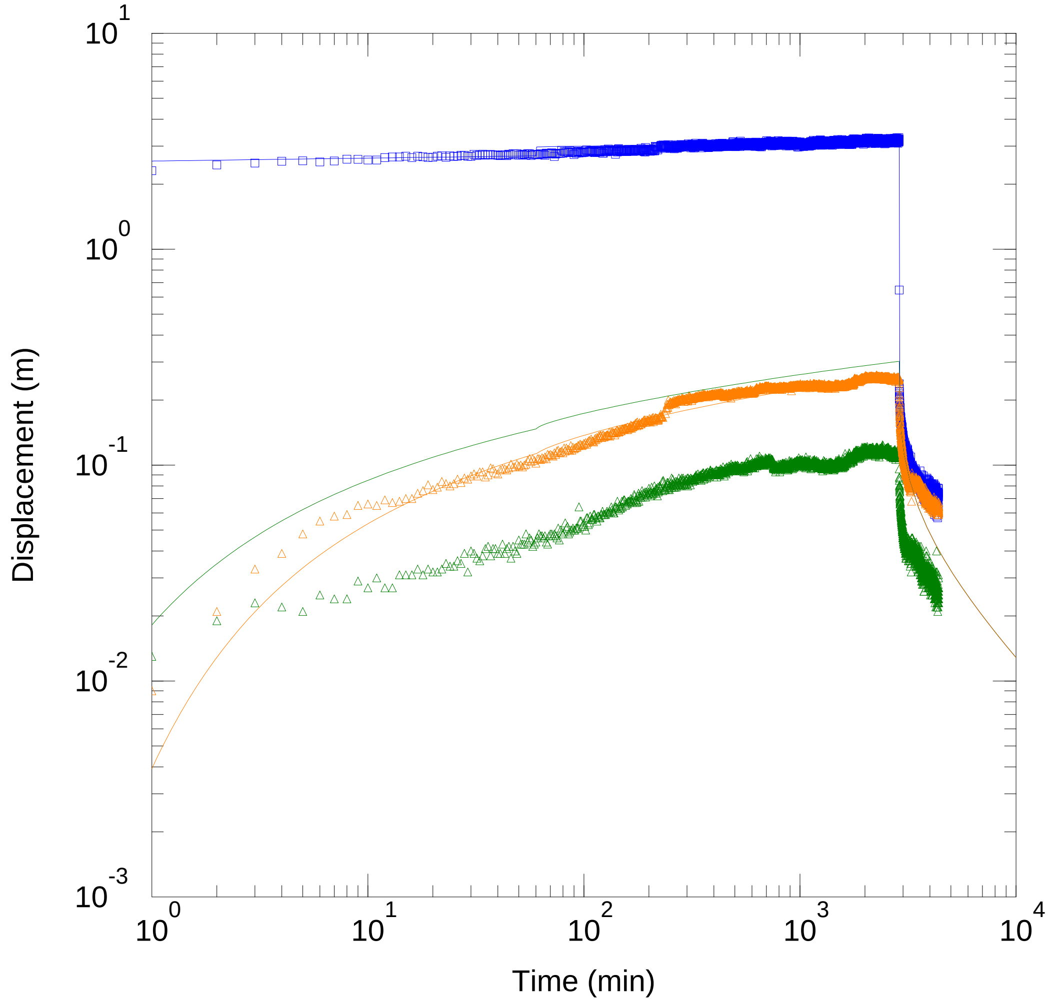
Well Name	X (m)	Y (m)
P2/2	0	0

Observation Wells

Well Name	X (m)	Y (m)
□ P2/2	0	0
△ P2/1	18.05	0

Aquifer Test P2 - Kasanova

Prepared By: GReSP	Prepared For: DWA
Project: GRESP - Phase 2	Location: Kasanova, Lusaka West



Data Set: Z:\...\CDT_Kasanova.aqt
Date: 05/11/12 Time: 16:48:29

SOLUTION

Aquifer Model: Confined
Solution Method: Theis (Step Test)

T = 600. m^2/day S = 0.002775
Sw = 9.782 C = 44. min^2/m^5
P = 2.

