REPUBLIC OF BOTSWANA
DEPARTMENT OF WATER AFFAIRS

BOTLHAPATLOU GROUNDWATER EXPLORATION AND WELLFIELD DEVELOPMENT PROJECT

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Final Report

Final

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Presented by

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LIST OF ABBREVIATIONS

ACL	Analytical Compu-Log
AIA	Archaeological Impact Assessment
BH	borehole
CFCs	chlorofluorocarbons
CKP	Central Kalahari Project
Cl_{gw}	chloride in groundwater
Cl_{wap}	chloride in precipitation
CMB	Chloride Mass Balance
cps	counts per second
CRT	Constant Rate Test
CTD	Conductivity, Temperature, Depth
DC	Direct Current
DD	drawdown
DGPS	Differential Global Positioning System
DGS	Department of Geological Survey
DSM	Department of Surveys and Mapping
DTH	down the hole
DWA	Department of Water Affairs
E	east
EC	electrical conductivity
EIA	Environmental Impact Assessment
ENE	east northeast
ESE	east southeast
ESRI	Environmental System Research Institute
ETM	Enhanced Thematic Mapper
FC	Flow Characteristics
FCC	false colour composite
Formation	Formation
g/cm^3	grams per cubic centimetre
GIS	Geographic Information System
GPS	Global Positioning System
GRES	Groundwater Recharge Evaluation Study
hrs	hours
ILWIS	Integrated Land and Water Information System
km^2	square kilometres
m^2/d	square metres per day
m^2/hr	square metres per hour
m^3/hr	cubic metres per hour
Ma	millions of years before present
Mag	magnetic
mbgl	metres below ground level
mg/l	milligrams per litre
mm	millimetres
mm/a	millimetres per annum
mm/yr	millimetres per year
MoA	Ministry of Agriculture
mV	millivolts
NDVI	Normalised Difference Vegetation Index

NE	northeast
NGIS	National Geographic Information System
NIR	Near Infrared
NNW	north northwest
NW	northwest
ohm-m	ohm metre
P	precipitation
PCL	portable Compu-Log
pmc	percent modern carbon
R	recharge
RAD	Remote Area Dweller
RS	remote sensing
RWL	rest water level
RVWSP	Rural Village Water Supply Programme
S/cm	siemens per centimetre
SADC	Southern Africa Development Community
SE	southeast
SP	spontaneous potential
SSE	south southeast
SW	southwest
TDEM	Time Domain Electromagnetic
TDS	total dissolved solids
TGLP	Tribal Grazing Lands Policy
T, S	Transmissivity, Storativity
TU	tritium units
S/cm	micro siemens per centimetre
USGS	United States Geological Surveys
UTM	Universal Transverse Mercator
VES	Vertical Electrical Sounding
WCS	Wellfield Consulting Services Pty Ltd
WGS	World Geodetic System
WMA	Wildlife Management Area
WNW	west of northwest
WRC	Water Resources Consultants Pty Ltd
W/S	water strike
WSW	west southwest
"	inches
%	percent
~	approximately
0/00	per millilitre
^{0}C	degrees Celsius
^{13}C	Carbon 13
^{14}C	Carbon 14
^{18}O	Oxygen 18
^{2}H or D	Deuterium
3-D	three dimensional
^{3}H or T	Tritium

1. INTRODUCTION

1.1 Background

In Botswana groundwater is undoubtedly the fundamental natural resource required in any sustainable approach to development in the sandveld areas. Unfortunately, the semi-arid and increasingly variable climatic conditions prevailing in country provide only limited and sporadic replenishment of this vital natural resource, with the result that Botswana’s potentially available and sustainable water resource options are seriously restricted. The sustainable utilisation, protection and management of the nation’s water resources are thus imperative if the country is to continue to thrive.

It is against this background that groundwater resources have traditionally supplied most of Botswana’s rural water needs. However, in utilising groundwater as a primary, and often sole, water source the challenge lies in adequately quantifying the resource and its sustainability when used for long term supply and thereafter providing potable, reliable and affordable water to rural communities to contribute to regional and national development.

The Botlhapatlou Groundwater Resources Exploration and Development Project thus constitutes a component of the continuous and commendable effort being made by the Government of Botswana Department of Water Affairs to implement this Policy and to address the issue of water supply in the rural areas of the country. The project is designed to contribute to both national and regional socio-economic development by the provision of an adequate quantity of suitable quality water for human sustenance.

The significant groundwater potential of the Ecca sedimentary strata forming the southern margins of the Central Kalahari Karoo Basin has been identified and explored by various projects over the past 30 years, with major development work resulting in two highly productive wellfields that now provide that main source of supply to the diamond mining town of Jwaneng and the Kweneng District administrative centres of Molepolole Thamaga and the Botswana Defence Force (BDF) Thebephatshwa air base.

The Gaotlhobogwe Wellfield in the southern part of the project area was developed during the mid-1990’s initially as the supply for Thebephatswa BDF air base and subsequently as the principal supply for Molepolole and Thamaga villages. The Gaotlhobogwe Wellfield has since been slightly expanded and re-developed but despite this the relatively restricted wellfield is now not able to keep pace with rising demand and is becoming over-exploited. The ToR indicates that the 2016 water demand for Molepolole, Thamaga and the surrounding villages is approximately14,000 m^3/day whereas the sustainable available resource is estimated at 7,300 m^3/day. At the time of ToR compilation the abstraction rate of 5,600 m^3/day from the Gaotlhobogwe Wellfield, was estimated and it was apparent that the sustainable yield will be surpassed unless additional resources are developed.

As a result a new (or expanded) wellfield source is required to be explored, quantified and developed. The most obvious potential wellfield area is that identified by BRGM in the mid-1990’s in the same Ecca aquifer in the Malwelwe area, some 20 kms to the north of Gaotlhobogwe, but this particular zone may not, by itself, be the best or only possible wellfield area that will be required to satisfy the long term and ever escalating water demand of Molepolole and Thamaga as well as other growing villages in this region of Kweneng District.

In order to ensure that other possible resource areas as well as Malwelwe are examined, the DWA Terms of Reference (ToR) have thus very sensibly defined a very large project area (Figure 1.1) that is essentially centred on Malwelwe but which encompasses the whole of the Karoo basin margin sub-crop between longitudes 260000 and 400000 and also includes a portion of the Upper Karoo Lebung Group strata which elsewhere in the country constitutes a very important aquifer.

In the Project Area current supply sources are largely village specific with different boreholes supplying different villages by various transmission systems. The exceptions are Molepolole and Thamaga villages which are outside the project area but which draw water supplies from within it. With increasing demand from other villages such as Letlhakeng, Kudumelepye, Salajwe, Hatsalatlhadi and Boatlaname to the north, a comprehensive resources quantification and a co-ordinated groundwater resources development in this project area is thus imperative if the groundwater resource is to be conserved and managed successfully.

1.2 Overview of Project Objectives

As stated in the Terms of Reference, the ultimate goal of the Botlhapatlou Groundwater Exploration and Development Project is to develop the groundwater resources of the region to meet the future water supply to Molepolole, Thamaga, Thebephatshwe BDF camp and the surrounding villages of Letlhakeng, Khudumelabjwe, Hatsalatladi, Salajwe, Ngware, Malwelwe and others.

The Terms of Reference state that the specific objectives of the project are as follows:

- *To collect, collate, analyse and review all relevant geological, geophysical, remote sensing data, hydrochemical and hydrogeological data in that project area with a view to produce an Inception Report detailing a comprehensive wellfield development strategy*
- *To select target areas based on the above for geophysical investigations*
- *To site 10 exploration boreholes to cater for data gaps and site 25 production borehole using appropriate groundwater investigation techniques*
- *To prepare documents for drilling and test pumping of boreholes*
- *To supervise the drilling , construction, and test pumping of all drilled exploration and all production boreholes, supervise the test pumping of existing 8 production boreholes and to determine the hydraulic properties of the aquifer for use in the quantification of the available resources*
- *To survey and determine in terms of X, Y and Z coordinates the exact location and elevation of all newly drilled boreholes and other existing boreholes in the investigated area by any appropriate levelling technique (accuracy of 1m in Z and Y direction and 0.1m in Z direction). The aim of this exercise is to facilitate the generation of data for input into the groundwater resources model.*
- *To set up a hydrogeological monitoring network in the project area by the purchase and installation of data loggers and rain gauges. The aim is to compliment the existing network and where appropriate, a complete groundwater monitoring network, hydrometeorological stations and water quality monitoring network and programme with the objectives to:*
    - *i. Determine the groundwater flow pattern*
    - *ii. Assess the groundwater pollution potential*
    - *iii. Continuously follow the magnitude of groundwater abstraction*

  iv. *Monitor the response of water levels to abstraction and climatological response*

- *To review the available recharge data with a view to determine the spatial and temporal groundwater recharge distribution and mechanisms of the area and carryout recharge measurements to elucidate and refine recharge for use in the quantification of groundwater resources.*
- *To develop a computer based groundwater model to determine the groundwater resources under different pumping scenarios and to determine the most efficient design for new wellfields. To assess and review the groundwater resources in the existing wellfield areas (Gaotlhobogwe and Botlhapatlou). The groundwater model should have a journal detailing all the parameters used to quantify the groundwater resource. The model should also be subjected to peer review and audit by a recognised institute with a proven track record so as to cross check the accuracy and reliability.*
- *To propose the most cost effective water supply routes to deliver water to the demand centres and their estimated cost.*
- *To report all findings, conclusions and recommendations in the following reports:*
    i. *Inception Report is to be produced before the fieldwork starts based on the analysis of the data available. The report will also summarise the technical approach to be adopted when the project commences*
    ii. *Regular monthly progress reports outlining the progress of the project, obstacles and milestones*
    iii. *Final report summarising and highlighting the salient features of the findings and recommendations of the project. Together with this report an executive summary will be required.*

In order to achieve these objectives the nature, distribution and hydraulic properties of the various aquifers and the quality, quantity and replenishment potential of the groundwater contained within them, has been delineated to the best possible level of confidence. This has been undertaken by the interpretation of both airborne and ground geophysical surveys, exploration drilling, aquifer testing, hydrochemical and isotope data evaluation and a variety of other complementary activities. Following the identification and evaluation of potential source areas production boreholes have been installed during the later stages of the project and the engineering and financial aspects of development of these resources has been assessed.

The successful achievement of the primary goal of the project has required the application of a variety of investigation techniques to satisfactorily resolve the critical questions of aquifer distribution, aquifer geometry and hydraulic parameters, recharge potential and water quality, optimum abstraction technology, and resource quantification.

1.3 Report Structure

This Final Report contains the integrated results and conclusions pertaining to the evaluation of the groundwater potential of the Project Area with specific reference to groundwater resources investigation and developments that have emanated from Project activities undertaken during the period November 2008 to August 2011.

The Final Report constitutes a stand-alone document, but a series of Technical Reports, as listed in the Table of Contents, have also been produced and contain the bulk of the Project data sets. These Technical Reports include reports covering regional geology, geophysical interpretation, ground geophysical siting surveys, exploration drilling and test pumping, hydrochemistry, groundwater modelling and monitoring, remote sensing, recharge and geomorphology, as well as a comprehensive Project Data Book. These comprehensive Technical Reports are referenced wherever necessary throughout the Final Report and only illustrative data set is thus included herein.

Chapters 1 and 2 of the Final Report provides the background, objectives and physical setting of the Project, together with a summary of prior information relating to previous studies and the geological and hydrogeological environment of the Project Area.

Chapter 3 details the activities undertaken and the results of the Inception Phase, initial existing data compilation and review.

Chapter 4 presents the conceptual models of the sub-regional aquifers as defined from the Inception Phase, and discusses the critical aquifer parameters and the potential for groundwater replenishment.

Chapter 5 presents details of the Exploration Programme activities, namely the geophysical surveys, the exploration drilling and test pumping and geophysical borehole logging. It also brings together a hydrogeological evaluation of the aquifers, hydrochemistry, groundwater recharge and monitoring information, as well as the discussion realting to the selection of Production Target Zones for potential development.

Chapter 6 presents a comprehensive evaluation of the hydrogeological regime of the project area, including a detailed discussion of aquifer distribution, hydrochemistry, groundwater potability and groundwater recharge derived from data gathered during the Exploration Programme.

Chapter 7 documents the resources development (production borehole) stage of the Project, including additional geophysical surveys, drilling and testing results, and final production borehole details.

Chapter 8 presents an evaluation of groundwater potential and a quantification of regional groundwater resources as derived from the numerical groundwater model, as well as a full discussion of the predictive abstraction modelling and the regional water balance.

Chapter 9 sets out a development strategy, including matching supply and demand, a preliminary engineering option and cost estimates, and the requirement for resource monitoring.

Chapters 10 and 11 contain a summary of recommendations and conclusions followed by a list of references used during the preparation of the Main Final Report.

1.4 Project Area Physical Setting

The Project Area is situated on the edge of the central zone of the ‘Kalahari Desert’, a vast area of arid to semi-arid terrain of subdued dune landscape with largely north-south trending fossil local drainage zones with large patches of grassland amidst extensive thorn scrub vegetation. Wildlife is common, and free-range cattle rearing is the most widespread agricultural activity.

1.4.1 Location and Access

The Botlhapatlou project area is in Kweneng District and is located some 80 kilometres northwest of Gaborone. Jwaneng is some 50km southeast of Letlhakeng which is situated in the south-centre of the project area.

The project area (Figure 1.1) extends from the village of Kweneng in the east all the way to Salajwe in the west and is approximately 8,500 km^2 in size. The Terms of Reference indicates that the size of the Project Area has been determined largely by the extent of the Ecca sandstone aquifer in relation to existing wellfields and water demand centres. Most of the areas occupied by private Tribal Grazing Land policy (TGLP) farms to the west have been left out.

Access to the project area is by tarred road from Gaborone northwest to Molepolole and Letlhakeng, with tarred roads also running from Molepolole northwards via Boatlaname and Lephephe to Serowe, and from Letlhakeng westwards via Maboane and Takotokwane to the Trans Kalahari highway and Ghanzi. Good gravel roads also connect Letlhakeng to the Khutse Game Reserve in the northwest via Khudumelabjwe and Salajwe, as well as from Hatsalatladi to Diphuduhudu via Ngware. Khudumelapye-Diphuduhudu villages are connected by sandy tracks and cut lines. The remainder of the area is well served by a number of straight sand tracks that were originally coal exploration traverse lines (Shell Coal, 1997) as well as by a multitude of tracks which link cattle posts, lands area and smaller village communities.

1.4.2 Topography

The project area is situated to the north and northwest of the hilly area around Molepolole and is relatively flat, sloping gently to the west and northwest towards the centre of the Kalahari Basin at an average gradient of less than 2.5m/km. The most striking variations in topography are the relatively deeply incised Meratswe and Kohiye valleys of the fossil Kalahari internal drainage system, which during previous pluvial periods formed part of the central Kalahari/Makgadikgadi drainage. These valleys are most pronounced in the Letlhakeng area (Gaotlhobogwe Valley) where the fossil valley is deeply incised some 20 - 30m below the general terrain surface with ‘cliffs’ of calcrete and silcrete being very evident.

The remainder of the project area has virtually no significant topographical variation except in the immediate vicinity of pans, where elevation changes as a result of pan deflation and adjacent dunes formation are evident. Over much of the area average elevations above sea level are between 1100m and 1190m and decrease from the SE to the NNW, although around Salajwe village elevations are slightly lower and range between 1000 and 1050 mamsl (Map 1).

1.4.3 Geomorphology (dunes, pans, drainage)

Dunes

Sand dunes are aeolian depositional landforms and are usually characteristic of semi-arid and arid environments such as the Kalahari. They vary both in size and form. In the Kalahari, Thomas and Shaw (1991) report that six types of dunes are found, namely parabolic dunes, blowouts, barchan dunes, transverse ridges, linear ridges and seif dunes. Linear dunes are said to be the most prevalent forms in the Kalahari.

In the Project Area there are no active sand dunes. The sand dunes appear to have been degraded and are currently covered with vegetation. The dunes were not visible on the satellite image covering the Project Area. Therefore it is not possible to determine with certainty the types of the existing fossil sand dunes in the area. In few areas, however, linear ridges can be observed in the field. In addition, in areas covered by the 1:50,000 topographic maps the presence of lunette dunes on the southwest or southern margins are indicated on the southwest or southern margins of some pans. According to Thomas and Shaw (1991), this is indicative of the fact that the prevailing winds during their formation were from the northeast.

Pans

Many pans exist in the Project Area and the surrounding region. Morphologically, the pans are shallow depressions with usually a hard sub-surface layer of calcrete, silcrete or clay. In Southern Africa they are characteristic of semi-arid and arid environments with low relief. During heavy rainfall events, local runoff collects in these pans for relatively long periods of time. As a result, pans are usually good (albeit temporary) sources of water and salts for the wildlife and cattle in such areas.

In the project area pans range in size from $0.25m^2$ to $3.25m^2$ and are either round or elongate in shape. Linear-shaped pans are not prevalent in the project area. Around the Botlhapatlou-Letlhakeng (Malwelwe) area, the general pan orientation is NW-SE and to a lesser extent N-S. Elsewhere, pan orientation cannot be established as they are either too small or round in shape.

In the Salajwe area to the northwest, the village itself is located within an N-S trending pan bound by a relatively low sand ridge on the eastern fringe.

Within and around some of the pans, shallow perched aquifers have been observed at depths of around 2.4m (eg Legape Pan). The hard subsurface layer of calcrete, silcrete or clay lining the bottom of the pans enables surface runoff during the rainy season to collect and be retained for relatively long periods.

Surface Drainage

Generally, the Kalahari environment is poorly endowed with surface water. This is largely due to the semi-arid/arid climatic conditions of this region. The sandy soils that cover much of the Kalahari sandveld also contribute towards the poor surface water occurrence in the area due to their inadequate water retention capacities.

The eastern and southeastern Kalahari, where the Project Area lies, is dominated by a broad, featureless interfluve at 1030-1240 metres above sea level, which has been termed the ‘Kalahari-Zimbabwe Rise’ (Thomas and Shaw, 1991) (or ‘Kalahari-Zimbabwe Upwarp’ in other texts). This feature trends approximately NNE/SSW from Molepolole through Serowe and to the east of Francistown into Zimbabwe and marks the approximate easterly limit of the Central Kalahari Basin and the Kalahari Group sediments, although lying slightly to the west of the actual physical margin of these deposits.

The Kalahari-Zimbabwe Upwarp separates the endoreic drainage system of the ‘Middle Kalahari’ (Thomas and Shaw, 1991) Okavango-Makgadikgadi internal basin from the Limpopo River and its Botswana tributaries (Lotsane, Motloutse, Serorome, Shashe), which drain eastwards ultimately to the Indian Ocean. These Limpopo tributaries that drain eastwards from this major surface water divide are largely active but ephemeral rivers that can have significant flow during periods of prolonged heavy rainfall and several (Shashe; Motloutse; Lotsane) are utilise by dams that contribute to the national water supply system. On the eastern side of the Kalahari-Zimbabwe Upwarp in the project area around Medie and Kweneng, drainage is south easterly and northerly into the Serorome system which flows north and then east into the Limpopo.

On the western side of the Kalahari-Zimbabwe Upwarp the Okavango-Makgadikgadi internal drainage is represented in the project area by a number of N and NNW trending dry valleys that under current climatic conditions very rarely carry any flow except over a short distance in relation to intense precipitation. They are thus commonly termed ‘fossil valleys’. These dry valleys are locally known as mokgacha (plural: mekgacha) (Thomas and Shaw (1991). According to Thomas and Shaw the mekgacha may have been formed by fluvial erosion during periods of wetter climate, though precise mechanisms for this erosion are not cited. It is also proposed that the morphology of the gorge sections of the mekgacha (eg Gaotlhobogwe) may have been formed as the result of deep weathering along preferential groundwater flow paths that may be structurally controlled, set against a background of long-term uplift of the Kalahari rim.

The Gaotlhobogwe/Meratswe valley is the largest and most pronounced mekgacha, which in the Letlhakeng area in particular is deeply incised. Elsewhere in the project area are the less pronounced Dikgonnyane, Kohiye and the Mmaporoka fossil valleys. All are northerly trending except the Kohiye valley which is north westerly trending.

The mekgacha may be useful in terms of understanding groundwater availability in the Kalahari. Thomas and Shaw observe that historically studies like that by Chapman in 1886 have indicated an association between the mekgacha and groundwater availability. As a result, this has led to the establishment of wellfields in valleys such as Naledi (Jwaneng Northern Wellfield) and Gaotlhobogwe. Furthermore, Thomas and Shaw also indicate that the mekgacha alignments are likely to be a principal method of recharge in the Kalahari Group strata as a whole.

Soil

The soil mapping has only covered 50 % of project area. The most common soil type occurring in the project is known as Kastanozems. The main constraint of Kastanozems is linked to the dry climate in which they generally occur and their dense packing, which results in a 'dead dry horizon' below the limit of wetting-front. Kastanozem soils have relatively high levels of available calcium ions bound to soil particles. These and other nutrient ions move downward with percolating water to form layers of accumulated calcium carbonate or gypsum.

They are also susceptible to erosion, and some suffer from high sodicity (sodium-rich) and the periodic lack of soil moisture and very little groundwater recharge is the main disadvantage of Kastanozems. Extensive grazing is an important land use on Kastanozems because the soils are usually covered by savannah type of vegetation (FAO, 1988).

The spatial distribution of soil types can have a significant influence on groundwater recharge and surface run-off and so the information on soils is crucial in trying to elucidate groundwater flow dynamics. Although soil characteristics are a key variable in groundwater projects, in-situ soil parameters are often not available and the use of soil maps in conjunction with remote sensing and GIS offer an alternative where ground data is absent. In consequence, careful calibration of remote sensing data and soil types is necessary to obtain meaningful soil moisture information.

1.4.4 Climate

Rainfall

Rainfall in the project area is best described as 'erratic' and is generally low to very low (from a high of 480mm to a low of 147mm between 1959 and 2006), with an average rainfall of approximately 420mm/yr with annual variation as high as 35% (Bhalotra, 1987). Most rainfall falls during the summer months of October to March when temperatures are highest and it is often characterised by highly localised intense storm events. However, this general seasonal rainfall pattern may change drastically during drought periods.