Step Test Model: Jacob-Rorabaugh
Time (t) = 1. min Rate (Q) in cu. m/min
s(t) = 5.573Q + 44.$Q^{2.}$
W.E. = 12.86% (Q from last step)

AQUIFER DATA

Saturated Thickness: 30. m Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

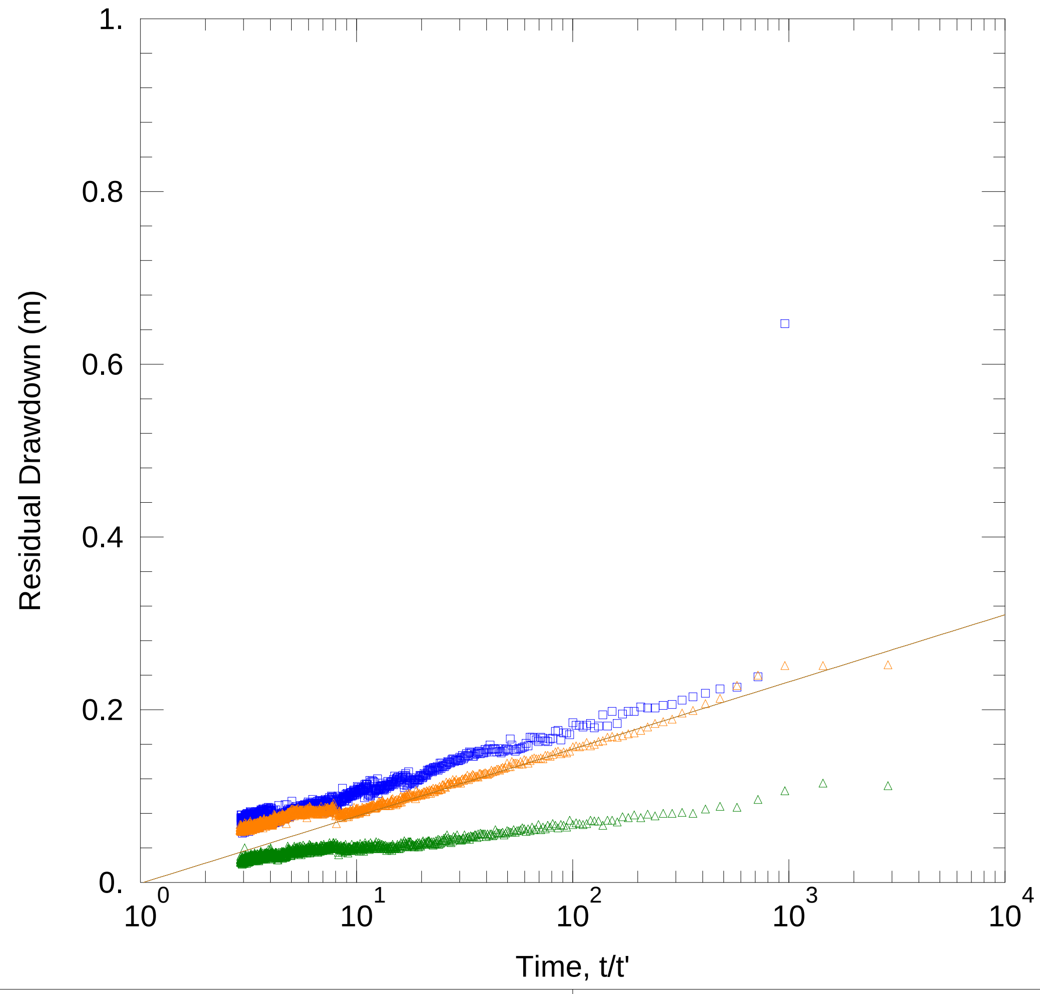
Well Name	X (m)	Y (m)
P2/2	0	0

Observation Wells

Well Name	X (m)	Y (m)
P2/2	0	0
P2/1	18.05	0
P2/3	29.35	0

Aquifer Test P2 - Kasanova

Prepared By: GReSP	Prepared For: DWA
Project: GRESP - Phase 2	Location: Kasanova, Lusaka West



Data Set: Z:\...\CDT_Kasanova.aqt
Date: 05/11/12 Time: 16:50:22

SOLUTION

Aquifer Model: Confined
Solution Method: Theis (Recovery)

T = 671.9 m^2/day S/S' = 1.035

AQUIFER DATA

Saturated Thickness: 30. m Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (m)	Y (m)
P2/2	0	0

Observation Wells

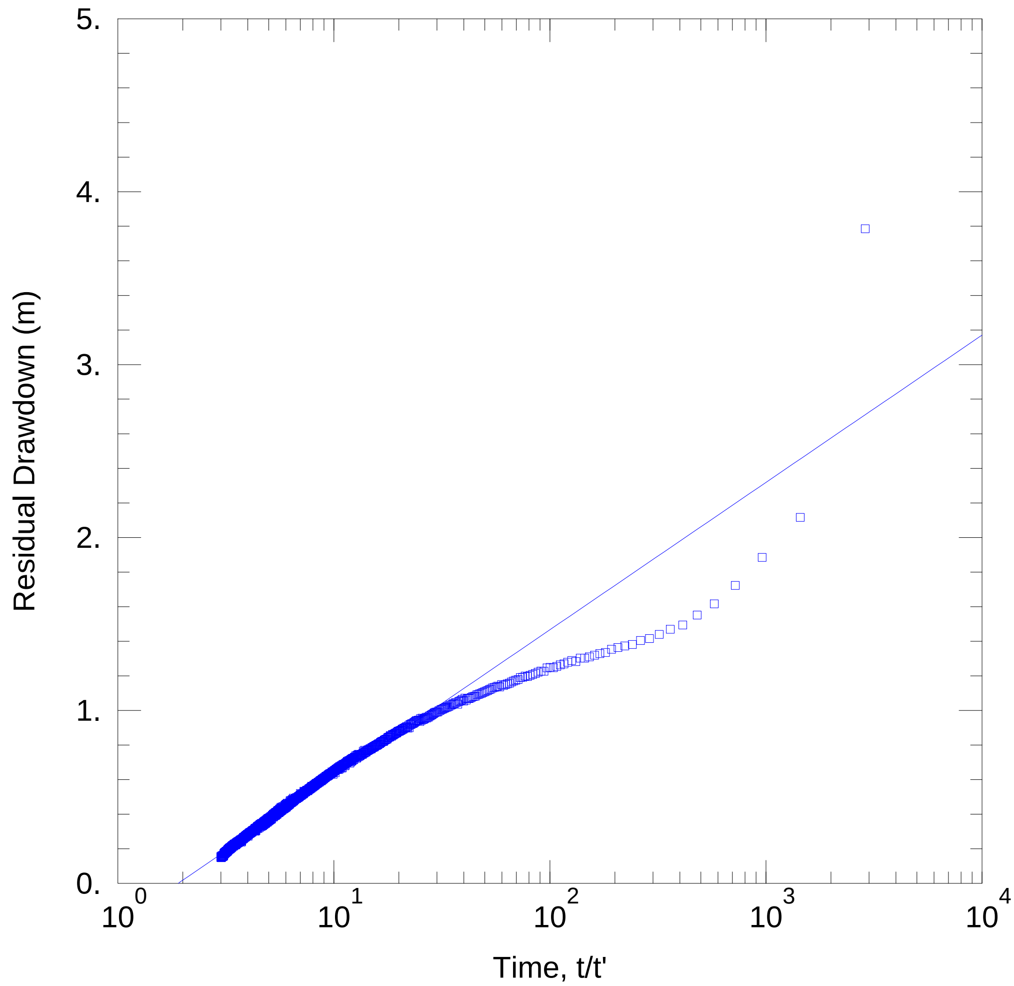
Well Name	X (m)	Y (m)
P2/2	0	0
P2/1	18.05	0
P2/3	29.35	0