Precipitation data recorded by the Department of Meteorological Services from 1978 to 2006 at a significant number of rainfall stations around the Project Area indicate that the long-term mean annual rainfall (Figure 1.2) ranges from 35 to 860 mm/a. However, the amount of rainfall that falls over the area is highly variable both in spatial and temporal terms. For instance, in 2000 Botlhapatlou village, which is about 15 kilometres from Hatsalatladi, received 793.8 mm of annual rainfall whereas the latter only received 111.3 mm (See Table 1.1). Similarly, Molepolole received 851.6 mm of annual rainfall in 1997 while Khudumelapye only received 53.2 mm (the two villages are separated by a distance of about 75 kilometres). That Botlhapatlou village received 651.3 mm of rainfall in 2001 only to drop to 94.7 mm in 2002 also clearly illustrates the temporal and spatial variation of rainfall in the area.

Table 1.1 Total Annual Rainfall (mm) from Stations in Project Area

Year	Weather Station										
	Molopolole	Letlhakeng	Boatlaname	Lephephe	Moshupa	Ngware	Salajwe	Botlhapatlou	Hatsalatladi	Sesung	Khudumelapye
1978	656.8	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1979	425.1	444	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1980	499.1	475.6	196.3	N/A	N/A	220.2	215.9	N/A	N/A	N/A	252
1981	541.5	478.6	233.7	N/A	N/A	374.8	16.7	N/A	N/A	N/A	511
1982	351.7	502.6	340.5	N/A	N/A	435.9	243.3	N/A	N/A	N/A	164
1983	243.8	263.2	117.9	N/A	N/A	297.7	28	N/A	N/A	N/A	120
1984	210.6	155.8	61.8	N/A	N/A	250.3	N/A	N/A	N/A	N/A	67
1985	152.5	230.6	38.3	62.8	N/A	157.1	N/A	36.1	N/A	N/A	53.8
1986	344.8	367.4	205.3	343.4	188.7	522.1	70.7	66.6	N/A	N/A	N/A
1987	243.1	66.6	320.9	294.4	329.3	286.8	96.2	260.4	173	N/A	N/A
1988	502.3	371.3	115.9	469.2	568.7	472.2	184.7	542.1	531	N/A	239
1989	467.7	257.4	363.3	563.8	422.7	510.2	N/A	628.1	432	267.5	N/A
1990	296.5	383.9	399.1	299.5	302	451.8	N/A	390.5	275	333	1
1991	437.8	408.1	241.4	403.3	537.7	396.6	N/A	578.1	378	N/A	N/A
1992	254.4	146.5	234.6	178.3	24.5	391.2	N/A	303.2	232	N/A	N/A
1993	298.3	207.6	229.7	275.3	59.6	329.7	N/A	414	205.1	N/A	88
1994	362.8	217.8	334.9	308.2	591.4	371	44	398.1	280.8	N/A	N/A
1995	405.7	238.3	353.2	267.9	690.6	327.7	N/A	496.8	503.5	N/A	N/A
1996	569.2	351.6	323.8	410.9	696.9	409.7	N/A	498	447.3	N/A	13.2
1997	851.6	365	180	459.8	702.2	357.8	0	641	431.5	N/A	53.2
1998	453.5	403.9	91.3	326.7	332.2	162.6	N/A	348.4	66.3	N/A	262.5
1999	313.5	244.4	304.4	216.4	651.7	352.1	N/A	295.6	54.3	140.7	121.3
2000	762.5	631.5	641.5	585	859	567.9	22	793.8	111.3	N/A	395
2001	639.5	418.8	402.7	482.4	159.7	455.3	415.1	651.3	255.9	165.2	5.1
2002	149.5	58	191.9	110.5	288.7	330.9	247.1	94.7	292	215.3	N/A
2003	417	166.2	165.6	135.1	407.8	328.5	216.1	259.9	325	61.8	N/A
2004	511.4	355.1	245.1	215.7	67.2	425.2	360.6	191.5	N/A	27	N/A
2005	349.2	237.6	N/A	123.4	188.7	202.1	333.4	106.5	N/A	0	N/A
2006	467	505.6	N/A	326	N/A		530	114.6	N/A	153.8	N/A
2007	277.7	387.7	269.6	N/A	N/A	197.9	87.7	233.3	N/A	N/A	72.3
2008	563	601.5	649.9	N/A	N/A	335.2	415.1	376.3	N/A	N/A	120.9
2009	624.5	322	55.4	N/A	N/A	N/A	112	N/A	N/A	N/A	N/A
2010	392	401.5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

N/A: Data missing or not available
Source: Department of Meteorological Services, Gaborone).

In general mean annual rainfall (Figure 1.2) decreases from the east to the west and most usually falls as high intensity storms. A summary of the rainfall data for few selected monitoring centres in Project Area is given in Table 1.1 above.

Temperature

Climatically, the project area is a semi-arid desert environment. The summers (October to March) are hot (>35°C) and winter temperatures frequently fall below 5°C and may be accompanied by frost during the months of June-August. No temperature data is available for the meteorological stations in the project area.

Potential evapotranspiration rates (PET) are high during summer months and are almost always considerably in excess of any precipitation which may be expected.

1.4.5 Vegetation

The preliminary vegetation study carried out in this Project with the use of remote sensing shows that the area is sparsely vegetated as shown in Figure1.3. The study by Weare and Yalala (1971) shows that the Project area is covered by shrub and tree savannah. The eastern part of the area is covered by shrub savanna and the western by tree savannah. The vegetation types identified in the area by their study are as follows:

- Northern Kalahari Tree and Bush Savannah,
- Central Kalahari Bush Savannah,
- Southern Kalahari Bush Savannah, and
- Arid Sweet Bushveld.

About 90 percent of the area is covered by *Terminalia sericea, Lonchocarpus nelsii/Acacia erioloba* (Timberlake, 1980) species association in the sandveld areas. In contrast a *Peltophorum africanum, Acacia tortilis, Acacia karoo/Ziziphus mucronata* association is found in the western hardveld areas.

1.5 Socio Economic Setting

1.5.1 Population

The current population of the villages and small settlements within the Project Area has been estimated to be approximately 104,424 people, projected to rise to some 164,875 people over the next 10 years by 2020. Outside the villages the population is sparsely distributed amongst minor settlements, cattle posts and ranches, some of which have their own individual groundwater sources.

Molepolole and Thamaga villages combined have substantial populations and their water supply demands are the main component of the current and future supply systems to be developed. Their current supplies are being met by water from Gaotlhobogwe and Ramaphatle wellfields with lesser inputs from Suping Wellfield.

It is estimated that the water demands for the major centres, smaller villages and settlements will also increase to around 14,000m^3/d by 2016 (ToR, 2008). An additional demand on village supply systems, albeit small, is also expected from an adjacent peripheral population who utilise the villages for provision of water for both human and livestock consumption.

Existing Population

There are at least fifteen villages which fall in the Project Area. These are Molepolole, Thamaga, Thebephatshwa, BDF camp, Letlhakeng, Khudumelapye, Hatsalatladi, Salajwe, Ngware, Malwelwe, Mantshwabisi, Boatlaname, Serinane, Botlhapatlou, Diphuduhudu, Ditshegwane, Sesung and their respective surrounding settlements and localities.

The total population of the 17 villages combined with their localities was 95,056 people in 2001 (2001 Population and Housing Census) and it is currently (2010) estimated at about 104,424 people excluding their localities. Table 1.2 below gives details of past, present and projected future populations of the villages. It is important to note that these population projections have been based on CSO projected growth rates for each individual village and that only a simple mathematical projection method (Geometric Method) has been used.

Table 1.2 Past and Projected Populations for Project Area Villages

Kweneng East	**Actual Population (from Census)**	**Population Projections**		
Village	**2001**	**2008**	**2016**	**2020**
Molepolole	54561	60055	73762	95703
Hatsalatladi	609	670	823	1068
Boatlaname	770	848	1041	1351
Monwane	375	413	507	658
Matlagatse	100	110	135	175
Dikgonnyane	159	175	215	279
Serinane Lands	23	25	31	40
Serinane	450	495	608	789
Matlagatse Cattlepost	17	19	23	30
Mantshwabisi	464	511	627	814
Kolojane	119	131	161	209
Thamaga	18117	19941	24493	31778
Matshwi	55	61	74	96
TOTAL	**75819**	**83453**	**102501**	**132991**
Kweneng West	**Actual Population (from Census)**	**Population Projections**		
Village	**2001**	**2008**	**2016**	**2020**
Botlhapatlou	915	997	1200	1517
Diphuduhudu	559	609	733	927
Ditshegwane	1766	1925	2316	2927
Khudumelapye	1837	2003	2409	3045
Letlhakeng	6032	6575	7911	9998
Malwelwe	930	1014	1220	1541
Ngware	573	625	751	950
Salajwe	1705	1859	2236	2826
Sesung	1281	1396	1680	2123
Thebephatshwa	2585	2818	3390	4284
Metsibotlhoko	355	387	466	588
Sorilatholo	472	515	619	782
Molengwana 1	22	24	29	36
Molengwana 2	58	63	76	96
Khokhole	55	60	72	91
Dinonyane	29	32	38	48
Seisante	63	69	83	104
TOTAL	**19237**	**20970**	**25228**	**31884**

Population Growth Rate

The population growth rates for the villages has been taken from the CSO projected growth rates published by the CSO entitled "Population Projections 1991 -2021" and have been used to determine population projections for the villages up to 2020. The annual projected growth rates for the villages for the period 2001-2031 are as shown in Table 1.3 below.

Table 1.3 Annual Growth Rates for Project Area by District, 2001-2031

District/Village	CSO Projected Growth Rates (% p.a)
	2001-2031
Kweneng East	1.38
Kweneng West	1.24

Design Horizon and Design Population

Population and water demand projections in this report are based on a design horizon of 2020, when new water supply sources that have been explored and developed as a result of this project are anticipated to be in operation.

The DWA Rural Village Water Supply Design Manual (RWSDM) recommends several methods of projecting village populations among them:

(i.) using growth projections published by the Central Statistical Office(CSO),
(ii.) using recorded growth rates in the particular village by comparison of earlier census figures and assuming the growth rate is maintained up to the design horizon,
(iii.)using growth rates recorded in the area or districts as a whole,

Population projections based upon the CSO predictions are available from the recent DWA project for the major village and these are presented in Section 1.5.2. The Kweneng District Development Plan (1996) and the National Water Master Plan Review (NWMPR) that seem to give similar figures have been adopted for calculating water demand projections in this report.

1.5.2 Water Demand

Major Villages Current 2010 Water Demand

The current demands for 2009/10 of Molepolole and Thamaga villages are set by DWA at 9744m^3/day and 2850m^3/day respectively, see Table 1.4 below. If the current supply is considered and using current Molepolole DWA demand figures, Molepolole village theoretically has a surplus supply of 288m^3/day indicating that the daily demand should be met by the current supplies. Thamaga indicates a deficit supply of 1018m^3/day. It is important to note that the village leakages losses should be a lot higher than those recorded in the Gaotlhobogwe Wellfield.

Table 1.4 Current 2010 Supply Status

Village	Current Demand ($m^{3/}$day)	Supply (m^3/hr)	Supply (m^3/day)	Surplus/ Deficit Status	Consumption (m^3/day)	Comment
Molepolole	9744	418	10032	288	6898	Surplus
Thamaga	2850	107	1832	-1018	1200	Deficit
BDF Air base	2400	100	2400	400	2000	Surplus
Total	12594	533	14264		8098	

However, all the operational production boreholes in Gaotlhobogwe and Suping Wellfields are currently pumping for 24 hours, seven days a week (24/7) as a result of a real supply deficit. Ramaphatle boreholes are at most pumped 12 hours in a day. Water demand in Molepolole is steadily increasing and therefore it is clearly imperative to establish additional supplies in order to both alleviate the supply deficit and reduce 24 hour abstraction from Gaotlhobogwe and Suping Wellfields.

Future Water Demand (to 2020)

Molepolole –Thamaga water demands have recently (2010) been assessed by Department of Water Affairs under 'The Design Study and Construction Supervision for Molepolole & Thamaga Major Villages Water Supply Distribution Network Rehabilitation Project'. During the Water Demand assessment both Kweneng District Development Plan (1996) and the National Water Master Plan Review (NWMPR) have been used because these two projection approach give very similar results as shown by population figure tabulated in Table 1.5 below.

Table 1.5 Molepolole and Thamaga Population Projections

Year	District Development Plan (1996)	National Water Master Plan Review (2006)	District Development Plan (1996)	National Water Master Plan Review (2006)
	Molepolole		**Thamaga**	
2001	48,205	54,461	18,117	18,117
2006	55,289	61,400	20,910	20,910
2011	63,475	68,793	23,565	23,428
2016	72,308	76,701	26,556	26,121
2021	88,210	85,100	29,927	28,981
2026	93,013	93,957	33,725	31,998
2031	105,236	103,229	37,999	35,155

Adapted from DWA

From the results it is apparent that the NWMPR results are similar to those of the DDP figure and it was decided that the NWMPR result are more recent that those from the district plan and NWMPR figures were adopted for this project.

Water demands were also analyzed in a similar manner and domestic, institutional, commercial and industrial requirement were considered and the present and future requirements for both Molepolole and Thamaga are tabulated in Table 1.6 below

Table 1.6 Molepolole and Thamaga Water Demands Projections

Molepolole	**Year (kl. Per day)**				
	2011	**2016**	**2021**	**2026**	**2031**
Domestic	5,635	5,867	6,758	7,603	8,518
Other Requirements	5,320	5,961	6,657	7,376	11,133
Totals	10,955	11,828	13,415	14,979	19,651
Thamaga	**2011**	**2016**	**2021**	**2026**	**2031**
Domestic	1,755	2,002	2,376	2,664	3,000
Other Requirements	1,679	1,925	2,216	2,512	2,792
Totals	3,434	3,927	4,592	5,176	5,792
Sum Total Demand	**14,389**	**15,755**	**18,007**	**20,155**	**25,443**

Adapted from DWA

These demand figures are based on guidelines for domestic uses and they accommodate percentage provision for Institutional, Commercial and Industrial uses.

For the purposes of this project a 2020 water demand projection of 18,000m^3/day for Molepolole and Thamaga is adopted. BDF supply has been maintained at current level of 2,400m^3/day giving a total system demand total of 20,400m^3/day.

Current Water Supply

Molepolole and Thamaga villages currently are supplied by two wellfields with additional water to Thamaga coming from Ramaphatle Wellfield boreholes. Currently, Gaotlhobogwe and Suping East wellfields supply Molepolole, Thamaga and thebepashwa Air Base with a total of 16,056m^3/day (669m^3/hr) on a 24hour pumping period. The supply from Molepolole to Thamaga is mostly 1,224m^3/day (51m^3/hr) unless it is interrupted by reservoir problems. Thamaga gets additional supply of 672m^3/day (56m^3/hr) on a 12 hour pumping period from Ramaphatle Wellfield boreholes, summing to a total supply of 1896m^3/day for Thamaga.

Production boreholes in the three wellfields are tabulated in Table 1.7 below and also included in the table are the current abstraction rates. It is important to note that all boreholes in both Gaotlhobogwe and Suping East wellfields are currently pumping at 24 hr pumping cycle without any period of recovery. Only Ramaphatle Wellfield for Thamaga is operated at 12 hr pumping period with 12 hrs recovery.

Table 1.7 Current Production Boreholes

Borehole No.	Recommended Abstraction Rate (m^3/hr)	Day Pumping period (hrs)	Actual Abstraction (m^3/day)	Wellfield
Gaotlhobogwe Wellfield				
10551	15	24	360	Gaotlhobogwe
7864	12	24	288	Gaotlhobogwe
10553	57	24	1368	Gaotlhobogwe
8132	60	24	1440	Gaotlhobogwe
9574	12	24	288	Gaotlhobogwe
10550	62	24	1488	Gaotlhobogwe
9572	18	24	432	Gaotlhobogwe
9571	18	24	432	Gaotlhobogwe
7966	42	24	1008	Gaotlhobogwe
10549	24	24	576	Gaotlhobogwe
6875	98	24	2352	Gaotlhobogwe
9379	100	24	2400	Gaotlhobogwe
10643	20		Not pumping	Gaotlhobogwe
10644	15		Not pumping	Gaotlhobogwe
Gaotlhobogwe total supply	**553**		**12432**	
Suping Wellfield				
6769	10	24	240	Suping
6744	49	24	1176	Suping
4296	14	24	336	Suping
6785	14	24	336	Suping
6786	34	24	816	Suping
6864	30	24	720	Suping
Suping total supply	**151**		**3624**	
Ramaphatle Wellfield				
4402	18	12	220	Ramaphatle
3029	6	12	77	Ramaphatle
6077	32	12	382	Ramaphatle
Ramaphatle total supply	**56**		**672**	

Gaotlhobogwe Wellfield has a total of 12 operational production boreholes and two boreholes Bh6875 and 9379 are operated by BDF and the rest are under DWA. From recorded meter readings of boreholes in Gaotlhobogwe wellfield, the boreholes are suppose to be pumping 518m^3/hr but only 485m^3/hr of water is metered at the DWA treatment plant in Serinane, indicating a total loss of 33m^3/hr. A leakage loss value of about 6.4% is calculated within the wellfield area. Metering of the two boreholes for the BDF indicate a higher loss factor of about 15%.

After treatment the DWA treatment plant then distributes to Thebephatshwa BDF Airbase and Molepolole with 100m^3/hr and 318m^3/hr respectively. Any supply excess to Thebephatshwa is added to Molepolole supply. Molepolole further gets 151m^3/hr of water from Suping East Wellfield summing to a total of 469m^3/hr of water supplied to Molepolole from which 51m^3/hr is transmitted to Thamaga leaving Molepolole with 418m^3/hr supply for 24hr day for local use, see Table 1.7 for the breakdown of the figures.

Suping East wellfield consists of six (6) boreholes as detailed in Table 1.7 and supplies Molepolole and has an auxiliary transmission line to Thamaga which only works at times of emergency. Ramaphatle water system consists of three (3) operational production boreholes. Ramaphatle boreholes are recorded at the reservoir to supply 50m^3/hr which differs from 56m^3/hr of metered at the sources. The 11% losses are attributed to leakages along the water transmission line between Ramaphatle and Thamaga.

Future Supply Requirements

In order to establish a more acceptable and operationally efficient abstraction regime it is projected that the two main wellfields (Gaotlhobogwe and Suping) should be reduced to an acceptable pumping period of 15 hours rather than the 24 hours currently operating. In this operational regime a total supply of 11,232m^3/day could be provided from the three existing wellfields in the current configuration (calculated from Table 1.7).

Considering a total year 2020 Molepolole-Thamaga-BDF demand of 20,400m^3/day estimated from Table 1.6 and on an assumption that the current wellfield supplies can be maintained until this date, additional 2020 water requirements are thus calculated at **9,168m^3/day.**

The proposed new Malwelwe Wellfield should therefore be capable of contributing a total of at least 9,168m^3/15 hr day to the Molepolole/Thamaga supply system by the year 2020.

Other Villages Current 2010 Water Demand

There are at least thirteen samaller villages which fall in the Project Area. These are Letlhakeng, Khudumelapye, Hatsalatladi, Salajwe, Ngware, Malwelwe, Mantshwabisi, Boatlaname, Serinane, Botlhapatlou, Diphuduhudu, Ditshegwane, Sesung and their respective surrounding settlements and localities.

The total population of the 13 villages combined with their localities was 95,056 people in 2001 (2001 Population and Housing Census) and it is currently (2011) estimated at about 104,424 people excluding their localities. Table 1.8 below gives details of past, present and projected future populations of the villages. It is important to note that these population projections have been based on CSO projected growth rates for each individual village and that only a simple mathematical projection method (Geometric Method) has been used.

Table 1.8 Past and Projected Populations for Project Area Villages

Kweneng East	**Actual Population (from Census)**	**Population Projections**		
Village	**2001**	**2008**	**2016**	**2020**
Hatsalatladi	609	670	823	1068
Boatlaname	770	848	1041	1351
Monwane	375	413	507	658
Matlagatse	100	110	135	175
Dikgonnyane	159	175	215	279
Serinane Lands	23	25	31	40
Serinane	450	495	608	789
Matlagatse Cattlepost	17	19	23	30
Mantshwabisi	464	511	627	814
Kolojane	119	131	161	209
Matshwi	55	61	74	96
TOTAL	**75819**	**83453**	**102501**	**132991**

Kweneng West	**Actual Population (from Census)**	**Population Projections**		
Village	**2001**	**2008**	**2016**	**2020**
Botlhapatlou	915	997	1200	1517
Diphuduhudu	559	609	733	927
Ditshegwane	1766	1925	2316	2927
Khudumelapye	1837	2003	2409	3045
Letlhakeng	6032	6575	7911	9998
Malwelwe	930	1014	1220	1541
Ngware	573	625	751	950
Salajwe	1705	1859	2236	2826
Sesung	1281	1396	1680	2123
Thebephatshwa	2585	2818	3390	4284
Metsibotlhoko	355	387	466	588
Sorilatholo	472	515	619	782
Molengwana 1	22	24	29	36
Molengwana 2	58	63	76	96
Khokhole	55	60	72	91
Dinonyane	29	32	38	48
Seisante	63	69	83	104
TOTAL	**19237**	**20970**	**25228**	**31884**

The population growth rates for the villages has been taken from the CSO projected growth rates published by the CSO entitled “Population Projections 1991 -2021” and have been used to determine population projections for the villages up to 2020. The annual projected growth rates for the villages for the period 2001-2031 are as shown in Table 1.9 below.