Annex 4-3

Aquifer Test Analysis, P-3 Makeni

Aquifer Test P3 - Makeni

Prepared By: GReSP	Prepared For: DWA
Project: GRESP - Phase 2	Location: Makeni (Kafue District)



Data Set: Z:\...\CDT_Makeni_P3-1.aqt
Date: 05/22/12 Time: 16:22:13

SOLUTION

Aquifer Model: Confined
Solution Method: Theis (Recovery)

T = 262.3 m^2/day S/S' = 1.906

AQUIFER DATA

Saturated Thickness: 30. m Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (m)	Y (m)
P3/1	0	0

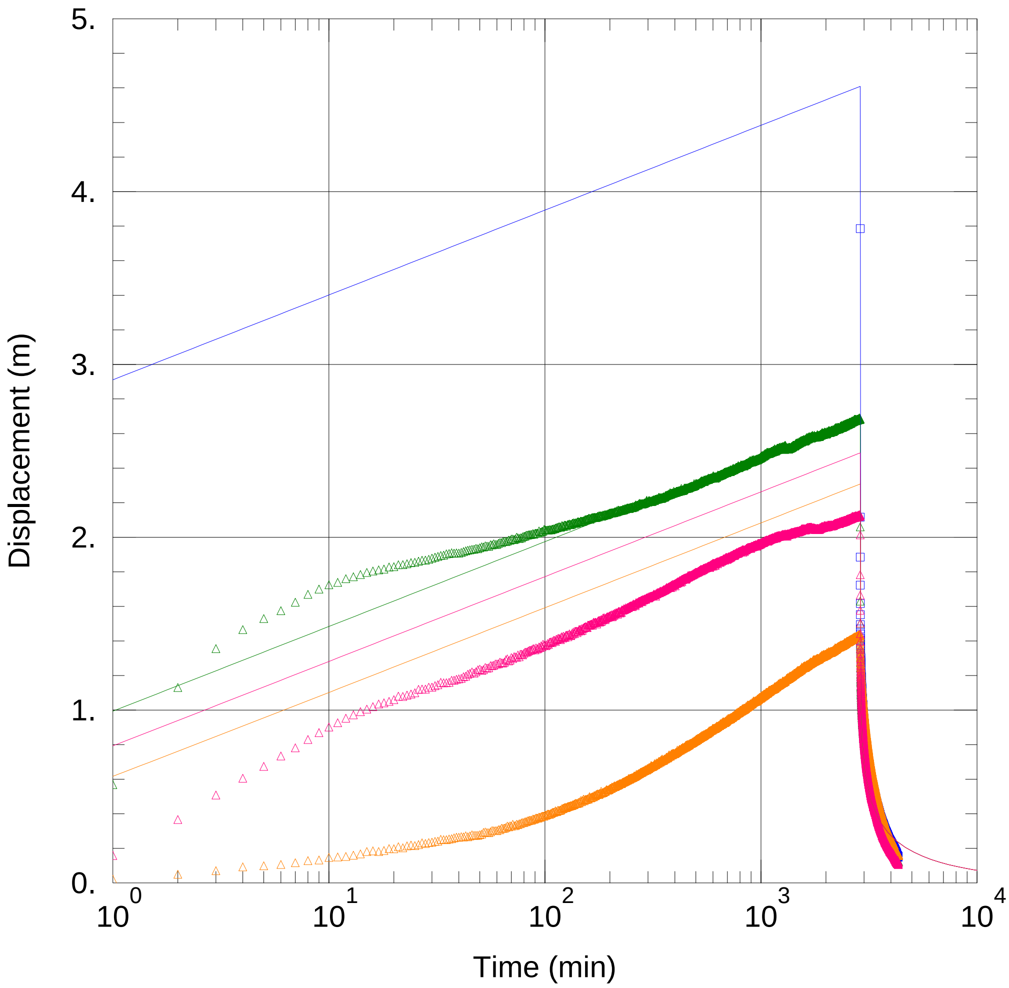
Observation Wells

Well Name	X (m)	Y (m)
□ P3/1	0	0

BGR

Aquifer Test P3 - Makeni

Prepared By: GReSP	Prepared For: DWA
Project: GRESP - Phase 2	Location: Makeni (Kafue District)



Data Set: Z:\...\CDT_Makeni_P3-3.aqt
Date: 05/14/12 Time: 11:42:22

SOLUTION

Aquifer Model: Confined
Solution Method: Theis

T = 455.4 m^2/day S = 3.712E-5
Kz/Kr = 1. b = 30. m

WELL DATA

Pumping Wells

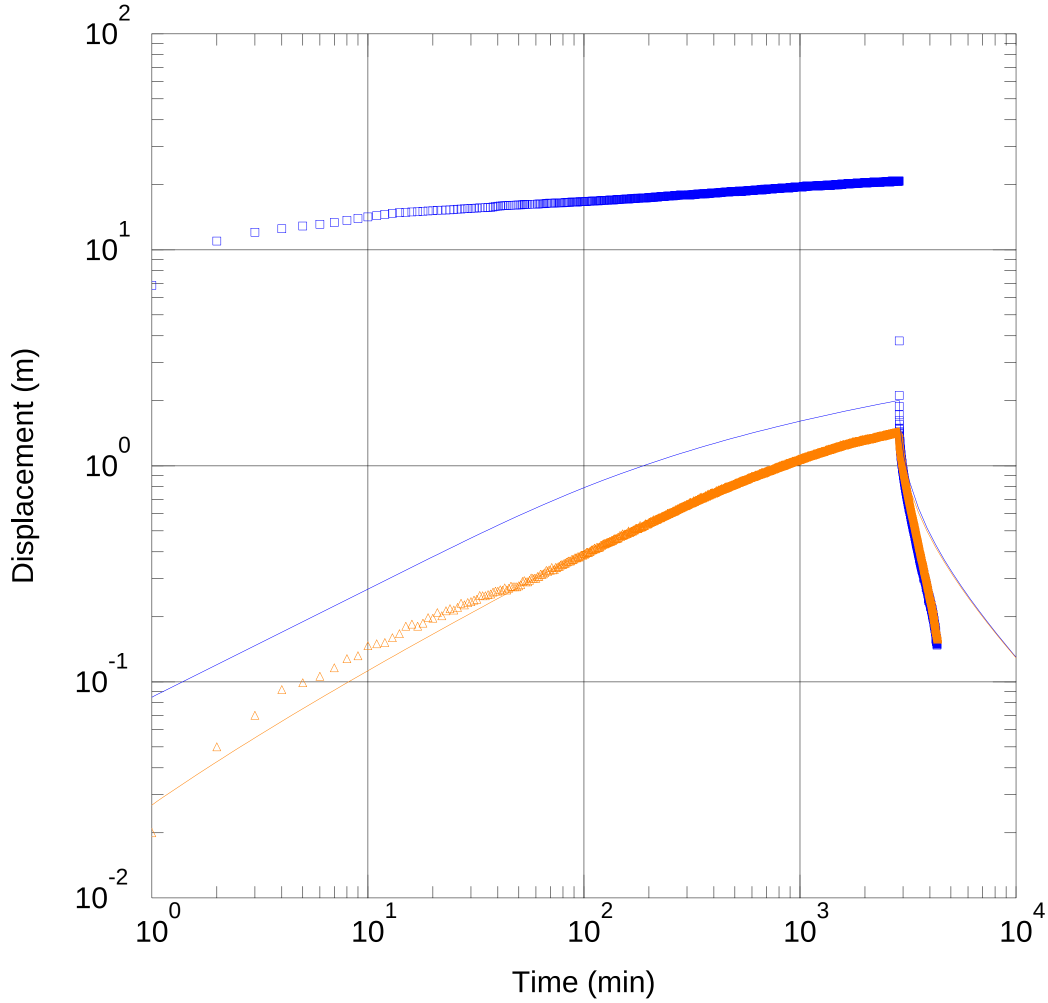
Well Name	X (m)	Y (m)
P3/1	0	0

Observation Wells

Well Name	X (m)	Y (m)
□ P3/1	0	0
△ P3/3	13.5	0
△ P3/4	33.1	0
△ P3/5	21.7	0

Aquifer Test P3 - Makeni

Prepared By: GReSP	Prepared For: DWA
Project: GRESP - Phase 2	Location: Makeni (Kafue District)



Data Set: Z:\...\CDT_Makeni_P3-4.aqt
Date: 05/14/12 Time: 12:29:55

SOLUTION

Aquifer Model: Fractured
Solution Method: Gringarten-Witherspoon w/vertical fracture