Table 1.9 Annual Growth Rates for Project Area by District, 2001-2031

District/Village	**CSO Projected Growth Rates (% p.a)**
	2001-2031
Kweneng East	1.38
Kweneng West	1.24

2. REGIONAL GEOLOGY AND HYDROGEOLOGY

2.1 Previous Studies and Data Sources

A considerable volume of work relating to the geology and groundwater potential of the project area and adjacent areas of Jwaneng to the west and the Waterberg area to the southeast, has already been undertaken. Coal exploration activities involving core drilling and down hole geophysical logging were carried out by Shell Coal, Botswana during the period 1974-76. The earliest groundwater work in the Ecca Group in this area was undertaken by the Department of Geological Survey during the original GS10 Groundwater Project in 1977. Further work by DGS was undertaken in 1983 and 1984 (Buckley 1984).

Wellfield Consulting Services carried out a groundwater exploration programme in 1989-90 as the first phase of establishing a water supply for the nearby BDF base. This work indicated the presence of significant groundwater resources in the middle Ecca sandstone, capable of supplying the BDF project and possibly other centres (DWA, Gaotlhobogwe Stage I). Reports on this earlier work constitute the current project data base. A tabulation of the relevant aspects of the principal reports is included below. Details on each of these previous projects were given in detail during the Inception reporting (DWA Inception Report, March. 2008). Data from these projects was comprehensively evaluated and formed the basis for the formulation of the Exploration Programme. The Karoo Ecca aquifers identified in these projects constitute the principal aquifers targeted by the current project.

- *Shell Coal (Botswana) 1974-76*
- *GS10 Project (Geol. Survey Dept, 1976-81)*
  A number of relevant project reports produced during the programme are as follows.
    - GS10 Record No 1 (1978)
    - GS10 Technical Note No. 8 (1980)
    - GS10 Report No 9 (1980)
- *Wellfield Consulting Services (Jwaneng Project, 1976-80)*
- *Aquatech Groundwater Consultants (Geol. Survey Dept., 1988)*
- *Wellfield Consulting Services (DWA, 1980)*
- *Buckley (Geol. Survey Dept., 1984)*
- *Timje (Geol. Survey Dept., 1987)*
- *Wellfield Consulting Services (DWA, Project 15:13:23; Stages I &II, 1989-91)*
- *Water Surveys (DWA, 1991)*
- *BRGM (DGS, 1991)*
- *GRES II (DGS, 1997)*
- *Groundwater Monitoring (DWA, 2001)*
- *Wellfield Consulting Services (DWA, Phase I 1995; Phase II 1996: Phase III 1998)*

General Data Sources

One of the main activities of the Inception Phase was data collection and subsequent compilation and analysis of all existing information pertaining to the Project Area. This involved the gathering of all available information such as geological, hydrogeological, water demand/supply and production, meteorological, geophysical, hydrochemical, topographic, borehole coordinate and remote sensing data.

The Government Departments and regional institutions that were visited during the data search and the nature of the data that was collected are outlined in Table 2.1 below. In addition, various private institutions were consulted and/or visited to gather essential material from previous projects carried out by the private sector within and/or adjacent to the Project Area.

Table 2.1 Government Sources of Information

Government Institution	Nature and Comments on Data Collected
Department of Geological Survey	Borehole logs, geological maps, water chemistry, groundwater resources investigation reports, aeromagnetic data, various geophysical reports on groundwater and mineral exploration by various private companies
Department of Water Affairs	Borehole logs, water level data, water chemistry, borehole siting reports and various groundwater resources investigation reports by various private institutions
Department of Surveys and Mapping	Topographic maps, aerial photographs, vegetation maps, District land use plans and reports
Department of Meteorological Services	Hydrometeorological Data
Kweneng District Council	Water demands/supply and borehole abstraction data
Letlhakeng Sub-Land Board	Borehole and field mapping data
Ministry of Agriculture	Soils maps of Botswana

Maps, Aerial Photographs and Satellite Imagery

The Project Area is covered by Landsat imagery and aerial photographs. In addition, various maps (topographic, geological, hydrogeological, water source location, land use, vegetation, soils and aeromagnetic maps), produced and published by various Government Departments are available. Some local maps of various types have also been produced during individual projects carried out in the area.

The Project Area is covered by published 1:250 000 scale land use maps and falls within the boundaries of the 1:500 000 scale DGS Hydrogeological Reconnaissance Maps Sheet 6 and 10. Geological maps which cover the area include the 1:1000 000 National Geological Map, the 1: 250 000 Molepolole Geological map (Sheet 2425B) which covers most of the south eastern part of the Project Area, and the Khutse Sheet 28 produced during the DGS

Aeromagnetic Interpretation Project (DGS, 2004). A summary of the maps relevant to the Project Area is compiled in Table 2.2.

The 1: 500,000 maps and aerial photographs are available from the Department of Surveys and Mapping. The area is covered by a number of aerial photography contracts with different sets of photographs of different vintage (Table 2.3) as well as new photography available in digital form (see Section D4). Four March 2003 scenes of Landsat 7 Enhanced Thematic Mapper Plus (ETM+) Satellite Imagery in digital form [Path 172, Row 076/077 Path and Path 173 Row 076/077 were purchase from Satellite Application Centre in South Africa.

Table 2.2 Maps Covering or Adjacent to the Project Area

Source	Map Title	Scale	Brief Description/ Used for Mapping
Department of Geological Survey	Quarter Degree Sheet 2425B, Geology Map, Molepolole	1:125 000	Geological Interpretation
	Quarter Degree Sheet 2525A, Geology Map, Kanye	1:250 000	Geological Interpretation
	National Geological Map of Botswana	1:1500 000	Geological Interpretation and Structural Interpretation
	Khutse, sheet 28,Geological Map, Central Kalahari Interpretation Project	1:250 000	Geological Interpretation
	Khutse, sheet 28,Geophysical Map, Central Kalahari Interpretation Project	1:250 000	Geophysical Interpretation
	Hydrogeological Reconnaissance Sheet 10	1:500 000	Groundwater Developments prospects at different locations
Department of Surveys and Mapping	Topographic Sheets	1:50 000	Base map production
Ministry of Agriculture	National Soil Maps	1:1000 000	Delineation of Soil Zones

Table 2.3 Standard Aerial Photography Covering the Project Area

Contract Number	Scale	Date of Acquisition
BOT A (ZONE 34)	1:80 000	2001
BOT B (ZONE 35)	1:80 000	2002
South East Kalahari	1: 50,000	1975

Borehole Information

Technical details relating to existing boreholes within the Project Area and adjacent areas were acquired from the National Borehole Archive held by the Department of Geological Survey and Department of Water Affairs. The basic data held by DGS is identical to that of

DWA, comprising copies of Borehole Completion Certificates, which detail borehole lithology, construction and groundwater data.

Detailed lithological logs were also available from relevant mineral exploration reports for specific projects from Department of Geological Survey. The Department of Geological Survey also has the responsibility of holding an archive of drilling chips and borehole cores if these were to be required for inspection and re-logging.

A reconnaissance borehole location survey was also carried out at the beginning of the Inception Phase to attempt accurately locate all boreholes within the Project Area and relate this data to existing records.

Distribution of existing boreholes within the Project Area indicates borehole density increases around settlements and in the vicinity of the production wellfields. Borehole density is also greater in the area around and to the north of Gaotlhobogwe valley, where considerable earlier groundwater exploration work has been undertaken, and in a zone some 25km south of Boatlaname in the east of the project where a close grid of presumably coal exploration boreholes were drilled. In this same area similar coal exploration is currently ongoing by Asenjo, but data is not available as it is still held under an Exploration License. In the outlying areas away from villages the borehole distribution is very sparse.

The borehole distribution is sparse in the northern portion of the project area, to the north of the Zoetfontein Fault in the zone underlain by the Stormberg Basalt formation. In this zone only a few cattle post syndicates and mineral exploration boreholes are found. Most of these boreholes are very deep ranging from a depth of about 300m to 600m. An example of such a borehole is Seitsantse Syndicate water point BGP185 with a depth of more than 600m. This is probably a result of the deep drilling that may be required to get to the water bearing formations, the Ntane Sanstone, beneath the basalt cover.

Most of the information related to specific aquifers has been derived from previous reports and several maps produced by Department of Geological Survey. Details of these maps are included in Table 2.2 above.

Aquifer Monitoring Information

As a result of the water point reconnaissance survey it was apparent that some groundwater monitoring is taking place within the project area, namely;

- Gaotlhobogwe Wellfield, which is managed by the Department of Water Affairs. DWA has a number of groundwater level recording points at several boreholes but unfortunately during visit their houses were locked and therefore not easy to get access to the data recorders. This data was acquired directly from DWA Monitoring Section.
- Monitoring boreholes installed by BRGM in the area around Malwelwe down to Segatse. These are fitted with recorders while others were just left with dipper hole for monitoring purposes.
- At some Council boreholes the operators record (somewhat intermittently) the abstraction data and water levels where there are monitoring boreholes but in most cases it is rare.
- Private individual boreholes are never monitored.

Reports and Other Sources

Numerous reports and scientific papers of varying detail have been produced both by Government and private institutions and by private institutions contracted by Government. These reports contain information on various aspects of geology, groundwater, and mineral exploration. Technical details relating directly to drilling activities as well as results of ground geophysical surveying and hydrogeochemical studies are especially well documented in mineral exploration reports where these are available. A full list of reports accessed is included in the List of References appended to this Main Final Report.

2.2 Regional Geological Setting

The project area is situated on the northern margin of the Achaean Kaapvaal Craton which is considered to be marked by the SSE-NNW sub-continental Zoetfontein Fault zone. The cratonic basement of the project area comprises a rapakivi-type alkali granite batholith which dominates the geology of south east Botswana (Gaborone Granite) together with a closely associated suite of fine grained felsitic rocks (Kanye Volcanic Formation). Overlying this ancient cratonic body are the Achaean and Lower Proterozoic sedimentary and volcanic sequences of the Ventersdorp, Transvaal, and Waterberg Supergroups. By the end of the Upper Proterozoic almost the entire present African continent was formed and has subsequently remained a stable continental shield incorporating polyorogenic activity in well defined fields.

On this continental shield the essentially unmetamorphosed central Kalahari Karoo sedimentary basin forms an important component of the cover. Subsequent widespread Phanerozoic anorogenic magmatism is linked to major faulting and rifting associated with the break-up of the Gondwanaland supercontinent and subsequent development of the African Rift System. In Botswana, this magmatism is represented by basic dykes and kimberlites, with dykes occurring as swarms, for example the late Karoo ENE swarm across the north central portion of the country.

The formation of the central Kalahari Karoo basin and the subsequent depositional history therein has been largely controlled by renewed movements along both major faults within the Palaeozoic mobile belts as well as on smaller intracratonic fracture zones formed in response to new stress systems generated by continental plate movement. Repeated tectonic movements along pre-existing structures subsequent to diagenesis, together with Phanerozoic basinal warping and anorogenic magmatic activity (dyke emplacement) have also played a great role in the present distribution and juxtaposition of the various individual Karoo units, and have had considerable influence on their localised hydrogeological properties.

The project area is largely underlain by strata of the Ecca and Dwyka Groups of the Karoo Supergroup, unconformably deposited in a basin margin environment on pre-Karoo strata comprising lower Proterozoic meta-sediments of the Waterberg Supergroup and/or an extensive dolerite/diabase unit that is considered to be of post-Waterberg origin.

The Karoo sedimentary strata in the area comprise a sequence of tillites, mudstones, siltstones, sandstones and coals, which are highly variable both areally and vertically, but which attain more than 200 metres in thickness at some localities. This sedimentary succession indicates a palaeo-climate and depositional progression from the lowermost Karoo Dwyka glacial and periglacial deposits, through a lower to middle Ecca lagoonal coal forming environment, into the upper Ecca non carbonaceous, lacustrine, argillaceous deposition. This uppermost Ecca surface is a major erosional unconformity on which Upper Karoo lacustrine and aeolian units comprising the Lebung Group Mosolotsane Formation and Ntane Sandstone Formation respectively were deposited. To the north of the Zoetfontein Fault the Lebung sedimentary succession is most usually overlain by the Stormberg Group basalt which is completely obscured beneath ubiquitous Kalahari Group Cainozoic deposits.

The stratigraphic nomenclature for the Karoo in the project area is adapted from DGS Bulletin 26 (Smith, 1984), and is summarised in Table 2.4 below. Previous investigations in the area (BRGM; GRES II; DWA WCS 1998) have utilised a slightly different stratigraphic nomenclature in which the Upper Ecca unit has been named the Dibete Formation, but in this report the uppermost Ecca unit is termed the Kwetla Formation due to the more widespread and accepted use of this name in the Karoo stratigraphy on the southern margin of the Karoo Basin. Each lithostratigraphic unit is described thereafter.

Table 2.4 Generalised Stratigraphic Sequence in the Sub-region

AGE	SUPER-GROUP	GROUP	FORMATION	LITHOLOGICAL DESCRIPTION	
CENOZOIC		Kalahari	*Kalahari Beds*	Loose sands, cretes, calcareous sandstone and mudstone.	
MESOZOIC	**KAROO**	Stormberg	Ramoselwana Volcanics	Crystalline, massive amygdaloidal basalts	**Karoo**
		Lebung	Ntane	Fine to medium grained, clean, friable sandstone, brownish red/pink. Often calcretised in zones.	
			Mosolotsane	Red/brown greenish mudstones and siltstones with fine to medium, occasionally coarse, intercalated sandstones. Basal conglomerate in places.	
		Beaufort	Kwetla	Grey mudstones and siltstones with minor sandstones. Non-carbonaceous. Occasionally arenaceous.	
		Ecca	Boritse	Fine to coarse, white, feldspathic sandstone interbedded with coal, carbonaceous mudstone and siltstone.	
			Kweneng	Predominantly medium to coarse grained feldspathic sandstone, grits with subordinate siltstone and mudstone. Minor coals.	
			Bori	Dark, micaceous	

				siltstone/mudstone and minor sandstone.	
		Dwyka	Dukwi	Purple siltstone and very fine sandstone. Massive, dark grey, sandy mudstone and siltstone. Purple mudstone rythmites/varvites with dropstones. Tillite, conglomerate with quartzite/granite clasts in sandstone matrix.	
PROTEROZOIC	**WATERBERG**			Reddish siliciclastic sedimentary rocks, mostly quartzitic sandstone and conglomerate.	**Pre-Karoo**
	TRANSVAAL			Interbedded reddish, grey and purple quartzite, carbonaceous siltstone and shale, chert, limestone, ironstone and volcanics.	

Geological units that are intrusive in nature and either form part of the Pre-Karoo basement or are intruded into Karoo strata are indicated in Table 2.5. As a result of their intrusive origin it is frequently not possible to accurately ascribe an age to these units, although their general period of origin may be deduced from their stratigraphic position and relationships with surrounding host rocks.

Table 2.5 Intrusive Geological Units in the Project Area

AGE	LITHOSTRATIGRAPHIC UNIT/EQUIVALENT	LITHOLOGICAL DESCRIPTION
Various ages, both Pre and Post Karoo	Dolerite dykes and sheets.	Greyish green to dark grey, fine to coarse, dolerite.
Mostly Pre-Karoo Achaean basement	Gabbro	Greyish green to grey, coarse to very coarse grained, pyroxene rich igneous rock.

Within the Project Area the nature and disposition of the pre-Karoo basement is largely unknown since most boreholes that have been drilled were terminated when ‘sufficient water was encountered’, mostly within the top unit (Boritse Fm) of the Ecca Group. However, a limited number of boreholes (DWA Projects) do indicate that a highly variable depth to pre-Karoo basement (whether as an original erosion surface or created by subsequent tectonics) is evident.

In general the tectonic elements in the Project Area exhibit expressions of the ENE/WSW trending Zoetfontein structures that are relatively clear near the basin margins but become more indistinct to the north, as well as strong WNW/ESE features that are related to the major structural trend found in the project area. In addition there are apparent NNW/SSE structures identified from the aeromagnetic data. These latter appear to cut the former features to produce some form of block faulting that have compartmentalise the Karoo aquifer and contributed to the relatively complex structural setting on the Proterozoic sub-basin margin.

2.3 Pre-Karoo Geology

Achaean gneissic rocks of the Kaapvaal Craton, including a large area of granitic intrusion termed the 'Gaborone Granite', are found in the south and southeast sectors of the project area and form the more elevated region in the vicinity of Molepolole. Lower Proterozoic strata of the Transvaal and specially the Waterberg Supergroup also occur at outcrop in the southeastern sector of the area. These strata form the southern margin of the Central Kalahari Karoo sedimentary basin and constitute the basin floor over the whole of the project area. The Achaean and Proterozoic strata also almost certainly constitute the source rocks of the Karoo sediments, with the Gaborone Granite being particularly important in this respect.

The Waterberg Group is the most widespread of the pre-Karoo geological units and largely comprises fractured, dark purple/pink ferruginous feldspathic and quartzitic meta-sandstone, siltstone and shale. Conglomerate and mud-flake conglomerate units are also present, with the Waterberg Group assumed to have been deposited in a semi-arid continental lacustrine to fluvial environment. The age of the Waterberg Group has been placed at around 1800 Ma (DGS, Bulletin 37) and the strata have been subjected to lower green schist metamorphic alteration.

From limited borehole evidence it is, however, believed that Proterozoic Transvaal /Waterberg Supergroup strata constitute the pre-Karoo basement within the Project Area, together with possible pre-Karoo gabbroic and doleritic intrusions. A significant feature of the Waterberg Group is the very extensive dolerite sheets thought to have been intruded into the upper most sedimentary units at around 1250 Ma. The dolerite is fine to coarse grained, greenish-grey in colour and microgabbroic in nature.

Both the Waterberg metasediments and the dolerite have been assumed to represent the pre-Karoo topographic surface on which Karoo deposition took place, although there is minor evidence (DWA, 1998) of very thin baked margins in Karoo rocks adjacent to some of the dolerite, which in turn would indicate that some of the dolerite bodies may have been intruded later along the Waterberg/Karoo junction.

The area of Waterberg strata in the southeast of the project area is important in terms of surface drainage and thus possibly plays a role in terms of groundwater recharge to the Karoo basin.

From limited borehole evidence it is, however, believed that Proterozoic Transvaal /Waterberg Supergroup strata constitute the pre-Karoo basement within the Project Area, together with possible pre-Karoo gabbroic and doleritic intrusions. No post Karoo doleritic intrusions have benn reported in the project area despite that these are quite common elsewhere.

2.4 Karoo Supergroup

Examination of the available geological maps and reports of the project area indicates that the whole of the Karoo Supergroup sequence appears to be represented at sub-crop below a veneer of Kalahari deposits in a basin margin environment. The upper units of the Karoo

(Lebung and Stormberg) occur almost exclusively to the north of the sub-continental Zoetfontein Fault zone that transects to northern portion of the area, and it may be reasonably assumed that the middle and lower Karoo also exists at depth below them.

The lithostratigraphy of the Karoo Supergroup as presented in Table 2.4 above

2.4.1 Dwyka Group (Lower Karoo)

The Dwyka group is the basal unit of the Karoo Supergroup and is represented by the Dukwi Formation. This formation rests unconformably on Proterozoic Transvaal and Waterberg Supergroup as well as Achaean basement strata. The Dukwi Formation represents a sequence of glacial and peri-glacial deposits associated with the late Palaeozoic Gondwana glaciation, and comprises pebbly mudstones, varved silty mudstones greenish-grey tillites, and heterogeneous sandstones. There may also be a pebble conglomerate consisting of a wide variety of purple to pink quartzite pebbles, weathered dolerite and coarse angular to subrounded quartz grains, chaotically set in a variable greenish/bluish grey to purplish grey muddy fine to coarse grained matrix.

In Malwelwe area boreholes (Bh 10671, 6858, 6762,) that have been drilled to pre-Karoo basement show that the Dwyka is laterally impersistent and that the thickness of the basal Karoo Dwyka Group rocks appears to be highly variable from one locality to another. This conforms to the glaciogenic environment of deposition of this unit, with Dwyka lithologies mostly restricted to depressions in the pre-Karoo erosion surface. It has, however, been noted (BRGM) that the Dwyka and the overlying Bori do also occur over basement ‘highs’ and are not solely restricted to basement depressions, although this could be due to subsequent structural changes over time.

A detailed lithological description is included in Technical Report No. 1, Geology and Structure.

2.4.2 Ecca Group (Middle Karoo)

The Ecca Group is divided into three separate conformable Formations, namely the Bori, Kweneng and Boritse in respective order from oldest to youngest.

Bori Formation (Lower Ecca)

The Bori Formation conformably overlies the Dukwi Formation and is thought to be an accumulation of mud from suspension in a post glacial lake, (Peart et al, 1984) indicating a waning of the early Karoo glacial depositional environment.

The Bori Formation is largely argillaceous and comprises shaly to silty, dark grey to light grey mudstones, micaceous siltstones and subordinate fine grained sandstone intercalations, which in many places are slightly carbonaceous and often have a calcareous band near the base. The darkest mudstones at the base of the formation grade upwards into the micaceous siltstones and interbedded fine grained sandstone towards the top of the unit. The shales are highly fissile with pyrite nodules having been observed within the sandstone units. Its main characteristics are the absence of coal in the unit. Earlier boreholes that fully penetrate the Bori Formation indicate a thickness which ranges from 9-10 metres (Bh 10674, 6479) to 109+ metres (Bh 10676).

Kweneng Formation (Middle Ecca)

The transition from the argillaceous units of the Bori Formation to grits and coarse sandstones of the overlying Kweneng Formation indicates a change to a short transport/rapid deposition fluvial environment. The Kweneng Formation is characterised by massive, poorly bedded, coarse to medium grain quartzo-feldspathic gritty arkose becoming finer grained and silty towards the base. The sandstone succession varys from light grey, brown, light pink to whitish in color, with the feldspars often very weathered. The unit also contains subordinate dull coals and coaly mudstone partings above the main sandstone, with sporadic carbonaceous horizons occurring in a fine grained silty sandstone underlying the coals at the base of Boritse Formation. It has also been observed that the sandstone units of the formation usually tend to coarsen upwards. Where the sandstones of the Kweneng Formation overstep earlier Karoo units to rest directly on pre-Karoo strata they may become pebbly or conglomeratic. The coarser sandstones, in particular, are characterised by their white, cream or yellowish colouration, the angularity of their quartz grains and the abundance of feldspar (which is often decayed to a clayey matrix).