Kx = 8.43 m/day Ss = 0.001413 m^{-1}
Ky/Kx = 1. Lf = 65.29 m

AQUIFER DATA

Saturated Thickness: 30. m Fracture Length: 65.29 m

WELL DATA

Pumping Wells

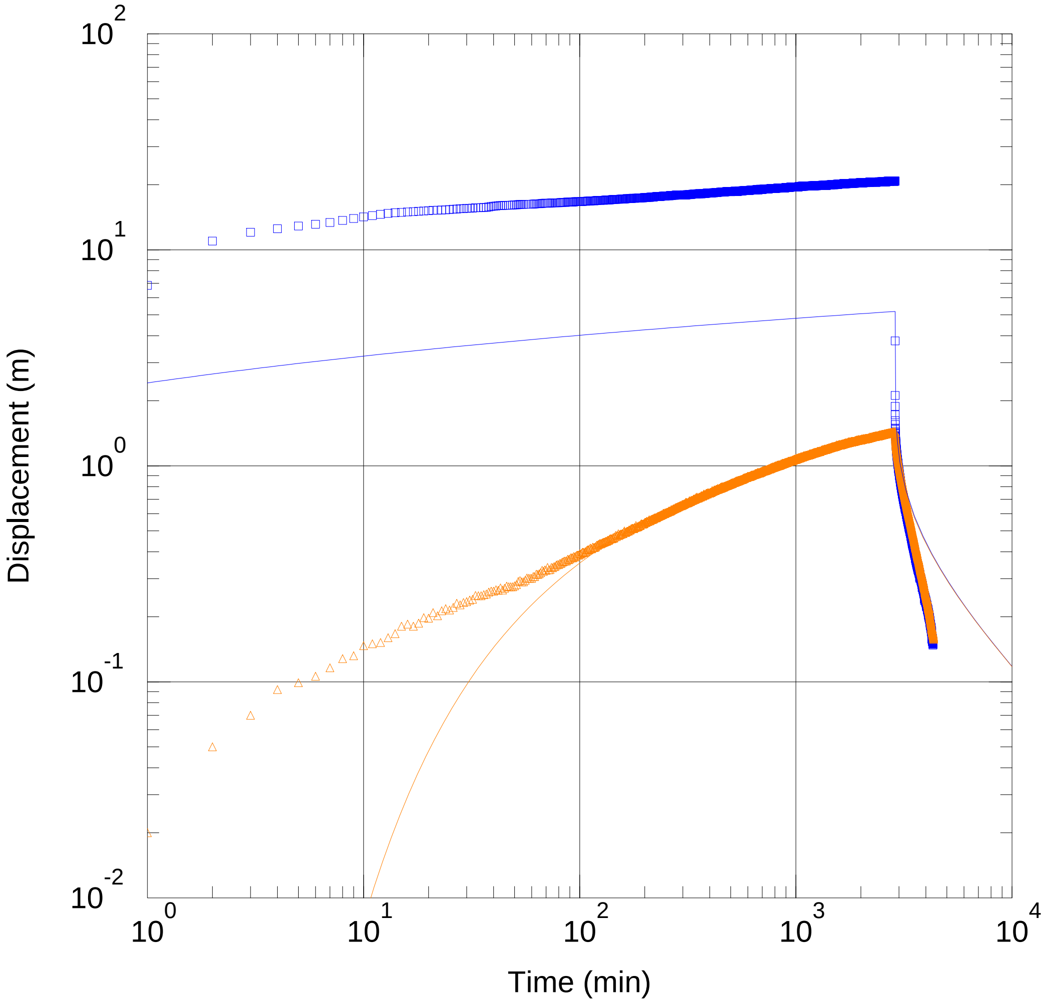
Well Name	X (m)	Y (m)
P3/1	0	0

Observation Wells

Well Name	X (m)	Y (m)
□ P3/1	0	0
△ P3/4	33.1	0

Aquifer Test P3 - Makeni

Prepared By: GReSP	Prepared For: DWA
Project: GRESP - Phase 2	Location: Makeni (Kafue District)