In the project area, the base of the Kweneng Formation is considered to be the base of a predominantly coarse to fine grained whitish feldspathic sandstone sequence overlying the predominantly dark grey sequence of siltstones and mudstones with thin sandstone intercalations. The recorded thickness of the Kweneng Formation in the Gaotlhobogwe area is variable, from 11 metres in BH 8148 to a maximum thickness of 121 metres BH 7858 and in Malwelwe it varies from 53m at Bh 10674 to 131m at Bh 10676.

On the basis of lithological composition and distribution, the environment of deposition of the Middle Ecca strata appears to have been one of a slowly subsiding central basin on the margins of a semi-stable platform, with localised sub-basinal deposition controlled by the differential subsidence associated with both the marginal areas of the main Karoo basin and with pre-Karoo fault blocks within the basin (so-called `basement highs'). This differential subsidence has, to a large degree, controlled the deposition of the thicker arenaceous units and has given rise to the splits and sandstone wedges within the coals. The abundance of coals indicates a warm climate with flourishing (Glossopteris) plant life distributed in interconnected swamps and lagoonal marshes, with river systems meandering across such floodplains and marsh land thereby producing the broadly cyclic sedimentation patterns found in the Kweneng Formation.

Boritse Formation (Upper Ecca)

The Boritse Formation in the study area consists of an alternating sequence of fine to coarse grained feldspathic sandstone, alternating with carbonaceous mudstones, muddy siltstones and silty mudstone intercalations, dull and bright coals and coaly carbonaceous mudstones. The coaly carbonaceous mudstones are in places sideritic and pyritic with pyrite nodules and veins, while the bright coal bands may have calcite veins. The sandstone beds tend to be variable in continuity and thickness, and the coaly mudstone and coals, although generally continuous, are also variable in thickness and are poorly developed in some places. The interpreted thickness of the Boritse Formation from the project boreholes and previously drilled boreholes vary from a minimum thickness of 16 metres (BH 8189) to a maximum thickness of 120 metres (BH 10676). Since all the Ecca Group succession is gradational, with no distinct marker horizons or discontinuities, the top of the Boritse Formation is considered to be represented by the first appearance of carbonaceous material, whilst the base of the formation is considered to be the bottom of the last coal seam that is more than 2.5 metres thick.

2.4.3 Beaufort Group (Middle Karoo)

The Beaufort Group of the Karoo is represented on the southern margins of the Central Kalahari Basin by the Kwetla Formation. This unit follows conformably from the Ecca and is characterised by a largely argillaceous non-carbonaceous multicolored, (yellow, brown, green, greenish grey, purple, cream, white and light grey) sequence of mudstones and subordinate siltstone, with minor fine to coarse grained sandstone intercalations. That the palaeoclimate was becoming progressively more arid is inferred from the lack of coal formation, and a number of possible intra-formational unconformities indicating periodic desiccation. Where it is overlain by the Mosolotsane formation the top of the Kwetla Formation is frequently red or brown in colour indicating a final transition to oxidising and sub-aeolian depositional conditions, making it difficult to distinguish from the base of the Mosolotsane Formation.

The thickness of the Kwetla Formation in the project area appears to be relatively thin averaging 35m but variable and it is possible that the extent of the Kwetla Formation shown on the geological map may be overstated. The variable nature of the Kwetla Fm can be partly attributed to the nature of deposition when the sedimentary Karoo basin was filling up, restricting its deposition to more localised depressions in the filling basin. At Bh 10678, 10754 and Bh 10751 a thickness of over 90 was interceted within the main Graben. The pale green and reddish colour occasionally associated with the Kwetla also indicates an oscillation between reducing and oxidising conditions related to water level changes in a shallow basin environment.

2.4.4 Lebung Group

Throughout Botswana the Lebung Group lies unconformably on the uppermost Ecca Group Kwetla Formation. Lebung strata are subdivided into two formations, the lower Mosolotsane Formation and the upper Ntane Sandstone Formation. The Ntane Sandstone Formation is the most areally consistent, the most widely understood and the most predictable aquifer in the Karoo sequence, and thus forms mostly the principal target for groundwater development in many regions of the country. Boreholes drilled into the lebung aquifer during the project include exploration boreholes Bh 10681 to Bh10688 and production

Mosolotsane Formation

The Mosolotsane Formation is the lowermost subdivision of the sequence of continental sediments and volcanics that comprise the Lebung Group and, although not positively identified in the project area, may be assumed to be present beneath the Ntane Sandstone where this exists. Descriptions of this formation are thus taken from other geologically similar areas. This unit follows unconformably from the underlying Kwetla Formation, although its base is often difficult to distinguish unless a very thin conglomeratic horizon is present.

The Mosolotsane Formation comprises a heterogeneous sequence of reddened, often variegated, fine calcareous sandstones, siltstones and mudstones. However, the dominant lithology in the Mosolotsane sequence is mudstone. The pink/grey siltstones/mudstones at the base most usually grade upwards into fine grained grey/red to red/brown sandy mudstone in which pale green reduction spots and lenses are common. The uppermost unit is most often a pale grey sandy mudstone, with minor partly laminated siltstone. Sandstone and siltstone lenses are usually present, but are laterally and vertically impersistent. The sandstone intercalations are poorly cemented and vary in colour.

The upper limit of the Mosolotsane Formation is a gradational transition from the predominantly silty Mosolotsane into the predominantly sandy Ntane Sandstone unit. In the boreholes drilled during the project, the Mosolotsane has generally been associated with the presence of a continuous, thick, red/brown siltstone/mudstone sequence. The variable thickness of the Mosolotsane presumably arises from the uneven, eroded nature of the Beaufort (Tlhabala) unconformity and the shallow lacustrine mode of deposition.

The sandstones have been interpreted as being channel fill deposits, and the mudstones as flood plain sediments. Deposition is envisaged to have taken place in terrestrial, fluviatile conditions, in a semi-arid climate under increasingly hot and arid oxidising environmental conditions in shallow lakes and estuaries, with considerable evidence of periodic emergence and drying (Smith, 1984). This type of depositional environment explains the impersistent nature of the sandstone and siltstone units.

Most boreholes drilled in Target area B did not fully penetrate the Mosolotsane Formation. Bh 10683 registered 40m into the formation before the borehole was terminated at 224m depth.

Ntane Sandstone Formation

The Ntane Sandstone Formation is the upper, predominantly massive, fine grained sandstone formation of the Lebung Group. It occurs in small sub-crop areas beneath the Kalahari Beds in the northeast and northwest of the project area but is assumed to be present everywhere beneath the Stormberg Basalt to the north of the Zoetfontein Fault zone.

The base of the unit is most commonly gradational, passing from the mudstones and siltstones of the Mosolotsane Formation into interbedded siltstones and fine sandstones with sparse mudstone partings and occasional mudflake breccias. As a result of this gradational geological junction this transitional section has often been assigned to the Mosolotsane Formation. The upper limit of the Ntane Sandstone Formation is marked by its unconformable contact, most usually somewhat metamorphosed or baked, with the overlying tholeiitic flood basalts of the Stormberg Group. Although this contact is recognised as being unconformable, intercalations of sandstone and basalt have been noted in several areas which could indicate a degree of contemporaneous deposition. In the project area Bh 10742 at a depth of 190m to 215m illustrates this feature.

The Ntane Sandstone Formation has been subdivided by some authors on the basis of argillaceous content into a lower Transition Member and an upper Massive Member (e.g. Smith, 1984). However, the dominant rock type of the unit as a whole is massive or well bedded sandstone, red to pale-cream in colour and variably cemented. The Transition Member, as the name suggests, passes upwards gradationally from the underlying Mosolotsane Formation into pinkish/white siltstones and fine sandstones with the proportion of sandstone increasing in an upward direction. Red/purple mudstone intercalations and some coarse (possibly fluvial) sandstone bands have also been noted. The upper Massive Member consists of well sorted, sub rounded sand grains with occasional calcareous concretions and thin bands of siltstone, all of which are indicative of aeolian depositional processes in an arid environment. However, since the junction between the Transition and the Massive Member is gradational and frequently ill-defined, and the whole Ntane Sandstone Formation constitutes a contiguous hydraulic unit, the division of the Formation into two Members has not been made with respect to the results of the current study.

The environment of deposition of the Ntane Sandstone Formation appears to have progressed from one of semi-arid, aeolian and fluviatile processes, with temporary lakes and alluvial flooding producing mudstone/siltstone bands, to one of virtually entirely aeolian processes giving rise to extensive dune fields with minor interdune fluviatile deposits. The red colouration of much of the sequence is indicative of an oxidising climate.

2.4.5 Stormberg Lava Group

This group forms the uppermost unit of the Karoo Supergroup and has been formally designated the Ramoselwana Volcanic Formation in the Mmamabula area (Williamson, 1991). However, since there are no other subdivisions of this group, the much older terms ‘Stormberg Lava’ or ‘Stormberg Basalt’ is used in this report.

The Stormberg strata consist of a very extensive, and often very thick, sequence of tholeiitic flood basalts which mark the end of the Karoo sedimentary succession. The basalt is black to greenish grey, but reddish brown in the amygdaloidal zones. Interflow weathering and/or palaeo soils are not uncommon and may constitute important groundwater conduits (Cheney 1981, 1985; Farr 1979, 1981).

The Stormberg Lavas appear to have been extruded onto a highly uneven, dune type landscape, which almost certainly had undergone a degree of pre-eruption erosion. The large thickness variation of the basalts may thus be partly inherent, as well as very considerably influenced by post-Karoo faulting. In general terms, however, the lavas thicken northwards and westwards towards the centre of the Central Kalahari Karoo basin.

Within the project area the Stormberg Lavas only occur almost exclusively to the north of the Zoetfontein Fault, although it may be reasonable to assume that they may have once extended further south but have been removed by post-Karoo erosion. The exception is in the extreme northwest of the area where Stormberg Lavas appear to the south of the main Zoetfontein structure, although in this vicinity the Zoetfontein Fault zone appears to bifurcate into several large faults that continue westwards.

Aeromagnetic interpretation of this northwestern area also indicates that the Stormberg Lava may be relatively thin or even absent in places north of the Zoetfontein such that ‘patches’ of basalt-free, Ntane Sandstone exist. Similar interpretation also indicates that there is a down faulted zone of varying width of apparently thick basalt immediately adjacent and to the north of zone of the Zoetfontein Fault across most of the northern section of the project area.

As elsewhere in the country, there is very likely to be considerable local variation in basalt thickness as a result of structural movement as well as a result of the uneven depositional surface. An extremely thick sequence in excess of 585m has been recorded a Diphuduhudu north of Ngware (within the downfaulted zone – see above), but thickness appears to decrease westwards. At Molengwane (Bh 10682) the basalt is around 150m thick whilst west of Salajwe it is only 5m thick or absent in places (Bh 761). Around Salajwe the basalt is less nthan 50m as comfirmed by Bhs 9347, 9345, and 9344 drilled around the village.

2.5 Post-Karoo Geology

2.5.1 Intrusives

Unlike the Karoo sequence further westwards along the southern margin of the Central Kalahari basin where intra-Karoo sills are widespread and often relatively thick (DWA, 2007) there is no record of doleritic sills intruded into the Karoo formations in the project area. The only dolerites recorded in the Gaotlhobogew/Malwelwe region (BRGM; DWA WCS 1997) are those encountered at the base of the Karoo, which are believed to pre-date the Karoo (late to post-Waterberg) and form the sedimentary floor to the basin. The presence of such sills is, however, noticeable on the aeromagnetic interpretation and they appear to be particularly prevalent in the zones of more elevated pre-Karoo basement ie over the ‘Bothlapatou High’.

The project area also appear to be largely devoid of the WNW and NW trending post-Karoo dolerite dykes that are relatively common further north on the eastern margin of the Central Kalahari basin, although some of the larger WNW/NW structures may contain dyke infills. In the Stormberg Lava area to the north of the Zoetfontein fault a number of dykes have been recognised from aeromagnetic data but they appear to almost exclusively follow the trend of major WNW or W fractures associated with the Zoetfontein fault patterns. In the pre-Karoo Waterberg strata in the southeast, a small number of doleritic and syenitic dykes are mapped on trends at variance to the general WNW/NW post-Karoo trend, and it is assumed that these dykes are pre-Karoo in age.

South of the Zoetfontein Fault zone the dolerite is most frequently encountered below the kweneng Formnation butdue to impersistent nature of the lower most karoo Dwayka Formation, it is difficult on every occation to positively dermarcate the dolerite unit asthe base ofthe Karoo. In most cases the method of drilling (air percussion) alo inhibits verification of the type of contact (cold or backed) between the Karoo and the dolerite

2.5.2 Kalahari Group

Post-Karoo superficial deposits of the Kalahari Group (commonly termed ‘Kalahari Beds’) are extremely widespread in Botswana and may attain considerable thicknesses in parts of the Central Kalahari Basin. In general terms the Kalahari Beds are thinner in the southeast of the project area over the pre-Karoo strata and generally thicken to the north and northwest further into the basin.

In the project area the Kalahari Beds comprise a discordant and highly variable sequence of loose to poorly consolidated sand, silcrete and calcrete intercalations of variable proportions, subordinate to minor ferricrete, silcretized/calcretized sandstones, poorly cemented sandstones and silty to sandy clays.

The uppermost aeolian deposits of the Kalahari sequence are represented by loose to poorly consolidated fine sand and silt of various colours ranging from orange, white, yellow, brown, cream greyish brown, with frequent minor sand, silt, and clay intercalated lenses. The uppermost sand consists of variable proportions of angular to sub rounded, fine to coarse quartz and feldspar grains, and over much of the central zone of the project area is generally less than 20 metres in thickness.

The crete deposits predominantly comprise silcrete and subordinate calcrete with minor ferricrete. The silcrete and calcrete may be of various colours, but are predominantly white cream with subordinate grey, purple and pink colours in horizons overlying mudstones. In some localities this unit is associated with silcretized/calcretized sand and sandstone, and the thickness of the whole unit is generally less than 20 metres. Ferricretes are very limited in their distribution, being largely restricted to the sub crop area of the Ntane Sandstone. Calcrete and silcrete is, however, particularly well developed in and on the margins of the northward trending fossil drainage system eg in the Gaotlhobogwe Valley and in the valleys around Khudumelapye and Ngware. Along these drainage features the Kalahari beds per se have also been re-worked and supplemented by more recent alluvial material which includes clays and thin gravels.

2.6 Structural Setting

The project area is located across a major structural feature of sub continental magnitude, namely the Zoetfontein Lineament (commonly known as the Zoetfontein Fault). This feature is considered to have developed during major orogenic episodes in the Lower Proterozoic (c. 2500-1500 Ma) which significantly affected the zones surrounding the Kaapvaal cratonic nucleus, with a wide range of tectonic styles, magmatic activity and metamorphic grades. Some of the most impressive structures to emanate from this period are major, linearly extensive, steeply dipping fractures such as the Zoetfontein/Murchison Lineament. These faults are thought to have originated as ductile shears during earlier orogenic history, with repeated subsequent movement including late brittle fracturing. Such faults also tend to be approximately parallel to the regional trend of the orogenic provinces and, as is the case of the Zoetfontein Fault, constitute the major marginal structures in relation to these provinces (Key 1992). This is reflected in research by Reeves (1978) and Pretorius (1985), who both regard the Zoetfontein Fault as the northern limit of the Kaapvaal Craton.

Clearly, such regional structural components are extremely ancient, fundamental crustal features, which have been involved in a number of major orogenic, or more localised tectonic, events since their genesis, and which therefore can be regarded as having been tectonically active throughout the whole of the Proterozoic and Phanerozoic geological history of the region.

It is also widely recognised that despite their persistent linearity, and as a result of the influence of widely differing stress patterns at various stages of geological development, the differential movement on both the Zoetfontein and other major faults related to these crustal features has been extremely varied. During Karoo Phanerozoic times there is evidence in South Africa of upthrow to the north, while in the same period there is evidence from exploration drilling in eastern Botswana and at Dutlwe (western Kweneng) of upthrow to the south.

This repeated movement, on the same tectonic feature, albeit in differing senses, is fundamental in the appreciation of the lithology and distribution of both the Upper Proterozoic and, particularly, the Phanerozoic strata of the region, since the varied movement on such structures have undoubtedly had considerable influence on the depositional history of all strata concerned.

Despite the varying vertical displacements that have apparently occurred on the Zoetfontein Fault, which is the principal structural influence in the project area, it is apparent that throughout its history there has consistently been major sinistral movement along this feature.

In addition to the brittle deformation discussed above, late Proterozoic warping produced a series of anticlinal and synclinal features, (aligned approximately northwest or west-north-west and plunging to the west), along the eastern margins of what was to develop as the Central Kalahari Karoo basin. Such pre-Karoo warp structures clearly played a significant role in Karoo deposition, albeit if only to provide the major sedimentary embayments on the margins the main Karoo basin in which recurrent fault activity determined local depositional patterns.

2.7 Karoo Depositional Environment

Previous work in project area, notably WCS (1996), Water Surveys Botswana (1992, 2010), BRGM (1991), Shell Coal (1976, 1979) and DGS(1991), all emphasize the role played by the pre Karoo Basement topography during the deposition and development of the Karoo Supergroup. In particular, horst and graben features of the pre Karoo basement clearly exercised considerable control on the diachronous nature and lithological composition of the various units during the deposition of the Karoo strata, and thus ultimately on groundwater occurrence and the hydrogeological properties of these strata.

Other work (Dietvorst et.al. 1991; DGS, 1991) also indicates an irregular, erosional, pre Karoo surface, forming a series of sub-basins or troughs completely or partially isolated by intervening ridges, and in which sedimentary patterns varied considerably.

This picture of grabens (or troughs) deepening generally to the west and northwest towards the centre of the Karoo basin forms a common theme to all previous hydrogeological studies in the region, and this conceptual model was particularly well developed by BRGM (DGS, 1991), who defined and named a number of horst and graben features in the Malwelwe area.

It is envisaged that such grabens would have formed sedimentary embayments on the margins of the Central (Kalahari) Karoo basin during much of Karoo times, gradually being inundated by sedimentation such that upper Karoo units were deposited over the adjacent horsts. Karoo sedimentation patterns are thus clearly controlled by topography, resulting in high energy depositional environments on or adjacent to basement highs and lower energy sedimentation in the deeper basins. Syn-depositional movement on structures defining these horst and graben features during the Karoo period would almost certainly have additionally varied the nature of local sedimentation (either giving rise to coarse deposits by uplift, or finer deposits by deepening of the embayment), and further served to create highly variable hydrogeological local environments as a result of the nature of deposited sediments.

All previous work has also clearly indicated that movement on pre existing structures subsequent to lithification, together with the development of new structures, has resulted in the complex fracture pattern which plays a significant role in the hydrogeological nature of the Karoo strata, as well as having a major influence on the yields of individual boreholes.

Within the project area both aeromagnetic data together with previous ground geophysical surveys and borehole drilling results have confirmed the uneven nature of the pre Karoo topography, as well as the precept that thinner Karoo sediments would be developed on basement highs, i.e. on horsts or upthrown blocks, with thicker sediments deposited in the lower topographic areas of the pre Karoo surface i.e. in grabens or downthrown blocks. Variations in the elevation of the pre-Karoo topographic surface in excess of 200 metres have been noted.

Previous work has also indicated (DWA, 1998) that in general the differences in the pre-Karoo basement elevation across major structures in the Gaotlhobogwe Compartment area are much bigger when compared to offsets in the base of Kweneng Formation. Adjacent to the big throw structures, the depressions in the basement topography are apparently filled with thicker Bori and Dukwi Formations as compared to the rest of the Compartment.

2.8 Fault Patterns and Displacements

With respect to the general structural pattern across the project area, three dominant structural trends are evident:

- NE-SW structures
- WNW- ESE to NW-SE structures
- ENE- WSW structures (Zoetfontein Trend)
- NNW- SSE structures

The NE/SW, WNW/ESE and the NW/SE trends are more visible in both the pre-Karoo strata as well as in the Ecca Group that occupies most of the central portion of the area.

Upper Karoo strata (Lebung Ntane Sandstone and Stormberg Basalt) in the northern zone are, however, significantly influenced by the ENE/WSW Zoetfontein trend, which appears to transect and maybe truncate the earlier NE/SW trend in particular. Since a number of the major NW/SE structures appear to cut and even displace the Zoetfontein Fault, then it may be assumed that movement on these features (likely to be re-activation of older structures) has occurred post-Zoetfontein and probably represents the most recent significant tectonic activity in the area.

In relation to the main NW/SE and NE/SW structures there is **no direct evidence of the magnitude of displacement on any of these faults, since the** depositional environment of the Ecca, and the lithological variation inherent in this, makes the identification of a spatially continuous ‘marker horizon’ extremely difficult and unreliable. However, schematic cross-sections (Figure 2.1, and 2.2 constructed from borehole information provide some indications of the presence of significant fault displacements and these tend to define the edges of the garbens. Major displacements are well defined across the Zoetfontein Fault as shown by the N-S cross sections (Figure 2.1 and 2.2. An attempt by BRGM was made to follow up a second coal in the Boritse as a marker bed and the results seem to be in line with the basement configuration. Significant vertical displacement along the NW/SE faults is implied by disposition of the Lebung-basalt to the northwest of the project area. The outcropping of the Ntane sandstone in the Salajwe area and the area further westwards suggests uplifted blocks. This thinking was further investigated during the Exploration Phase when target area B was investigated. An attempted E-W section (Figure 2.3) highlighted the presence of the faults but it is difficult to be conclusive on level of displacement along the faults. Very little detail is available concerning the folding history of the project area, except that it appears that the region experienced gentle to moderate bi-directional post-Transvaal, pre-Waterberg folding (E-W and NNW-SSE) associated with NW-SE faulting (DGS, 1991).

2.9 The Zoetfontein Fault Structure

This mega trans-continental structure is the single most important structural feature in the project area as well as in the sub-region as a whole. It is recognised not as a single fault feature, but as a complex fault zone that may in places be up to 2 km in width and which must have been reactivated innumerable times during its history and which is still occasionally seismically active today. As noted previously, principal sub-continental movement on the Zoetfontein Fault Zone (ZF) is left lateral (sinistral), with major movement of strata over ten's of kilometres in some sections of the ZF having been noted elsewhere. However, in the project area the most important movement on the ZF has certainly been sub-vertically, with a major throw of over 500 metres to the north deduced to the north of Ngware (DGS, 1991). It is also noted that the vertical displacement on the ZF decreases from east to west (BRGM).

Significant tectonic movement on the ZF, particularly in the northwest part of the project area, may also bring the Lebung Group Ntane Sandstone into juxtaposition with the Ecca Group formations (DGS, 1991).

The ZF zone itself comprises a series of sub-parallel structures that have enclosed within the zone 'slivers' of both Lebung and Ecca strata by means of both lateral and vertical movement on many of these structures. The hydrogeological role and behaviour of the ZF zone is thus extremely difficult to characterise in general terms, with various sections of the ZF acting as either conduits or barriers to ground water flow. That the ZF zone is highly transmissive in a lateral manner as a result of the very many fractures has been widely recognised and accepted, but the behaviour of the ZF zone with respect to transverse flow is hugely influenced by the nature of the major bounding faults on the north and south margins of the zone, as well as the influence of the large transverse NW/SE or NNW/SSE faults noted in Section 2.8 above.

3. INCEPTION PHASE

3.1 Objectives

The objective of this initial stage of the programme (Months 1-3) was to ensure the collection,collation and evaluation of all existing hydrogeological information relating to the Project Area, together with a re-examination and re-evaluation of earlier regional geophysical surveys, remote sensing data, and a detailed assessment of the data was required for groundwater modelling. Specifically, geological and structural features which are possibly significant with respect to the occurrence and movement of groundwater within the Project Area were identified for follow up with ground geophysical survey work to be undertaken during the subsequent Construction Stage 2A programme.

3.2 Activities, Timing and Difficulties Encountered

During the Inception Phase (Nov 2008- March 2009), activities essentially revolved around a thorough review of previous geophysical data (airborne, AMT, gravity, ground surveys and borehole logging), a compilation of all existing borehole and hydrogeological information, an assessment of hydrochemical, environmental isotope and basic environmental data, a review of the structural framework of the region, and the synthesis of all this knowledge into a conceptual hydrogeological model that was essentially based on work carried out by BRGM in 1999. In addition, the existing data and parameters for a numerical groundwater model were critically appraised, and data deficiencies identified. All pre-existing data sources were accessed and utilised, although to a very large degree the results and reports produced by Debswana, BRGM, WCS and WSB during the various stages of developing the same Ecca aquifer and some few isolated Department of Water Affairs during the Consolidated Villages Water Supply programme formed the main foundation of the current programme, and the principal source of information for the database established for the project.

Also included in the Inception Stage was initial work for groundwater monitoring network in the area. The 6 digital water level recorders and 4 rain gauges were purchased and were later installed during the early part of the Construction Stage in existing boreholes. The Inception Stage also saw the initiation of an ongoing collection, compilation and review of hydrochemical and hydro-meteorological data.

Of particular importance during the Inception Stage was a fairly detailed field reconnaissance survey in order to provide basic up dated location and/or other borehole data which was not in the existing archives. The water level data from the survey formed the basis for the generation of the 2010 groundwater surface of the Project Area. This was supplemented by a selective survey of some boreholes west of the Project Area where groundwater heads for modelling purposes were deemed insufficient which had become apparent during the initial data evaluation. The need to expand the Project Area westwards to include the Jwaneng Wellfield with respect to the modelling requirements was also thoroughly discussed and presented to the Client for approval.

The Inception Stage also included the discussion of the requirements for the drilling and testing works with the Client, as well as the formulation of technical specifications for this contracting work, in order to obviate any delays in the commencement of the contracting activities during the subsequent Construction Stage

On completion of the Inception Stage, an Inception Report was presented to the Client (end – March 2010). This report presented in detail the Consultant's proposed work-plan and staff inputs for the remaining two Stages of the project, based upon the evaluated outcome of the Inception Stage. The Inception Report also presented variations to the Consultants original proposal, and included technical and economic justifications of such variations for the Clients consideration.

During the Inception Stage, and during the data evaluation exercise, only a limited number of difficulties in terms of data availability and integrity became apparent. The most significant of these was the non-availability of hydrogeological data north of the Zoetfontein Fault.

Whilst data evaluation in relation to the groundwater modelling was underway, it was also established that there was significant lack of piezometric data from which to generate a useable piezometric surface to the west as well as for the Ntane/Lebung Aquifer to the north of the Zoetfontein Fault zone.

Other minor difficulties encountered during the Inception Phase related to previous ground geophysical surveys and geophysical borehole logging information, which was not available in digital form for possible re-examination.

3.3 Results

3.3.1 Geology and Structure

On the basis of all information gathered and assessed during the Inception Stage of the project, the main geological and structural characteristics of the Project Area (Map 1) was set and the project data set was also used and contributed significantly to the overall understanding.

3.3.2 Regional Geophysical Surveys

All regional geophysical surveys undertaken in and around the current Project Area were re-evaluated during the Inception Phase. These include the National Gravity and National High Resolution Aeromagnetic Surveys undertaken by the Government through DGS. Only hard copy interpretation maps with lineaments from De Beers were available. Detailed results of this evaluation are presented in the Inception Report (DWA, 2009).

In summary, the interpretation of various regional geophysical surveys has confirmed the existence of an Ecca sedimentary basin to the south of the Zoetfontein Fault and the existence of generally thick Stormberg Lava flows to the north.

It may be concluded that the findings of these regional geophysical surveys in and around the current Project Area made it possible to understand structures like grabens, horsts, regional/local faults and the Karoo Basalts which all control groundwater occurrence and flow. In addition, the Stormberg Basalt aeromagnetic signature north of the Zoetfontein Fault gave an indication of the relative thickness of the basalt sequence and hence the potential depth to the aquiferous Lebung Ntane Sandstone. Such information has enabled the Consultant to carry out ground geophysics with a foresight of the possible results.

3.3.3 Remote Sensing

The key objective of the remote sensing study was to identify and delineate all lineaments and other structures in the Project Area that could be of geological and hydrogeological significance. Such lineaments, in conjunction with information gathered from other specialist studies such as aeromagnetic data interpretation and hydrogeological data review, was then used in identifying potential target areas for the detailed ground geophysical surveys that were set out in the Inception Report.

The remote sensing study also assessed the vegetation patterns and structure of the Project Area and various zones which may have a bearing on groundwater recharge and/or discharge were identified and presented in the Inception Report.

The study entailed interpretation of Landsat 7 Enhanced Thematic Mapper Plus (ETM+) satellite images and Shuttle Radar Topography Mission (SRTM) elevation data.

The study area is covered by four Landsat satellite image scenes as listed below. Each image is defined by path (p) and row (r) numbers.

- Lephephe Scene - p172r076
- Gaborone Scene - p172r077
- Kutse Scene - p173r076
- Jwaneng Scene - p173r077

An attempt to use the SRTM digital elevation data was made during the study and mapping of lineaments in the Project Area. Lineaments were mapped from the pseudo relief images produced using ArcGIS Spatial Analyst and ER Mapper by artificial illumination of the SRTM elevation data. Geological structures with geomorphologic expressions that were normal or perpendicular to the artificial illumination were thus identified and delineated in the area due to shadow-effect.

The lineaments interpreted from the SRTM elevation data and the Landsat 7 ETM Plus satellite image are as follows:

- NW – SE to NNW – SSE
- NE – SW to ENE – WSW

The lineaments in the area are predominantly faults and fractures and are fairly pronounced on the SRTM digital elevation data. The lineament density decreases northwards over the areas covered by the Stormberg Basalt. Given that remote sensing data in the Kalahari is usually only capable of capturing subsurface structures in areas with thin sand cover, the decrease in the lineament density northwards may be a result of increased Kalahari sand cover in a northerly direction, but this does appear to be the case in the Salajwe area where basalt/Lebung outcrops have been mapped.

It was apparent from the remote sensing study that the lineament interpretations may indicate potential areas suitable for detailed groundwater exploration at a relatively large scale, but it was rather difficult to appreciate the remote sensing contribution to the examination of smaller ‘follow up’ target areas that emanated from the earlier BRGM investigations (DGS, 1991).

The lineaments delineated from the Landsat ETM+ satellite image and the SRTM data compared well with those interpreted independently from the aeromagnetic data.

3.3.4 Geophysical Ground Surveys and Borehole Logging

Previous ground geophysical surveys carried out in and adjacent to the present Project Area for major groundwater studies and several small scale rural village water supply projects were re-evaluated during the Inception Phase. Such studies included the following;

- Project 15.13.23 Groundwater Exploration Programme (DWA, WCS 1990),
- Project 15.13.23 Groundwater Resources Assessment and Wellfield Development (DWA, WCS, 1992),
- BRGM (DGS 1991),
- Department of Water Affairs (Water Surveys, 1991-92),
- Gaotlhobogwe Groundwater Investigation Phase 1 (DWA, WCS, 1995),
- Gaotlhobogwe Groundwater Investigation Phase 2 (DWA, WCS, 1996),
- Gaotlhobogwe Groundwater Investigation Phase 3 (DWA, WCS, 1998),

These geophysical surveys have generated a large volume of data and a review of the data is well presented in the Inception Report (DWA, 2009). Information has been gathered as comprehensively as possible on a regional scale as well as on a local scale from both mineral and groundwater exploration projects.

In addition the following regional geophysical surveys were examined and evaluated during the course of the Inception Phase:

- Aeromagnetic Surveys
- Gravity Surveys
- AMT Surveys

Details of this re-evaluation are contained in the Inception Report and comments and recommendations are briefly summarised below.

A variety of geophysical techniques have been used in previous projects, most of which rely on the contrast in resistivity between different lithological and/or aquifer units. Principal methods included resistivity (direct current) and electromagnetic (both time and frequency domain) techniques. The HLEM (Horizontal Loop EM) technique has depth penetration limitations and very low resolution at larger coil spacing necessary in the current Project Area. TDEM (Time Domain EM) is a deeper penetrating technique but is more time consuming and costly. However, it was concluded that a well balanced and appropriately spread combination of both EM techniques should prove to be technically and economically the best exploration option for the current Project.

It was concluded that geophysical logging data can be of great value in any groundwater project, especially if the accurate definition of aquifer geometry is needed for aquifer modelling and resources evaluation purposes. In particular, its applicability in lithostratigraphic interpretation and the definition of the base of the Ntane and Ecca sandstone aquifers was previously demonstrated in various projects undertaken by the Consultant for both DWA and DGS.

3.3.5 Hydrochemistry and Environmental Isotopes

The hydrochemical setting of the groundwater of the Project Area has been extensively discussed in previous groundwater resources projects (DWA, 1995, BRGM, 1991), and has been investigated in detail by the DGS GRES II Project (GRES II, 1995). In the Inception Report a review of existing hydrochemical data for the Project Area and surrounding areas derived from both the DWA and DGS databases, plus water analyses of samples collected during the course of the field reconnaissance survey, was presented in summary form in order to develop a regional synopsis of the groundwater chemistry of the Project Area.

The groundwater in the Project Area was generally classified into any of the following three groups, although a few exceptions to this generalized classification were noted.

❖ Ca-Mg -HCO_3	Water type	A
❖ Na-HCO_3	Water type	B
❖ Na–HCO_3/Cl	Water type	C

Other less important water types include Ca-Na-HCO_3, and Ca/Na-Cl water types.

Water type A is mostly found in the Gaotlhobogwe area and extends northwards to Malwelwe and all the way to the Government Ranch next to the Zoetfontein Fault. Southwards the Water type A zone extends west and south-west to the Jwaneng Northern Wellfield. Very little data is available in the eastern portion of the Project Area but indications are that Water type A is dominant as indicated by borehole BH 300.

3.3.6 Recharge

The project region has seen three major recharge investigations during the past two decades (BRGM 1991, GRES 1995). These form the basis for any evaluation of recharge data for the project and were discussed in detail in the Inception Report.

During the GRES II Project (GRES 1995) a range of recharge determination activities were carried out that culminated in different recharge estimates covering the study area, which now forms the central block of the present Project Area. The various activities included the following:

- Soil moisture measurements
- Chloride mass balance calculations
- Soil profile samples were taken and analysed for chloride
- A finite element flow model utilizing water levels
- Integrated the hydrochemical and isotopic evaluation(14C and 13C)

The assembled recharge data was sorted out by method and it was clear that systematic differences exist. During the Inception Phase a number of techniques used during earlier projects were re-evaluated, and the project data set was added to this process. A comprehensive recharge review is presented in Technical Report No. 5, Hydrochemistry and Recharge.

3.3.7 Groundwater Modelling

One of the most essential asks of the project was the establishment of a numerical groundwater model from which it was envisaged that quantitative resources estimates will be derived. However, on commencement a review previous models was carried out and this was presented in the Inception Report.

During the course of the project a new numerical model covering the current project area was developed. This modelling exercise is presented in summary in Chapter 8 of this report and in detail in the Technical Report No. 4, Groundwater and Resources Modelling Report.

3.3.8 Hydrogeological Regime

Preliminary work carried out during the Inception Period identified and examined the properties and distribution of two major aquiferous horizons in the Ntane Sandstone Formation and the Upper Ecca Group. The nature of these aquifers varies greatly in terms of lithology, mineralogy, distribution and hydrochemistry, which in turn affects their potential as economically viable aquifers.

Other minor aquifers were identified within the Kalahari Group, the Mosolotsane Formation, the Kwetla Formation, the Dwyka Group and other Pre-Karoo rocks. However, it was considered unlikely that these would constitute useful sources of groundwater, and they were therefore not investigated further.

The principal aquifers of the Lebung and the Ecca Groups are described fully in this report.

3.3.9 Selection of Exploration Target Areas

The Inception Phase of the project concluded with the identification of certain sections of the project area as zones to be subjected to detailed investigation by means of surface geophysical surveys, exploration drilling and aquifer testing. Selection of these zones was based on a number of important pre-requisites, namely;

- The requirement to gather substantially more data from which to further refine the geological and hydrogeological understanding of the project area as developed by BRGM/ GRESS II and later WCS programmes.

- The requirement to attempt to answer questions raised by earlier exploration and production drilling and testing both in the Malwelwe and Gaotlhobogwe wellfield areas.

- The requirement to up-date the preliminary conceptual groundwater model in preparation for the formulation of a sub-regional groundwater numerical model.

- The requirement to investigate prospective aquifer areas outside the central Ecca aquifer zone, in particular the Lebung aquifer on the northern side of the Zoetfontein Fault where the basalt is not so thick, and the nature and extent of the Ecca aquifer in the eastern basin.

- The requirement to identify and quantify specific aquifer areas suitable for the development of additional wellfield sources capable of meeting the 2020 water demand for BDF, Molepolole-Thamaga and other project area villages.

The locations of the Target Areas were selected largely on the basis of the initial Conceptual Model and the important questions it raises, together with the overriding and urgent requirement to identify and develop new wellfield sources.

Three Target Areas were thus selected and were denoted A, B and C (Map 3). Each Target Area and the reasons for its selection are detailed below.

Target Area A

Target Area A constituted the principal target zone of the project. It is located in central part of the project area in the western Ecca basin and was the focal investigation area for the Letlhakeng - Botlhapatlou Project (DGS, BRGM, 1991). This area was specifically mentioned in the ToR for the current project as an area of investigation to follow up on the BRGM recommendation on wellfield development at Malwelwe.

In Target Area A the Kalahari Group cover averages about 20-25m and the groundwater flow is north-westwards with very little gradient. From the high resolution aeromagnetic data set it would appear that the Malwelwe area is situated in a magnetic ‘low’ which would imply that the area has the thickest Karoo sedimentary cover. The general groundwater development potential within the Ecca system within this zone may thus be assumed to be relatively high with respect to other Ecca zones, but evidence indicates that maximum potential is only realised where significant fractures occur.

Within Target Area A there are a number of sites previously identified by BRGM as potential production borehole sites during their 1991 study. Additional work was envisaged with respect to these specific production sites other BRGM potential sites identified by BRGM.

In addition to the BRGM selection it was also proposed that additional work is carried out in this zone in order to more fully establish Ecca aquifer geometry and aquifer layering within specific ‘grabens’, the thickness of the Kwetla for recharge assessment, groundwater chemistry with respect to variation with depth as well as the lateral recharge to the area, and more detailed information on hydraulic head within the Ecca aquifer.

Target Area B

Target Area B is located in the extreme northwest of the project area and is largely to north of Zoetfontein Fault zone. This zone has been selected in order to investigate the Lebung Ntane Sandstone aquifer in an area where several major NW-SE structures are very evident and clearly have had considerable influence on the disposition of the Lebung units. These structures may also have had some influence on the Kalahari Group deposition as the Kalahari is thinner over this elevated block of Ntane Sandstone. In addition, the Stormberg basalt overlying the Ntane Sandstone aquifer is relatively thin or even absent in some places. The aeromagnetic signature over the Investigation Zone suggests that the Stormberg basalt occurs as blocks of different thicknesses, implying that the blocks have been subject to several episodes of what is almost certainly block faulting similar to that exhibited in several other previous project areas (e.g. Serowe; Palla Road).

On the basis of fairly limited existing hydrogeological data on Target Area B, but drawing parallels with other highly productive areas of Ntane Sandstone aquifer under relatively thin Stormberg basalt cover elsewhere in Botswana, suggests that an investigation of the block faulted structures that influence the Lebung Ntane Sandstones may reveal substantial groundwater resources in this northwestern zone.

In addition, it was considered important to examine the nature of the hydraulic continuity between the Ecca aquifer and the Ntane Sandstone across the Zoetfontein Fault, since this area is the focus of the sub-regional groundwater flow from the western Ecca basin and a more complete understanding of this area will be essential for reliable numerical modelling.

It was further proposed that an evaluation of the groundwater potential of the underlying Ecca formations should also be carried out in an area where the overlying Lebung (and Kwetla, if present) is relatively thin, as there may be the possibility of a ‘dual aquifer’ system that could be exploited.

Target Area C

Target Area C is located in the extreme northeast of the project area and was selected in order to investigate the Ecca aquifer within the eastern basin in an area which currently has very little hydrogeological information. Target Area C has also been located so that it is on the eastern edge of the Botlhapatlou High, which may have influenced Ecca sedimentation and also appears to generate a separate groundwater flow system that is directed eastwards, although definition of this is problematic due to paucity of data in the area.

There is substantial geological data derived from earlier coal exploration work in the zone that indicates on average >100m of Ecca aquifer (Boreholes S19, S29 and S23 on Map 3) but there is no accompanying hydrogeological information. From the structural interpretation, NW-SE trending structures appear to be more prominent than NE-SW structures and these were targeted with ground geophysics to assess their hydrogeological influence and groundwater potential.

In addition, other data acquired include Ecca aquifer geometry and lithology, Kwetla thickness, possible Lebung presence plus more information on groundwater head, borehole yields and water quality were anticipated.

4. CONCEPTUAL MODEL

On the basis of information gathered and assessed during the Inception Phase, the principal hydrogeological characteristics of the Project Area with respect to the geological and structural setting, groundwater occurrence, hydrochemistry and recharge were assessed and presented in detail in the Inception Report. This initial assessment was finally combined into a conceptual model of the Project Area that has subsequently been used as a basis for the formulation of a numerical groundwater model.

The conceptual model developed during the Project incorporates and synthesises the results and conclusions drawn from the comprehensive evaluation of all the various data sets into a conceptual overview of the hydrogeological regime in the Project Area. From this model the most important issues relating to the groundwater resources were identified and distilled into a specific programme of activities designed for execution during the various phases of the project.

The main elements of the conceptual model are summarised below as follows;

Structural

- The Project Area is set on the southern margins of the Western Central Kalahari Karoo basin and the Karoo sequence wedges off against basement, meta-dolerites and Waterberg.
- The northern margin of the targeted Ecca aquifers (Boritse and Kweneng Fms) is essentially demarcated by a faulted contact along the line of the prominent SW-NE Zoetfontein sub-continental fault system.
- The varying nature and depth of the intercepted pre-Karoo surface must be attributed to tectonic movement enhanced by significant erosional features that enhanced the graben and horst dispositions.
- The area is influenced by three dominant structural trends.
- The NNE/SSW trend is probably deep seated (pre-Karoo), is largely subdued and in the northeast appears to be part of the Zoetfontein Fault system.
- The NE/SW to ENE/WSW (Zoetfontein) trend is probably a basin margin feature and contributes to major faulting of the Karoo. A down faulted 'graben' bounded by two of these structures (Z1 and Z2) is apparent across the north-centre of the area.
- The WNW/ESE or NNW/SSE trend is most prominent and appears to have an important influence on groundwater flow. The trend appears to disrupt the Zoetfontein Fault system and allows hydraulic continuity between the Lebung/ Ntane to the north and the Ecca to the south of the Zoetfontein Fault system.

Geological

- The Project Area is underlain by Lower (Dwyka), Middle (Ecca/Kwetla) and Upper (Lebung and the Stormberg basalts) Karoo units of various thickness and persistence (see Map 1 and Table 2.4)
- The Dwyka is laterally impersistent and conforms to the glaciogenic environment of deposition, with Dwyka lithologies probably restricted to depressions in the pre-Karoo erosional surface.