Data Set: Z:\...\CDT_Makeni_P3-4.aqt
Date: 05/22/12 Time: 16:14:03

SOLUTION

Aquifer Model: Confined
Solution Method: Theis

T = 279.6 m^2/day S = 0.0183
Kz/Kr = 1. b = 30. m

WELL DATA

Pumping Wells

Well Name	X (m)	Y (m)
P3/1	0	0

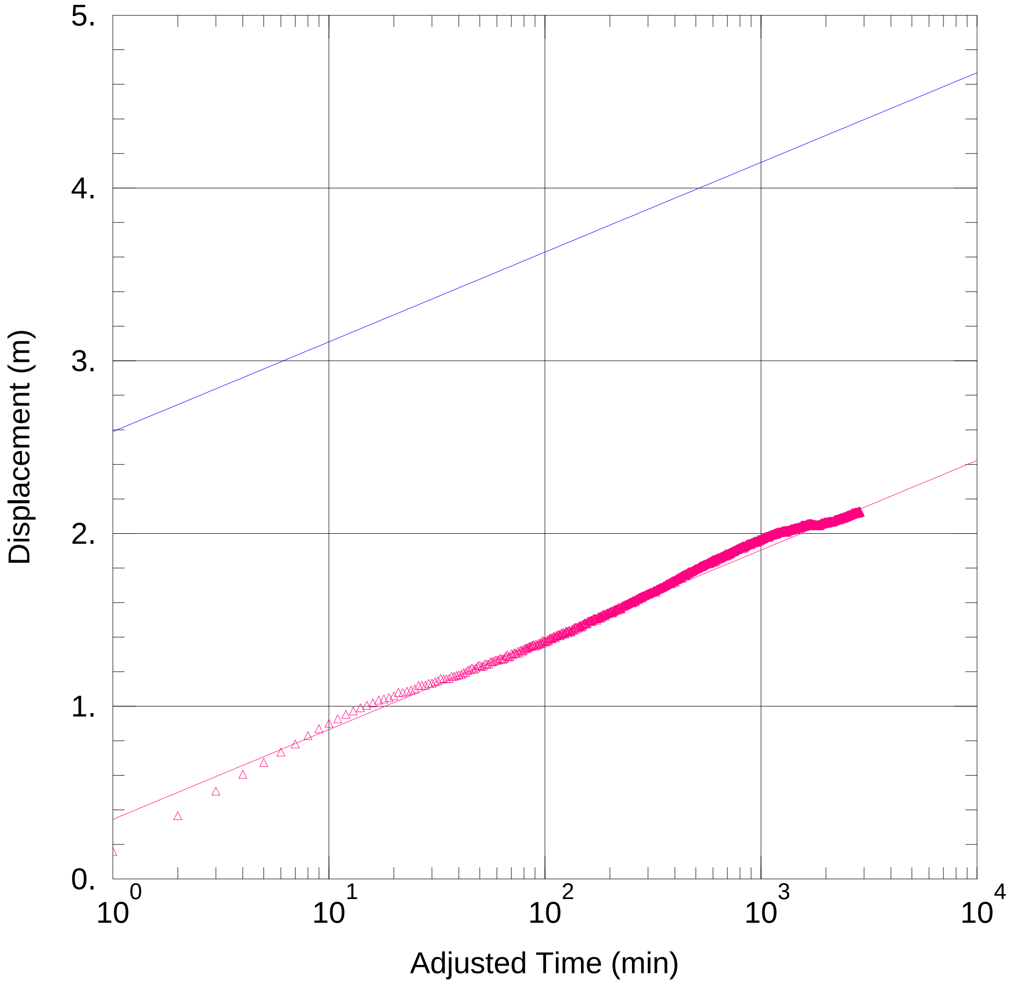
Observation Wells

Well Name	X (m)	Y (m)
□ P3/1	0	0
△ P3/4	33.1	0

BGR

Aquifer Test P3 - Makeni

Prepared By: GReSP	Prepared For: DWA
Project: GRESP - Phase 2	Location: Makeni (Kafue District)



Data Set: Z:\...\CDT_Makeni_P3-3.aqt
Date: 05/14/12 Time: 11:44:19

SOLUTION

Aquifer Model: Confined
Solution Method: Cooper-Jacob

T = 430.3 m^2/day S = 0.0003097

AQUIFER DATA

Saturated Thickness: 30. m Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (m)	Y (m)
P3/1	0	0

Observation Wells

Well Name	X (m)	Y (m)
□ P3/1	0	0
△ P3/5	21.7	0

BGR

Annex 5

HYDROCHEMICAL RESULTS

Site ID		P1/3	P2/2-1	P3/1-1
Name		Katete	Kasanova	Makeni