- The Ecca Group is divided into three conformable Formations, namely the Bori, Kweneng and Boritse Formations in respective order from oldest to youngest.
- The uppermost Boritse Formation is the most frequent unit intercepted by existing water boreholes in the Project Area.
- The Bori Formation is the lowermost unit of the Ecca and conformably overlies the Dwyka. The main characteristic of the Bori Fm is the absence of coal measures.
- The Kweneng Formation is characterised by massive, poorly bedded, coarse to medium grain quartzo-feldspathic gritty arkose becoming finer grained and silty towards the base and thinly laminated with carbonaceous mudstone, siltstone and coal. The top of the formation was taken as the base of a persistent coal seam that is usually over 2m thick.
- The Boritse Formation is characterised by the presence of an alternating sequence of fine to coarse, clean quartzo-feldspathic sandstones, coals and carbonaceous mudstones and siltstones. The transition from the Kweneng Formation to the overlying Boritse Formation is conspicuous by a sequence of interbedded predominantly carbonaceous siltstone and coal with occasional coarse grained to gritty sandstone. The Boritse Fm is relatively thick (30-120m).
- The Kwetla Formation comprises a sequence of grey, non-carbonaceous siltstones and mudstones with occasional sandstones lenses, is highly variable in distribution and over most of the southern portion of the Project Area is completely absent Its main characteristics are the absence of coal. The Kwetla Fm rapidly thickens towards the north and northwest.
- Upper Karoo (Lebung and Stormberg) strata are divided into two conformable formations that are restricted to the north of the Zoetfontien Fault.
- The Mosolotsane Formation lies unconformably above the Kwetla Formation and comprises red and brown mudstones and siltstones with pale green reduction spots and lenses. Poorly cemented, variegated sandstone and siltstone lenses are also common but are laterally and vertically impersistent.
- The Ntane Sandstone Formation is the uppermost aquiferous Karoo sedimentary unit, conformably overlies the Mosolotsane Formation and comprises red/pink, fine to medium grained, clean, well sorted, quartzitic sandstone deposited in an arid, aeolian environment. An increasing proportion of siltstone and mudstone occurs towards the base of the Ntane Sandstone Formation, often making the boundary with the top of the Mosolotsane Formation indistinguishable.
- The Storberg basalt overlies the Natane Sandstone and has thicknesses in excess of 500m to the north of the Zoetfontein Fault system.
- Within the Project Area there is insufficient data to enable mapping the Ntane Sandstone Fm and the Mosolotsane Fm individually. However, a general observation is that the Ntane Sandstone Fm is prevalent beneath the basalt north of the Zoetfontien Fault.
- Kalahari Group deposits of varying thickness obscure all bedrock formations. This unit comprises a largely terrestrial sequence of sands, clays and cretes of Cretaceous to Recent age, ranging in thickness from only 20m to 160m.
- No post Karoo dolerite dykes have been intercepted in the area.

Hydrogeological

- Groundwater occurs in all geological units present in the Project Area, but only the sandstones of the Karoo Lebung/ Ntane and Ecca Group constitute major productive aquifers.

- The Lebung aquifer occurs only to the north of the Zoetfontein Fault system and southwest and appears to be significantly controlled by structures.
- The Ecca aquifer occurs throughout the Project Area and constitutes the principal aquifer. This aquifer is generally at a depth below the Lebung north of the Zoetfontein Fault system.
- The Ecca and the Lebung (Ntane, Mosolotsane) aquifers are in continuity in the area between Khudumelepye and Salajwe villages where groundwater flow crosses the Zoetfontein Fault system.
- The various arenaceous layers of the Ecca (Boritse, Kweneng Fm) are mostly in hydraulic continuity due to lack of persistent inter-formational aquicludes.
- The Lebung groundwater flow is generally towards the north and conforms to the piezometric trend of the Ecca, although this must be viewed with caution due to paucity of Ntane head data.
- Regional groundwater flow (in the Ecca) is from the southeast to the north and north-west.
- The groundwater system is thought to have outlets to the north and to the west in the extension of the Ecca aquifer.
- The fossil valleys in the area are thought to be discharge zones due to shallow water levels.
- A groundwater divide has been observed on the Botlhapatlou Basement ‘high’ and divides a western and an eastern flow system
- Piezometric gradients are generally very low such that in some areas piezometric contours appear disrupted.

Hydrochemical

- There is an inflow of fresh groundwater from the S and SE edge of the Karoo basin into the Ecca aquifer. The inflow is from the south and south-east.

- In general the Ecca and the Ntane groundwater is potable and TDS values are generally less than 1000 mg/l.

- The inflow into project area appears to ionic exchange as evidenced by fresh water which progressively becomes more mineralised with distance from basin edge.

- A substantial body of low TDS (<350 mg/l) groundwater exists in the Ecca aquifer in the Malwelwe Wellfield, possibly an indication of some direct recharge.

- Slight vertical mineralization differences within the Boritse/Kweneng aquifers are governed by presence of coal/mudstone/siltstone inter-layers, many of which may be laterally impersistent.

- In the Kweneng village area the water is of the Na-HCO_3 /Cl type with lower TDS values (<600mg/l) whereas the rest of the fresh water in the Ecca is Ca/Mg - HCO_3 type.

- Hydrochemical evidence from the low chloride concentration and less dominant sodium concentrations hint at the possibility of local recharge.

- The Ntane/Lebung aquifer has high (>75%) Na percentage ratios indicating long residence time.

4.1 Aquifer Spatial Distribution and Geometry

The aquifer thickness was generated from boreholes drilled during various studies in the area from the 1960s to 2011. Thickness of the Ecca aquifer varies from 62m to 300m within the project area.

Ecca aquifer thickness increases from the basement highs to the south and to the east which form a groundwater divide in the area to the north into the Karoo basin. Along the basement high where the Ecca pinches out, the thickness is around 60m-80m. The thickness attains a maximum of 300m to the north of the Jwaneng and Malwelwe wellfields. Along the Gaotlhobogwe valley and around the wellfield, the thickness is reduced to 60m-170m as the valley has deeply incised into the upper Ecca aquifer.

In Malwelwe Wellfield the aquifer thickness varies from 60m to 300m. Cross-sections reveal a high variability of aquifer thickness in the vicinity of the Gaotlhobogwe and Malwelwe Wellfields. The two wellfields sit within “two semi-separate internal basins” with a local groundwater divide in the middle, but are in hydraulic continuity.

In Jwaneng Wellfield the Ecca aquifer thickness varies from 200m to 300m and results in comparatively high transmissivity within the wellfield area. Disposition and thickness of the Ecca aquifer is relatively uniform in the Jwaneng Wellfield.

With respect to the Ecca aquifer the conceptual understanding is that the graben/horst surface represents the original Karoo sedimentation topography. It is thought that the edges of the grabens are more likely to be characterized by coarser sandy sediments in a higher energy environment with the centre of the graben receiving the fine more argillaceous material in a much lower energy environment. It is also very likely that the sharp edges of the grabens are structurally controlled, with tectonic movement occurring during Ecca sedimentation thus contributing to the marginal higher energy deposition and possibly even ‘fault scarps’.

The doleritic pre-Karoo basement depths in Target Area A (Malwelwe Area) have been mapped out by use of both the ATM (by BRGM) and by TDEM soundings during the current project. The pre-Karoo surface in the area is dominated by the ‘Main Graben’.

Boreholes drilled on horsts were practically dry and the dolerite basement was intercepted at shallow depth indicating a reduced thickness of Ecca aquiferous formations.

4.2 Transmissivity (T)

Ecca Aquifer

Test pumping data has revealed highly variable transmissivity values throughout the project area. However, there appears to be a clearly recognizable zone of high values around the Jwaneng Wellfield with an average value of about 560m^2/day. The average value in Gaotlhobogwe and Malwelwe Wellfields ranges between 180- 200m^2/day.

The available test pumping data interpretation suggests a high transmissivity area within the central portion of Target Area A centred around Bh6827 - Bh6825 - Bh10679 - Bh10674, with transmissivity on the upper end of the range around 600 m^2/day. High values seem to occur where the Ecca aquifer is thickest, as at Bh10674 and Bh10679. The area around Bh6829, located on the steep edge of the Main Graben, seems to be a low transmissivity area, probably due to a reduced thickness of the aquifer. A similar trend is also observed at Bh10671 some 3.7km west with an intercepted basement at 172m depth. This low transmissivity trend related to reduced Ecca aquifer thickness is also evident at Bh6828 to the south and the recently drilled project borehole Bh10677 with an airlift yield of only 2.3m^3/hr.

Ntane Aquifer

Transmissivity values determined from the Ntane sandstone during the Exploration Phase were significantly affected by shallow pump installation in relation to the deep water strikes experienced in Target area B boreholes. The confined section of available drawdown responded quickly to initial pumping periods and drew down to the pump rapidly. Transmissivity values derived ranged from 4m^2/day to 25m^2/day and the data distribution does not and specific trends. The drilling data indicated high yields in the thick basalt areas as compred to the area west of Sориratholo where Bhb 10683 and 10684 intercepted reduced Ntane aquifer thickness.

4.4 Storativity

Borehole drilling in the Ecca during the production phase enabled drilling and test pumping of production boreholes next to some of the previously drilled exploration boreholes. During test pumping of the production boreholes, exploration boreholes drilled ±20m away were monitored as observation boreholes.

Calculated Ecca storage coefficient ranges from 5E-2 to 6E-4.The values are within the range for confined aquifers with a value of 9.9E-3 being regarded as the upper limit. These values are regarded to represent both the fractures as well as the inter-granular storage.

4.5 Recharge Potential

From the assembled recharge data summarized in Table 4.1. It is clear that current recharge may occur in some parts of the project area.

Table 4.1 Summary of Past Recharge Assessments done in the Project Area

Project	Method	Recharge (mm/a)	local/areal	Time scale	Reference
BRGM	^{14}C model	1.8-3.5 [1]	areal	millenia	DGS (1991)
GRES II	^{14}C model-MBR	1.2	areal	millenia	Beekman & Selaolo (1997)
Jwaneng	^{14}C model	3.7-4.7	areal	millenia	Verhagen (1993)
BRGM	CMB-GW	6.2-11.8 [2]	areal	millenia	DGS (1991)
GRES II	CMB-GW	5-10	areal	millenia	Beekman & Selaolo (1997)
Jwaneng	CMB-GW	6 [2]	areal	millenia	DGS (1991)
GRES II	He model	2.2-3.1	areal	millenia	Beekman & Selaolo (1997)

GRES II	CMB-soil profile	1-10	local	centuries	Beekman et al (1997)
GRES II	Deuterium offset	1-10	local	centuries	Beekman & Selaolo (1997)
BRGM	Flow model	2 - 7	areal	decades/years	DGS (1991)
GRES II	Flow model	3-7	areal	decades/years	Nijsten & Beekman (1997)
Jwaneng	Flow model	3.0-4.9	areal	decades/years	Van Rensburg & Bush (1994)
BRGM	Soil moisture balance	3.5-5.0	local	months	DGS (1991)

1. Recharge values re-calculated with a porosity of 0.1
2. Recharge values re-calculated with the more recent T_D = 500 mg/m^2/a

The local methods derived from profiles and individual groundwater samples show large variations. The CMB methods show higher recharge values than the other techniques.

The recharge values over millennia do not differ significantly from those with shorter time span even though the longer time span of the oldest water in the aquifer (5000 to 40 000 years) includes both wet and dry periods (Thomas and Shaw 2002). It must be noted that even though the CMB methods include samples with great ages, the estimate of TD is only based on data collected over not more than ten years (Selaolo 1998).

5. EXPLORATION PROGRAMME

5.1 Overview

The Construction Stage-Exploration was the second stage of the project programme, and constituted approximately 35% of the project activity. The work was the close examination of hydrogeological significant features and potential aquifer boundaries identified from regional geophysics and remote sensing by ground geophysical surveys. Investigation of such features was undertaken by exploration borehole drilling and subsequent evaluation of aquifer and individual site potential by controlled testing. This work, together with a number of other contributory activities such as hydrochemical/isotope analyses and recharge studies utilizing the monitoring network and other sources, have then been used to provide adequate and reliable information with which to develop a numerical aquifer model from which an eventual groundwater resources assessment has been derived.

Other activities during the Construction Stage were the assessment of existing production boreholes (camera inspection and re-testing), execution of geophysical logging, the surveying of all project boreholes and few existing old boreholes to the west. The assembly of an initial steady state sub-regional numerical groundwater model was achieved.

During the Construction Stage 2A, the very specific objectives may be summarised as follows:

- To determine as reliably as possible by means of geophysical surveys and exploration drilling the lateral and vertical extent of both the Ecca aquifer to the south and the Ntane/Lebung aquifer to the north.

- To evaluate by controlled test pumping the aquifer parameters of both the Ecca and the Ntane/Lebung aquifers.

- To establish the presence and spatial distribution of potentially exploitable aquifers in the Ecca sequence of the Project Area.

- To assess the recharge processes and groundwater quality distribution in the Ntane/Lebung and Ecca Aquifers in the Project Area.

- To determine as reliably as possible the piezometry of the Ntane/Lebung and Ecca aquifers, and the hydraulic connectivity between them, if any.

- To assemble an appropriately calibrated steady state numerical model of the Ecca aquifer of the Project Area from which to quantitatively assess the groundwater resource potential of the sub-region.

- To determine possible interference between the various existing wellfields (Jwaneng Northern Wellfield; Gaotlhobogwe Wellfield) and the new wellfield to be established around Malwelwe.

The Exploration Phase was the examination and evaluation of potential structurally controlled aquifers in a number of pre-defined Investigation Areas, as well as the clarification of the basic geological disposition and lithostratigraphy of the area.

Information emanating from the Exploration Phase enhanced the knowledge of the hydrogeological regime of the Project Area and was used to revise the conceptual model developed during the Inception Phase. The resultant Project data set was fully analysed to provide an assessment of the overall groundwater potential of the Project Area.

It is also from this data-set that conclusions and recommendations for the location and development of a number of production boreholes were made.

Each of the above principal activities of the Exploration Phase is discussed in detail in the following sections.

5.2 Activities, Timing and Difficulties Encountered

During the Exploration Stage approximately 133.6 km of ground geophysical surveys and drilling of 20 exploration boreholes was achieved.

A summary of the principal activities, and specific difficulties encountered, is presented below.

- **Geophysical Surveys**

  Exploration ground geophysical surveys started in April 2009 and were completed by end of September 2009, when it became apparent that the drilling contracting works would be delayed. *The initial planning approach was to have an overlap of the geophysical surveys and the drilling operations to facilitate some modification of the survey interpretation depending on drilling results.*

- **Drilling**

  The exploration drilling was carried out by one contractor (Dewet Drilling) under DWA contract conditions. The drilling process was fairly straight forward, with the use of minimal casing in the exploration boreholes. Some problems arose due to the relatively deep water strikes that generated high heads in deep Ntane Sandstone aquifer in the Sorilatholo area. Minor and occasional formation collapse also created drilling problems in the Mosolotsane Formation necessitating frequent cleaning during drilling. Borehole BH10682 was terminated prematurely due to formation collapse.

  With respect to boreholes drilled into the Ecca Aquifer, some problems were experienced when using air percussion methods due large inflows and to the very high groundwater head. The contractor was able to complete all boreholes by use of two compressors and a compressor booster.

  Exploration drilling started in 9th February 2010 and all 20 exploration boreholes were completed by end 20th of April 2010.

- **Test Pumping**

  Test pumping was undertaken by the Contractor, and the work was undertaken by a sub-contractor, Mobitec to Pty Ltd, under the DWA Contract conditions. Three test pumping units were mobilized to site early February 2010. Equipment breakdowns during the testing programme were minimal, although some delays were experienced as a result of the high yielding nature of some of the existing production boreholes (Bh 6824, 6825 and 6826). In the Sorilatholo area (Target Area B), the rapid drawdown to pump suction of water levels also necessitated deep pump setting.

5.3 Exploration Borehole Ground Geophysical Surveys

5.3.1 General Survey Characteristics

The main ground geophysical survey programme has been completed and included the following components:

- Evaluation of regional geophysical surveys (aeromagnetic, magneto-telluric, gravity and other previous groundwater studies)

- Follow up surveys (TDEM, HLEM, magnetics and VES) on previous BRGM survey work in Target area A.

Conclusions from the previous surveys that preceded the project played a deciding role in the choice of exploration methodology and selection of the exploration Target Areas.

5.3.2 Survey Methodology

A total of 35 traverse lines totalling more than 133.6 km were surveyed in all three Target Areas A, B and C (Map 3). The ground profiling geophysical surveys included magnetometry and Horizontal Loop Electromagnetic (HLEM) profiling. Data was collected at a station spacing of 20m along the traverses. Some anomalies picked by the profiling methods were later followed up by TDEM and VES soundings.

Calibration surveys were performed in Target A and Target B so as to characterize the geologic settings against geophysical anomalies. In Target A, the calibration borehole was BH6827 on Line 9 while in Target B, BH9133 along line L28 was chosen for this purpose. Table 5.1 below summarizes the geophysical quantities used during the Exploration Stage.

Table 5.1 Geophysical Quantities Used During Exploration Stage

Target Area	Line Cutting (km)	Magnetics (km)	HLEM (km)	No. of VES Soundings	No. of TDEM Soundings
A	53,700	52,700	53,980	10	25
B	60,200	60,200	60,340	0	39
C	19,700	19,700	19,780	0	6
Total	**133,600**	**132,600**	**134,100**	**10**	**70**

5.3.4 Instrumentation

A portable GSM-19 Overhauser magnetometer was used to measure the earth’s total magnetic field on all traverse lines. Readings were collected at a station spacing of 20m. A Maxmin I-6 system was used to collect HLEM readings at a coil spacing of 100m. Four frequencies; 440Hz, 880Hz, 1760Hz and 3520Hz in a maximum coupled mode were used. Readings were collected every 20 m along all the lines in the Project Area.

A PROTEM TEM57 receiver and a generator powered TEM37 transmitter were used to collect TDEM soundings. The transmitter loop was 200m by 200m and readings were sampled using three frequencies H (25Hz), M (6.25Hz) and L (2.5Hz) with the intention of getting the thicknesses and geoelectrical properties of the different stratigraphical units.

A CSIR resistivity meter was used to conduct resistivity soundings using a Schlumberger array method.

5.3.5 Selection of Survey Targets and Traverse Alignment*s*

The three Target Areas (A, B and C) were identified during the Inception Phase and surface geophysics and exploration drilling has been undertaken in each area. Of importance has been the determination of the dimensions (spatial extent and thickness) of prospective aquifers and, most particularly, the role played by the major and minor structures that have been identified largely from the regional geophysical interpretation. In terms of future resource development it has been demonstrated by previous studies that these structures play a crucial role in determining favourable sites for production yields during wellfield development.

The following is a summary of each specific survey target and the reasons for its selection.

Target Area A - Malwelwe

Target A (Fig 5.1) constitutes the principal target zone of the project. It is located in central part of the Project Area in the western Ecca basin and was the focal investigation area for the Letlhakeng - Botlhapatlou Project (DGS, BRGM, 1991). This area was chosen as a follow-up on the BRGM recommendation on wellfield development around Malwelwe.

Existing information in previous BRGM, WCS, WSB and other studies in the area helped in deciding the placement of traverse lines and the choice of exploration methodology. The key findings of previous studies in Target A are noted below:

- The regional geophysical surveys carried out in this target relate mostly to the Ecca geologic units and the underlying basement basin structures. Such structures have an influence on groundwater occurrence and development.

- BP Coal boreholes provided stratigraphical information which was essential in determining lithological thicknesses and depths.

- BRGM **Gravity** and **AMT** surveys were very critical in outlining the graben-horsts structures and mapping the basement morphological settings.

- **VES** and **TDEM** techniques contributed to better resolution of shallower layers as well as basement mapping as compared with the EM techniques. Aquifer thickness and resistivity properties could be derived using these methods. Limited application of VES was noted in areas of deep and thick Kwetla Mudstones.

- **HLEM** profiling proved very efficient in mapping the Graben-Horst contacts as well as faults and fracture zones in such environment compared to the **magnetic** method which tend to respond to deep seated basement disturbances. It was noticed that the magnetic method at a station spacing of 10m or 20m would give same anomaly wavelength because of the smooth variation of the total field in the area.

- From the BRGM study, it turned out that there was no exploration drilling at the centre of the Main Graben. Also the BRGM reports revealed that most of their recommended sites for production or exploration drilling were restricted to the then-existing cut lines. It was therefore necessary during this programme to modify the approach and include structures from the **aeromagnetic** interpretation outlined during the Inception Phase (WCS, 2009).

- BRGM concluded that **"steep Graben-Horst structures" play a more significant role in groundwater occurrence in Letlhakane-Botlhapatlou area compared to any other structures.** *Apart from following this conjecture, the current exercise was also intended to check the faults at the centre of the Main Graben and at horsts, which to some sense posed enormous groundwater development potential.*

As a result of the critical assessment of this earlier work it was possible to locate a total of 25 short survey lines in Target Area A (Fig 5.1). Table 5.2 outlines the criteria used in selecting the lines. All geophysical traverse lines are shown on Fig 5.1.

Table 5.2 Criteria Used To Select the Surveyed Lines in Target Area A

LINE No.	START		END		Length (km)	Reasons for Line Selection
	X_Cape	Y_Cape	X_Cape	Y_Cape		
L1	316739	7332290	315530	7333293	1.6	Follow up on WSB work and targeting **F9** and NW-SE structures intersection.
L2	313284	7335156	313270	7338020	2.7	Southern edge of the Lotlhakolane Graben. Intersection of **F10** and **NW-SE** faults. Steep basement slope.
L3	315080	7354040	315080	7356227	2.2	Within Main Graben, intersection of **F11** and NW-SE faults
L4	321193	7348823	321193	7349937	1.0	This was a reoriented line and was intended to target E-W structure picked up by EM survey on lines L19 and L20. Its within the Main Graben.
L5	335198	7339016	336306	7340027	1.5	South-west edge of Mopipi Graben within a steep zone, similar position as BH6828 which produces 25 m^3/hr
L6	329738	7342560	331153	7343966	2.0	On the Sethunya Horst – Mopipi Graben contact. Area picked by BRGM as potential site north of BH6828.
L7	309317	7343191	309301	7345307	2.1	Across E-W structure on the edge of Dipuo Graben. Influenced by coal exploration BH6 lithological sequence.
L8	312074	7343341	312052	7346140	2.8	Across E-W and **F5** structures intersection, edge of Dipuo Graben. Influenced by coal exploration BH6 and BH6827 lithological information.
L9	314845	7344779	314772	7348579	3.8	Across E-W structure edge of Dipuo Graben. Influenced by production BH6827 and dry BH6766. A calibration line for the target area.
L10	317523	7347978	317502	7349966	2.0	Across NW-SE structure within a Main Graben at the edge of basement high.
L11	318976	7344132	320622	7345243	2.0	Across NW-SE trending minor Dipuo Graben, south of high yielding boreholes. BRGM

LINE No.	START		END		Length (km)	Reasons for Line Selection
	X_Cape	Y_Cape	X_Cape	Y_Cape		
						classified this site as high for wellfield development.
L12	323786	7344313	323783	7347690	3.4	Across E-W structure. Southern edge of Main Graben. Influenced by production BH825. Across **F10** and NW-SE structures intersection. BRGM's SITE 21 selected for wellfield development
L13	327207	7341077	327195	7343176	2.1	Across NW-SE and **F9** structure intersection. Within a minor Graben.
L14	328436	7345800	328422	7349325	3.5	Across E-W and **F10** structure. Southern edge of Main Graben. Influenced by BH6829.
L15	331649	7347232	331631	7349175	1.9	Across E-W structure within Main Graben. Follow up on BRGM SITE 15 along profile D3.
L16	331587	7350168	331560	7351641	1.5	Influenced by BH6740, across NW-SE and **F10** structures intersection. Follow up on BRGM SITE 1, along profile D3.
L17	329189	7351545	329189	7353616	2.1	Across NW-SE and NE-SW lineaments. Extensive fractures expected. Northern edge of Main Graben is targeted.
L18	325260	7350014	326280	7351738	2.0	Northern edge of Main Graben also crossing the NE-SW structure.
L19	323125	7349216	323147	7350948	1.7	Within Main Graben intended to intersect NW-SE and NE-SW structures. Influenced by BH593 geological stratigraphy.
L20	325211	7347616	325211	7349465	1.8	Intended to intersect of NW-SE and NE-SW structures within the Main Graben. Influenced by coal exploration boreholes S99 and S100 lithology.
L21	325568	7353876	326088	7355802	2.0	Across NW-SE structure and northern edge of Main Graben. Follow up on BRGM SITE 16.
L22	323979	7354916	323982	7356985	2.1	Across E-W and NW-SE structures intersection. Extensive fractures expected. Influenced by BH6830. Steep basement edge to the south.
L23	320358	7358441	320367	7360482	2.0	Across **F11** and the NW-SE structures intersection. Extensive fractures expected. Influenced by high yields on BH6830
L24	311146	7353005	311150	7354515	1.5	Across **F11** and NW-SE structures intersection. Extensive fractures expected deep into the Main Graben.
L25	303578	7348868	303583	7350864	2.0	Across **F5** and **F11** structures intersection. Extensive fractures expected deep into the basin. On the western parts of the BRGM Area D.

Target Area B - Salajwe

Target Area B (Fig 5.2) was selected in order to investigate the Ntane/ Lebung sandstone in an area where several major NW-SE and E-W structures were expected to have considerable influence on the groundwater occurrence within the Lebung sandstone. The Stormberg basalt overlying the Lebung sandstone occurs as blocks of different thicknesses while it is even absent in some places to the northwest. This implies that the blocks have been subjected to several episodes of conjugate block faulting.

To the east of Salajwe there are relatively thick Karoo Basalts which are most likely to have preserved a full sequence of the main aquifer (Lebung Ntane Sandstone) at depth. Significant faulting will also have created double porosity and enhanced permeability of the Ntane

Sandstone. In contrast, exiting boreholes drilled on regional structures in and around Salajwe Village have proved low to marginal yields due to the reduced Ntane Sandstone aquifer thickness. It therefore implies a thicker basalt cover is essential for better yields.

The aeromagnetic map (Fig 5.3) provided a picture of the thickness of the basalt. The western portion of Target Area B indicates thin or absent Karoo basalt while the eastern part indicates thickening basalt. No direct information on the Lebung Ntane Sandstone aquifer could be derived from the aeromagnetic data sets.

Geophysical surveys carried out in Target Area B were both along sub-regional lines and as well as on short lines. Line L26 was a 20km sub-regional line and was designed to traverse across different basalt blocks and fault patterns picked up from aeromagnetic data set. Most lines were placed roughly N-S so as to better understand hydrogeological settings and the possible relationships of different structures.

The criteria used to site the lines are outlined in Table 5.3 below and Fig 5.3 shows the location of the geophysical lines in Target Area B.

Table 5.3 Criteria Used To Select the Surveyed Lines in Target B

LINE No.	START		END		Length (km)	Reasons for Line Selection
	X_Cape	Y_Cape	X_Cape	Y_Cape		
L26	314443	7366988	314190	7386999	20	This line crosses three major structural blocks of different basalt layer thicknesses. It crosses the NW, NNW and EW structural trends
L27	306454	7369027	306454	7374025	5	Across E-W lineaments and to investigate the thick basalt and thin basalt blocks north of the Zoetfontein Fault.
L28	288913	7360085	289746	7375707	15.6	Across the Zoetfontein Fault and three major structural blocks are crossed. Boreholes BH9133 and BH619 will be use to calibrate the geophysics results.
L29	2280892	7367633	280871	7377679	10	Oriented in a N-S direction and is intended to investigate the lineaments forming a shear zone associated with a moderate yielding BH9346 ($30m^3$/hr) borehole north of Salajwe.
L30	287738	7395282	283920	7388467	7.7	Across **NW-SE** and **E**-W trending lineaments.
L31	294575	7377565	296663	7378242	2	Across **N-S** structure north of the Zoetfontein Fault.

Target Area C- Kweneng Dyke Swarm Zone

This Target Area was also selected in order to investigate the Ecca aquifer within the eastern basin in an area which currently has very little hydrogeological information. It is on the eastern edge of the Botlhapatlou High, which may have influenced Ecca sedimentation and also appears to generate a separate groundwater flow system that is directed eastwards, although definition of this is problematic due to paucity of data in the area.

Groundwater potential of this zone is not fully known while available literature indicates only limited drilling success around Kweneng Village. Exploration coal drilling geological logs which suggested the possibility of a thick Boritse aquifer (more than 100 m thick in some places) and the existence of regional faults which might have been reactivated on several occasions made this area worth investigating.

Groundwater flow in this area is assumed to be from the Botlhapatlou High to the east and northeast. The thin Kalahari sand cover over the area suggests good potential groundwater recharge conditions. Basement topography from the aeromagnetic data indicates BRGM type steep graben-horst contacts just like in the Malwelwe Target A.

The main objective of the ground geophysical investigation in this Target Area was to identify the main fractures and lineaments which may have favourable groundwater development potential. As a result four lines (Table 5.4) were sited using geological information from exploration coal holes and the aeromagnetic lineaments (Fig 5.4) in order to investigate both the NW-SE and the E-W dominant structural trends.

Table 5.4 Criteria Used To Select the Surveyed Lines in Target Area C

LINE No.	Start Point		End Point		Length (km)	Reasons for Line Selection
	X_Cape	Y_Cape	X_Cape	Y_Cape		
32	369945	7369677	373809	7369677	4.0	To investigate the **NW-SE** fault as interpreted between BH20 and BC54 boreholes.
33	379713	7369667	385660	7369720	5.0	To investigate the NW-SE fault displacement as interpreted between BM39 and BM3 boreholes.
34	371963	7374701	372651	7378522	4.3	To investigate the potential of the **E-W Zoetfontein** Fault Zone.
35	398273	7359843	398903	7366087	6.4	On the eastern edge of a **NW-SE** fault.

5.3.6 Evaluation of Geophysical Survey Results

Selected geophysical profile results are in included in Technical Report No.2, Gephysical Siting Report. The profiles include only sites where drilling took place as they will be referenced during the next discussions.

Target Area A and Target Area C

The results of the geophysical surveys from Target Area A and Target Area C will be discussed in this section mainly because the same important Ecca aquifer occurs in both areas.

The magnetic and electromagnetic geophysical results collected in Target Areas A and C produced several anomalies of different value and significance and these were weighted according to groundwater development potential. The EM and magnetic anomalies in most cases coincided with regional features picked from aeromagnetic data set. The anomalies were evaluated and characterized using calibration surveys along Line L9 and on boreholes BH6826 and BH6766 which are high yielding and marginal yielding boreholes respectively as guidelines. A table in Appendix A illustrates all the major geophysical anomalies identified during this exploration exercise.

In order to identify potential sites for drilling a number of parameters were considered and these included horst/graben relationship, geology, hydrogeology, structures, geophysical response and (in specific sites) the previous BRGM hypothesis that was based on the host-graben relationship. The distribution of these structures controlled the nature and the thicknesses of the Ecca aquifer. In places where the per-Karoo basement is deeper, thick aquifer is expected although the nature of the sediments is depends on the location of the site within the depositional basin.

The geophysical anomalies were put into groundwater development potential weighted classes taking into consideration the aquifer properties like resistivity and thickness. Figure 5.5 highlights the criteria used to group the various sites into three classes.

Class 1_A - High Groundwater Development Potential

Both magnetic and electromagnetic anomalies coincide with the BRGM graben-horst structures which essentially have been proved to have very high groundwater development potential. The geophysical anomalies are in total agreement with geology and the hydrogeological setting of the site.

Groundwater is typically encountered at a depths ranging between 100m to 250m, in the Boritse Sandstone Formation underlying the Kwetla mudstones and shales. Historical information on the occurrence of groundwater is based on the exploration/production boreholes drilled along such structures. Depths to the basement on these sites range between 150m and 350m. However, yields are extremely variable depending on the extensiveness of fracture systems, thickness of the saturated Boritse/Kweneng sandstones and the thickness and occurrence of the mudstones which act as aquiclude and influence the recharge.

Class 2_A - Moderate Groundwater Development Potential

This class includes magnetic and electromagnetic anomalies coinciding with less proven insignificant geological structures with moderate groundwater development potential. Few sites may have very weak geophysical anomalies but are located on good geological and hydrogeological settings conducive for high yields. This is particularly true if we consider local structures/faults with minimum occurrences of argillaceous sequences.

Class 3_A - Low to Marginal Groundwater Development Potential

This class includes strong EM anomalies with weak or no magnetic anomalies and in areas with shallow (<180m) basement topography. The strong EM anomalies are usually deceptive as they tend to pronounce the existence of clay minerals rather than water saturated fracture zones.

There are some instances where only geological and in the absence of geophysical explanation are high yielding sites discovered. This is particularly true in areas with good direct recharge conditions like valley floors or fossil valleys.

<u>Target Area B</u>

The EM and magnetic methods were very helpful and outstanding in defining faults and fractures since most of the anomalies picked up represent direct evidence of the presence of conductors and therefore fractures in the underlying Stormberg Basalt and the Lebung Ntane Sandstone. Ground truthing of aeromagnetic lineaments (Fig 5.2) by use of EM and magnetic methods helped in defining several anomalies. TDEM soundings were used to determine depth to the Stormberg Basalt-Ntane Sandstone contact (Fig 5.3) which culminated in the zoning and spatial distribution of basalt block that are referred to as ‘hydrogeological blocks’ (Fig 5.6).

Kalahari Beds

From TDEM results, the Kalahari beds can be defined by two layers – the dry highly resistive top soil and the calcrete layer which has a lower resistivity values. The Kalahari Beds can be interpreted as having thickness range of 10 m to 80 m on average but may exceed 80 m in some places. It can be deduced from the TDEM interpretation that the Kalahari Beds inherited a fairly flat to gently undulated surface which was exposed to extreme weathering and erosion processes.

Stormberg Basalt

Visual inspection along all the lines surveyed in Target Area B revealed that there are no Stormberg Basalt outcrops. The TDEM results revealed depth to the top of the basalt surface ranges between 10 m and 80 m. Determining the base of the basalt was important in getting an idea of the depth of the possible water strikes in this area.

The most reliable and useful information from TDEM was the Stormberg Basalt-Ntane Sandstone contact since this is critical in determining the thickness of the basalt layer. The results from geophysics also enabled the subdivision of the basalt sheet into conjugate blocks with different resistivity and thicknesses.

Stormberg Basalt can be both weathered and fractured and has a resistivity range of 400 to 700 ohm-m. Solid to partly fractured basalt has resistivity values above 700 ohm-m. Thin basalt block that are highly fractured and weathered have low resistivity (< 400 ohm-m). Where basalt is thin and weathered/fractured, groundwater recharge conditions into the Ntane Sandstone below should be good. These characteristics have implications on the confinement and recharge of the main Lebung Ntane Sandstone aquifer which the basalt overlies.

Lebung Ntane Sandstone

TDEM resistivity of the Ntane Sandstone varied from 100 ohm-m to 250 ohm-m. It was not possible to define the base of the Ntane Sandstone.

A spatial classification of groundwater development potential of Target Area B (Fig 5.6) shows that it is highly variable since it is controlled by the following:

- the occurrence and thickness of the Ntane Sandstone,
- the thickness of Stormberg Basalt which was responsible for preserving and confining the Lebung Ntane Sandstone aquifer,
- depth to the Stormberg Basalt-Ntane Sandstone interface

- the regional faulting structures which play an important part in enhancing secondary porosity and permeability.

The geophysical anomalies in target area as was the case in A were put into groundwater development potential weighted classes taking into consideration the aquifer properties outline above . The potential weighting highlights the importance of the block faulting in the areas close to the Zoetfontien Fault.

Class 1_B - High Groundwater Development Potential

Confined conditions prevail where the productive section of the Ntane Sandstone aquifer is saturated. The preserved Ntane Sandstone below a thick basalt layer and network of fracture zones play a vital contribution in creating double porosity and recharge conduits. Approximate Basalt-Ntane Sandstone interface 250 – 450m.

Class 2_B - Moderate Groundwater Development Potential

Confined to semi-confined conditions where the water strike is below the Basalt-Ntane Sandstone contact such that the most productive sections of the Ntane Sandstone is partially saturated. Approximate Basalt-Ntane Sandstone interface 150 – 250m.

Class 3_B - Low to Marginal Groundwater Development Potential

The Ntane Sandstone is exposed or partially/completely eroded or where the remnants of basalt are thin. The water table is below the upper productive Ntane Sandstone unit. Only faults contribute as marginal groundwater storage and flow conduits. Approximate Basalt-Ntane Sandstone interface 50 – 150m.

5.3.7 Selection of Exploration Drilling Sites

A total of 20 sites were selected for further exploration by drilling in Target Areas A, B and C. The exploration drilling exercise was intended to investigate the hydrogeological conditions at each of these geophysically-selected sites (e.g. thickness of aquifer, presence of fractures, borehole yield). Table 5.5 below is a borehole siting summary list.

Table 5.5 Selected Drilling Sites In All Targets Areas

Site No.	Peg No.	UTM Coordinates		Aquifer Resistivity	Aquifer Thickness (m)	Comments
		X_Cape	Y_Cape			
1	L1/930	315968	7332801	146	88	This site is on the northern extension of the Gaotlhobogwe Wellfield. Groundwater development potential is expected to be moderate to high because of the lineaments. **Class 2_A**
2	L3/1210	315122	7355245	200	110	Site is on a gently sloping terrain north of Marotswane Village on the axis of the Main Graben. Very little information is available in terms of groundwater development potential of this main Graben. However, deep water strikes and slightly salty water should be expected. **Class 2_A**
3	L5/400	335502	7339311	150	98	The site is on the Segatse Horst-Mopipi Graben contact. This is a high priority site but for logistical reasons the site is recommended as a backup exploration site. **Class 1_A**

4	L8/1530	311966	7344877	80	127	This site is 2.5 km west of production borehole Bh6827 on a flat terrain. Groundwater development potential is expected to be excellent because of the network of fracture systems. **Class 1_A**
5	L12/1650	323656	7345931	155	150	The site is on a flat terrain about 2.5 km east of Malwelwe Village. Groundwater development potential is excellent. **Class 1_A**
6	L16/970	331615	7350901	150	80	This site is on the eastern edge of the Main Graben. It was initially identified by BRGM and confirmed as having a high groundwater development potential. **Class 2_A**
7	L18/1050	325897	7350849	100	153	Site on the edge on the main Graben with high groundwater development potential. **Class 1_A**
8	L19/90	323127	7349325	116	146	The site is 3.5 km north of Malwelwe Village at the axis of the Main Graben. Groundwater potential is good because of the expected thick Boritse sandstone. **Class 2_A**
9	L21/850	325782	7354685	174	124	Site on the edge on the main Graben with moderate groundwater development potential. **Class 1_A**
10	D6/8400	328714	7351537	123	127	The site is within the Main Graben were deep water strikes are expected. Class 3_A
11	L26/2140	314426	7369115	131	200	Site characterised by negative magnetic anomaly and strong EM conductor defining two structural sub-blocks. **Class 1_B**
12	L26/15370	314234	7382261	126	291	Peg is on a small magnetic anomaly associated with a weak EM conductor. **Class 1_B**
13	L27/3730	306490	7373066	162	230	The peg is on an EM conductor and magnetic gradient anomaly. **Class 1_B.**
14	L28/9100	289750	7369191	210	160	Strong HLEM conductor coinciding with a regional fault zone. **Class 1_B**
15	L29/1290	280866	7368911	169	113	The site is at the centre of a block on a between two close EM conductors. **Class 2_B**
16	L29/6830	280869	7374594	108	86	The site is within a fault zone. **Class 3_B**
17	L30/6210	284324	7390209	103	131	The site is on a prominent regional fault between two Basalt blocks of different thicknesses. **Class 1_B**
18	L31/1110	295503	7378174	170	139	The site is on a major fault between two blocks with same basalt thicknesses. **Class 2_B**
19	L32/1470	371492	7369960	174	210	Site is on a fault within the Dyke Swarm Zone. **Class 3_C**
20	L35/710	398371	7360934	185	238	Site is on a graben-horst type fault major which is on the edges of the Kweneng Dyke Swarm Zone. **Class 1_C**

5.4 Exploration Drilling Programme

5.4.1 Overview

Exploration drilling activities commenced early February 2010 with an initial deployment of 2 drilling rigs. The 3rd rig was later deployed after 2 weeks.

Exploration boreholes were drilled by rotary air percussion methods. Drilling foam additives were used at the Contractors discretion. In general the exploration boreholes were designed and constructed ‘open hole’ (without casing) in order to minimise costs and maximise the application of geophysical borehole logging.

The general borehole design for both the Lebung and the Ecca southern areas air percussion boreholes was a telescoping design, starting the borehole with an initial diameter of 12” (304 mm) to the base of the unconsolidated Kalahari deposits and then installing 10” (254 mm) casing. The boreholes were then continued at 10” diameter to the first water strike below the Kwetla mudstones or Ecca mudstones where 8” (203 mm) casing was installed and grouted before continuing 8”. It was anticipated that should a multi-layered aquifer be encountered, a string of 6½” (165 mm) casing could then be inserted and grouted to separate the two aquifer units and the borehole could be completed at either 6½” (154mm) or 6” (152 mm) open hole. This would enable aquifer parameters for each of the aquifer units to be determined and water samples taken for each.

However, partially due to delays in the drilling progress, this design allowing potential separation of the aquifers could not be adhered to. Water quality and head data was, nevertheless, collected at each water strike before drilling deeper. Water quality and yield were also recorded at regular interval so as to identify any major changes resultant upon subsequent water strikes.

Due to the difference in the geological environment between Target Area A, south of Zoetfontein Fault which is predominantly Ecca and Target Area B which is almost exclusively basalt, the drilling specifications were varied. In Target Area A (Malwelwe area) the Kalahari and the Kwetla mudstones were cased off at 8 inches and the aquiferous units, the Boritse and the Kweneng Formation were drilled open hole. In the Target Area B the 8 inches casing was set into solid basalt below the Kalahari beds and thereafter an open hole was drilled through the basalt into the Lebung (Ntane – Mosolotsane).

In total 20 exploration boreholes have been completed, with a total meterage of 5634m, which is an average of 282m per borehole. Borehole details are given in Table 5.6 and locations indicated on Map 2. Borehole logs are shown in Technical Report No. 3, Geophysical Logging Report.

Ten boreholes (BH 10671-10680 inclusive) were drilled to explore Target Area A (Map 2), the Malwelwe area which is primarily underlain by the Ecca. The remaining 10 boreholes were shared between Target Areas B and C. In Target Area B, Eight boreholes (Bh10681 – 10688) were drilled to investigate the Ntane /Lebung aquifer.

Table 5.6 Exploration Borehole Drilling Summary

	BH ID	**Peg No.**	**Date of Completion**	**UTM Coordinates (Cape Datum)**		**Bh Depth (m)**	**Blow out Yield (m^3/hr)**	**Water Strikes (mbgl)**	**Rest Water Level (mbgl)**	**Confining Head (m)**	**TDS Water Quality (mg/l)**
				Easting	**Northing**						
1	BH10671	L12/1650	11/02/2010	323656	7345931	174	16.74	101	58.00	53.0	367
2	BH10672	L21/850	12/02/2010	325782	7354685	306	30.5	111	56.59	54.41	420
3	BH10673	L16/970	16/02/2010	331615	7350901	162	20.19	106, 130	69.04	36.96	316
4	BH10675	L1/930	19/02/2010	315968	7332801	174	2.0	100	81.08	18.92	366
5	BH10674	L18/1050	22/02/2010	325897	7350849	280	89	106, 121	63.4	42.6	365
6	BH10676	L3/1210	05/02/10	315122	7355245	416	6.6	145, 413	52.0	93.0	430
7	BH10677	L5/400	02/03/10	335502	7339311	137	2.3	112	76.60	35.4	340
8	BH10678	L8/1530	08/03/10	311966	7344877	266	DRY	NIL	76.3	-	-
9	BH10679	L19/90	15/03/10	323127	7349325	300	65 -100	147	67.0	80	-
10	BH10680	D6/8400	11/03/10	328714	7351537	228	0.46	160	89.95	70.05	-
11	BH10681	L28/9100	23/03/10	289750	7369191	365	41	45, 85, 118, 167, 290	42.92	2.08	380
12	BH10682	L31/1110	18/03/10	295503	7378174	198	59.4	106, 125, 152	65.96	40.04	510
13	BH10683	L30/6210	23/03/10	284324	7390209	224	0.8	125	**?**	-	352
14	BH10684	L29/6830	24/03/10	280869	7374594	200	1.8	115	65.96	49.04	415
15	BH10685	L29/1290	30/03/10	279366	7369911	337	43.92	191, 228	76.9	114.1	930
16	BH10686	L26/15370	12/04/10	314234	7382261	468	25	388	79.90	308.1	240
17	BH10687	L27/3730	09/04/10	306490	7373066	310	44	226	96.28	129.71	454
18	BH10688	L26/2140	22/04/10	314426	7369115	557	51	177, 522	79.30	477.7	390
19	BH10689	L35/710	17/04/10	398371	7360934	251	dry	nil	73.79	-	
20	BH10690	L32/1470	21/04/10	371492	7369960	288	1	nil	148.48	-	520

Target Areas A and C

In Target Areas A and C the Ecca Aquifer drilling was fairly straight forward and there were no major drilling problems encountered. Massive groundwater inflows that slowed down the drilling rates were encountered in boreholes Bh10674 and Bh10679 but these were quickly attended by the Contractor by the introduction of a booster compressor to site. Each of the three drilling rigs deployed on site had two compressors coupled up in parallel and some special high pressure down hole hammers were used. This approached doubled the drilling rate such that most boreholes (averaging 200m) were completed in 3 to 4 days as compared to the normal 7 to 10 days when only one compressor is in use.