K	mg/l	1.60	0.70	0.70
Na	mg/l	40.50	17.30	12.60
Mg	mg/l	35.80	26.50	26.90
Ca	mg/l	82.00	100.00	101.00
Cl	mg/l	1.16	36.60	21.60
SO4	mg/l	20.80	23.90	8.59
HCO3	mg/l	516.00	375.00	428.00
NO3	mg/l	7.22	25.00	18.10
NO2	mg/l	0.016	0.012	-0.003
NH4	mg/l	-0.01	-0.01	-0.01
Fe(II)	mg/l	0.034	0.033	0.009
Mn	mg/l	0.009	0.004	0.001
F	mg/l	0.733	0.14	0.336
Br	mg/l	0.003	0.025	0.015
PO4	mg/l	-0.03	-0.03	-0.03
Al	mg/l	-0.003	-0.003	-0.003
As	mg/l	-0.02	-0.02	-0.02
BO2	mg/l	0.02	0.01	0.02
Ba	mg/l	0.048	0.017	0.025
Be	mg/l	-0.0005	-0.0005	-0.0005
Cd	mg/l	-0.002	-0.002	-0.002
Co	mg/l	-0.003	-0.003	-0.003
Cr	mg/l	-0.003	-0.003	-0.003
Cu	mg/l	-0.003	-0.003	-0.003
Li	mg/l	-0.003	-0.003	-0.003
Ni	mg/l	-0.003	-0.003	-0.003
Pb	mg/l	-0.02	-0.02	-0.02
Sc	mg/l	-0.001	-0.001	-0.001
SiO2	mg/l	21.1	5.5	17.3
Sr	mg/l	0.43	0.103	0.214
Ti	mg/l	0.001	0.001	0.001
V	mg/l	-0.003	0.003	-0.003
Zn	mg/l	0.017	0.011	0.188