The Kalahari Beds range in thickness from 20m to 30m, comprising loose sand, silcrete and calcrete and occasional sandstone. Calcified mudstone is often found underlying these sediments, and has been classified as part of the Kwetla Formation. The Kwetla Formation is relatively thin in Target Area A although borehole Bh1068 registered maximum thickness of 111 m. Bh10675 in the south registered the least Kwetla thickness. The Kwetla is characterised by grey, non-carbonaceous, often calcareous siltstones and/or mudstones and distinctly different from the Boritse mudstones that are carbonaceous in nature.

The coals in the Boritse were generally soft and in borehole Bh10679 and Bh10680 substantial part of the upper coals were cased-off to prevent possible collapsing. Water strikes were generally within the Boritse sandstone and coals.

Target Area B

In Target Area B the Kalahari Beds range in thickness from 15m to 66m, comprising loose sand, silcrete and calcrete and occasional sandstone. Calcified and in places fractured basalt is often found underlying these sediments. At borehole Bh10686, 66m of the Kalahari sediments were registered indicating a general Kalahari sand cover increase from the west to the east.

The Lebung Group is generally divided into two units, the upper Ntane Sandstone Formation underlain by the more argillaceous Mosolotsane Formation. All eight “Lebung” holes penetrated both these formations as intended.

The Ntane Sandstone is characterized by uniform, fine to medium grained, friable and poorly cemented, clean sandstone of aeolian origin. The average thickness of the Ntane from these seven boreholes is 60m, ranging between 45 and 65m. Occasional moderately or well cemented horizons occur. Colour varies significantly in any given profile, with the most common colours being, pink, reddish brown, cream and orange. Often the upper portion of the Ntane Sandstone is baked (e.g. Bh10681, 10682, 10688) as a result of basalt lavas that were extruded on top. Another significant feature noticed during dry drilling was the general argillaceous nature of the sequence with depth that is well pronounced in the Mosolotsane Formation and this may have a significant influence on the hydrogeological characteristics of the aquifer.

The Mosolotsane Formation was taken from the first argillaceous unit encountered at the base of the Ntane Sandstone, although the formation is not restricted to argillaceous units alone. Generally, the formation comprises reddish brown siltstones and/or mudstones, often intercalated with greyish argillaceous sediments particularly towards its base. Sandstone horizons can be quite significant, varying between 1m and 5m in thickness, and are reddish brown or pale grey in colour (e.g. Bh10684 and 10685). The Mosolotsane varies quite significantly in thickness from 4m (Bh10682) to 42m+ (Bh10684). It should be noted that two of the holes (Bh10686 and 10688) did not penetrate the Mosolotsane Formation. The Mosolotsane in Bh10683 and Bh10684 appears to be predominantly arenaceous, and the junction with the overlying Ntane Sandstone was taken where thin reddish siltstone and pinkish mudstone laminae within the Ntane Sandstone begin to occur. This formation is also predominantly sandstone in Bh10683 and Bh10684, the top of which has been defined where thin red mudstone horizons were first encountered.

The Kwetla Formation that underlies sediments of the Lebung Group was not intercepted in these boreholes since all the boreholes were terminated in the Mosolotsane Formation.

5.4.2 Drilling Results

Ecca Aquifer

A total of 12 exploration boreholes were drilled in the Ecca Aquifer. Ten (10 no.) exploration boreholes (Bhs10671-10680) were drilled in Target Area A (Malwelwe area) and were to help identify the margins and the extent of the Ecca aquifer as a follow up on work done by BRGM. The other two boreholes (Bh10689, 10690) were drilled in the Target Area C to the east and were to investigate the Ecca sediments to the east of the Botlhapatlou 'High' elevated basement zone.

The Malwelwe area is centred on the Main Graben (Fig 5.7) as defined by BRGM (see Inception Report). The conceptual understanding is that the grabens represent original sedimentation topography and that the edges of the grabens are more likely to be characterized by coarser sandy sediments in a higher energy environment with the centre of the graben receiving the fine more argillaceous material in a much lower energy environment. It is also very likely that the edges of the grabens are structurally controlled, with tectonic movement occurring during Ecca sedimentation contributing to the marginal higher energy deposition and possibly even 'fault scarps' with development of very coarse scree and talus fans in these graben edge zones.

Since the immediate pre-Karoo basement in the Malwelwe area is mostly doleritic in nature this has enabled the overall thickness of the Karoo sequence and the disposition of the various grabens and horsts to be well defined by ATM (by BRGM) as well as by TDEM soundings during the current project surveys.

As the most prospective exploration sites, most Target Area A boreholes were drilled on the edges of grabens (Map 4) that had been generally defined by the BRGM ATM and then specifically examined by TDEM soundings.

Boreholes Bh10676 and Bh10679 were drilled in the middle of this graben and had the deepest water strikes (145 m and 147m respectively), but in both cases the pre-Karoo basement was not intercepted and both boreholes were terminated in the Bori Formation. Borehole Bh10676 was mostly argillaceous sediments and only marginal yield of 6.6m^3/hr was encountered at considerable depth of 413m in the Bori Formation. Borehole Bh10679, also in the middle of the Main Graben, did however, intercept some 162m of sandstone and a significant blow out yield of about 89m^3/hr was registered during drilling. During production drilling more boreholes were drilled in ths zone and the results were similar.

Boreholes drilled on graben edges produced different results. Boreholes Bh10671, 10673 and 10674 drilled on the Main Graben edge were successful and the yield ranged from 17 to 89m^3/hr. Other boreholes drilled on smaller graben edges are Bh10672, 10677 and 10678 but only Bh10672 was successful with a blow out yield of 30m^3/hr.

Boreholes Bh10675 and Bh10680 were located on horsts that indicated fractures (F5, F9 and other minor linear structures) but the results were disappointing as both boreholes were practically dry and in both cases the dolerite basement to the Karoo sediments was intercepted at relatively shallow depth indicating a reduced thickness of Ecca aquiferous sediments.

The groundwater in the Ecca was mostly struck at the contact between the Kwetla mudstones and the Kweneng arenaceous coaly sandstones. A confining head was recorded in all the boreholes as indicated in Table 5.7 below.

Table 5.7 Confining Heads in the Ecca Aquifer

BH No.	Aquifer Base (m)	First Water Strike (FWS) (mbgl)	SWL (mbgl)	Confining Head (m)	Sat. Thick FWS (m)	Sat. Thick SWL (m)
10671	170	101	58.00	43.00	69	84
10672	278	111	56.59	54.41	167	33
10673	162+	106	69.04	36.96	56+	135
10674	280+	100	81.08	18.92	80+	71
10675	151	106	63.40	42.60	23	42
10676	-	145	52.00	93.00		
10677		112	76.60	35.40		
10678		dry	76.30	-		
10679	294	147	67.00	80.00	147	-
10680	112	115	89.95	25.05	0	

Individual borehole yields are extremely variable and range from dry boreholes (Bh10675, 10678, 10680) to high yielding boreholes like Bh6824, 6825, 10674, and 10679 thus highlighting the importance of secondary porosity and that hydrogeological system is not as homogeneous as previously thought.

A tabulation of blow-out yield and CRT test yield is presented in Table 5.8 and a cross plot (Fig 5.8) of the values indicate two distinct groups in the Ecca. An Ecca “low yielding” group with blow-out yields 1-35m^3/hr is evident and this assumes a steep gradient linear relationship with the test yields up to 60m^3/hr. The “high yielding” Ecca group has test yields 80-110m3/hr and displays a low gradient slope. Borehole Bh6825 recorded a blow out yield of 15 m^3/hr and has been tested at 90m^3/hr is anomalous in the system although it plots well with the “high yielding” Ecca boreholes.

The addition of the Ntane/ Lebung boreholes on the cross plot produced a 3rd group with a moderate gradient. Due to test pumping logistical problems, it is difficult to comment much on the Ntane/Lebung grouping but the indications are that the Ntane/Lebung aquifer has different characteristics.

Table 5.8 Comparison of Blow-out Yield and Specific Capacity

Borehole No.	Airlift Yield	CRT Rate	Borehole No.	Airlift Yield	CRT Rate
	(m^3/h)	(m^3/h)		(m^3/h)	(m^3/h)
6824	36	65.1	10677	2.3	3.5
6825	15	90.4	10681	41	20
6826	30	50.8	10682	59.4	40
6827	45	100.4	10683	0.8	not tested
6828	18	30.1	10684	1.8	not tested
6829	12	8	10685	43.92	30
6830	18	not tested	10686	25	10
10671	16.7	20	10687	44	25
10672	30.5	50	10688	51	30
10673	20.19	25.1	10689	dry	Not tested
10674	89	110.2	10690	1	Not tested
10676	6.6	5			

Water quality in the area is generally good with TDS values ranging from 300 – 650 mg/l, with the highest values recorded to the south in borehole Bh10677. Water quality is further discussed in Section 3.2

Drilling results reveal that the arenaceous sediments of the Ecca Group in the Malwelwe area are high yielding (10-90m3/hr) and groundwater is fresh with TDS values less than 650mg/l. Towards the west, south, south-east the Ecca groundwater resources are limited because of reduced aquifer thickness and presence of horst structures. To the north west of Malwelwe the Ecca is too argillaceous indicating that the general Karoo basin is deeper. The northern area, around Bh6830, appears to display some potential although the graben-horst structures are dominant. Cross-sections of the wellfield development area around Malwelwe are in Fig 5.8 and these show the graben-host influences.

Lebung Ntane Sandstone Aquifer

Three of the eight ‘Lebung’ boreholes (Bh10681, 10682 and 10688) encountered groundwater in the basalt although major water strikes were struck within the Ntane Sandstone Formation. The contact zone between the basalt and the Ntane Sandstone was always the first water strike in the Ntane Sandstone and thereafter the yield increased with depth as more sanstone aquifer was penetrated.

Table 3.10 below illustrates the changes in blow out yield and water hydrochemical signatures between the Stormberg Basalt and the Ntane Sandstone as monitored during the drilling of Bh10681. Elevated TDS and conductivity values are evident in the basalt. The composite head is at 42.92m where as the basalt head before the Ntane was struck is at 38.95m depth. In general the Ntane Sandstone aquifer is confined as shown in Table 5.9.

Table 5.9 Bh 10681 Water Strike Details

Depth (m)	Blow out Yield (m3/hr)	pH	Conductivity (u/cm)	TDS (mg/l)	Comments
45	no yield				1st water strike - basalt
85	6.7				2nd water strike - basalt
92	12.96	8.74	1520	780	
107	19				
162	9.8	8.45	1720	850	
167	13	8.74	1520	780	38.95 swl - basalt
233	8.6				
293	10.5	7.87	950	470	1st water strike - Ntane
302	22.3	8.68	840	420	
303	22.39				
305	27.4	8.6	730	360	
307	10.6				
311	40	8.12	760	380	
321	41	8.53	940	470	
331	43				
343	44	7.5	740	370	
349	44			300	
358	44	8.45	800	400	
365	44	8.31	770	380	42.92 swl - composite

Hydrogeological details for the last boreholes (Bh10689, 10690) are limited as the boreholes were essentially dry and only sizeable seepage yield could be recorded in Bh10690.

The relationship between saturated thickness and blow out yield is difficult to appreciate because the blow out yields were significantly affected by the groundwater head (Table 5.10) and does not reflect the true borehole yield. It is probably best to compare aquifer thickness with test pumping results rather than blow-out yields.

Table 5.10 Lebung Boreholes - Confining Heads

Bh No.	Ntane - Base Depth (mbgl)	Ntane 1st Water strike (mbgl)	SWL (mbgl)	Ntane Confining Head (m)	Saturated. Ntane (m)
10681	340	300	42.92	257.08	40
10682	194	152	65.96	83.04	42
10683	198	125	66.93	58.07	73
10684	158	115	65.96	49.04	43
10685	308	228	76.90	151.1	80
10686	468	388	79.90	308.10	80
10687	292	226	96.28	129.72	66
10688	557	522	92.45	429.55	35+

Target Area A

Target Area A (Malwelwe) was both extensively and intensively investigated so as to refine and test the geophysical hypotheses developed during the Inception Phase primarily on earlier BRGM information. From current surveys targeted on the basis of these hypotheses numerous ground geophysical anomalies defining potential structures were identified along various lines. It was then necessary to prove their groundwater development potential by executing an exploration drilling exercise which was reviewed as the drilling results became available.

The exploration boreholes in Target Area A are shown on Figure 5.7 which also illustrates the structures (grabens, horsts, faults and lineaments) which were investigated. Below is a discussion of the drilling results and their comparative analysis of geophysical survey outcome on a borehole basis and also in relation to the targeted graben/horst zone.

Main Graben

Both the edges and the centre of the graben were investigated and the results as tabulated in Table 3.12 indicate that structures are important and these are easily mapped by both magnetometry and EM profiling. The location of these survey lines were primarily guided by the previous BRGM AMT and TDEM soundings that mapped out the post Karoo horst and graben structures very well. The sub-regional approach adopted by BRGM on the use AMT together with gravity in order to determine the pre-Karoo basement configuration would appear to be the most effective the initial approach to a Karoo basin groundwater investigation.

The individual exploration borehole yields appear to be definitely related to the following site characteristics:

- aquifer thickness (arenaceous material in particular)
- location of site in relation to the graben configuration, (ie edges, centre and distance into the basin)
- local fracture systems which are important in enhancing transmissive properties and thus borehole yields.

However, these general observations are at times not always indicative for the location of a successful borehole, as examination of several boreholes (eg Bh10674, 10679 and 10680), illustrates (Table 5.11). Boreholes located on the graben edge are straight forward to explain, (Bh10674). However there is no obvious reason why Bh10680, located on a minor graben edge, was dry when all the geophysical parameters indicated a highly prospective site with a considerable thickness of Kweneng Formation (143m). Conversely, Bh 10679 was located in the middle of graben and may have been expected to produce poorer results due to possibly more argillaceous sediments, but it did reveal a thick arenaceous sequence and gave a high yield. The importance of structures can not be over-looked and from these results much of the flow is heavily influenced by structures.

Dipuo Graben

Only one Bh10678 was drilled in this graben and the results at this site are similar to those at Bh10680 in the Main Graben. The southern edge of the Dipuo Graben was targeted. The borehole was dry despite having intercepted 150m of the aquifer, although much of it is argillaceous.

Resultant geophysical EM/magnetic anomalies pointed to a steep basement gradient also defined by BRGM gravity/AMT anomalies. This site was thus graded $\mathbf{1_A}$ in terms of groundwater development potential and was in fact provisionally earmarked for a straight production drilling site considering its proximity to BH6827 which is along the same E - W feature.

Drilling chips indicated some fracturing of the formations and it is difficult to explain the negative drilling results of this site. *However, from downhole geophysical electrical log, the coarse grained sandstone defined by the 150 ohm-m to 250 ohm-m, is from 170m to 230m which implies that there is only 60m of arenaceous horizon within the Ecca.*

The results of this borehole do not fit into the conceptual hypothesis and it is risky to attempt drilling a production site west of this borehole.

Letlhakolane Graben

An attempt to develop a borehole (Bh10675) in this zone was made based on the results of exploration drilling within the Gaotlhobogwe Valley. High yielding boreholes had been drilled south of this site and the objective was to investigate the possibility of an extension of the Gaotlhobogwe Wellfield northwards.

Current EM and magnetic profiling data picked the F9 and the NW-SE faults from aeromagnetic data set and TDEM results indicated a basement depth of 230m. However, drilling proved dolerite basement at 170m and the final yield was only 2m^3/hr. Minor fracturing was confirmed during drilling. It is apparent that the uplifted doleritic basement and the resulting reduced aquifer thickness have negatively influenced the drilling results.

Mopipi Graben

The Segatse Horst – Mopipi Graben contact investigation was intended to extend the wellfield southeastwards from BH6828. The EM/magnetic results show twin faults which define the graben-horst contact along where a production borehole BH6828 is located. TDEM soundings indicated a potential aquifer from 84m to 182m and the resistive basement at 227m.

Drilling of Bh10677 revealed that the pre-Karoo basement is much shallower (127m) than indicated by the geophysical survey and the yield was only 2.3m^3/hr. The failure of this site is attributed to the possibility of the borehole being placed on shoulder of a steep edge of the graben-horst contact zone rather than on the edge itself. On this premise a thicker sandstone sequence is expected further into the graben, to the NE of the present borehole location.

It is apparent that the very specific definition of the steep horst-graben edge zone is critical in siting a successful borehole. A series of TDEM soundings across these structures would generate a pseudo-section and this may then enhance success rate.

Table 5.11 Summary of Geophysical Survey Results and Exploration Drilling – Target A

Bh No.	Peg No.	Site Classification	Location	Structure Targeted	Blow out Yield m^3/hr	Comments on Geophysical Interpretation and Drilling Results
Main Graben						
10671	L12/1650	**1_A**	Southern edge of Main Graben	steep sharp edge on Mag. and EM anomaly	17	• sharp edge is confirmed. • Thin aquifer on host intercepted. • Edge resolution is critical for siting borehole on edges, • Successful site
10672	L21/850	**1_A**	Northern edge of graben	gradual, faulted edge	30	• gradual edge is confirmed, quite deep to basement • thick aquifer on subdued host interpreted. • structure resolution is critical for siting bhs on gradual edge. • Successful site
10673	L16/970	**2_A**	Northern edge of graben	steep sharp faulted edge on Mag. and EM	20	• sharp edge is confirmed. • Thin aquifer on horst intercepted. • Edge resolution is critical for siting bhs on edges • Successful site
10674	L118/1050	**1_A**	Northern edge of graben	Faulted zone in the near graben centre	89	• gradual edge is confirmed, quite deep to basement • thick aquifer on subdued horst interpreted. • structure resolution is critical for siting borehole on gradual sloping edge. • structure enhance yields • Successful site
10676	L3/1210	**2_A**	Middle of graben	F11 and NW- SE intersection zone	6.6	• thick sediments confirmed, quite deep to basement • argillaceous sequence within basin interpreted. • structures not important in argillaceous sequence for siting boreholes • geophysically successful site, but low yield
10679	L19/90	**3_A**	Middle of graben	Faulted zone in the graben centre	106	• thick sediments confirmed, quite deep to basement • arenaceous sequence within basin interpreted. • structure are important in arenaceous sequence for siting bhs for high yields • Successful site, with high (89m3/hr) yield
10680	D6/8400	**3_A**	North of Main Graben	Local fault on Ranch Horst	0.46	• sharp edge is confirmed. • Thin aquifer on host intercepted. Thin Boritse(19m) but thick Kweneng (143m) • location with respect to graben configuration is critical for siting bhs on edges • structure location is important • not a successful site

Bh No.	Peg No.	Site Classification	Location	Structure Targeted	Blow out Yield m^3/hr	Comments on Geophysical Interpretation and Drilling Results
Dipuo Graben						
10678	L8/1530	**1_A**	Southern edge of graben	Graben edge, F5 and E – W fault	dry	• sharp edge is not confirmed. • thick Kwetla mudstones intercepted (20-107m depth) • Thin aquifer (170- 230m depth) intercepted. thick Boritse(100m) and Kweneng (50m) • location with respect to graben configuration is critical for siting bhs on edges • structure location is important • not a successful site, not properly understood why it is dry
Letlhakolane Graben						
10675	L1/930	**2_A**	Edge of a Graben	F9 and NE-SE fault	2.0	• horst is not confirmed. • thick Kwetla mudstones intercepted (20-107m depth) • Thin aquifer (82- 169m depth) intercepted. thick Boritse(48m) and Kweneng (39m) • location with respect to graben configuration is critical for siting bhs on graben edges • structure location is important • not a successful site, not properly understood why it is dry
Mopipi Graben						
10677	L5/ 400	**1A**	Southern edge of graben	Local twin faults along which BH6828 is situated	2.3	• sharp edge is confirmed by basement at 227m depth • Thin aquifer on Segatse host intercepted, Boritse (40m) and Kweneng (40m) • Edge resolution is critical for siting bh on edges. • not a successful site but still a good potential site which warrants further exploration.

Target Area B

A complete and fully saturated Ntane Sandstone aquifer is known from elsewhere in Botswana to be optimum with respect to higher borehole yields. It is also known from experience that the top most sections of this aquifer are more productive than the lower sections due to increase in clay content with depth.

If it can be assumed that the presence of the overlying Stormberg Basalt is more likely to ensure that a full sequence of Ntane Sandstone is preserved, it therefore follows that the most economic zones for drilling will be where the Stormberg Basalt is relatively thin, with the full saturated Ntane sandstone sequence beneath.

Following this reasoning, in Target Area B, it was thus considered most appropriate to investigate the different structural blocks within the Stormberg Basalt area with respect to the presence or absence of the basalt cover as well as its thickness. Fig 5.9 shows the spatial distribution of these different blocks as well as the exploration borehole drilling sites.

The results of the exploration drilling sites are presented according to groundwater development potential classes (Table 5.12) and the boreholes drilled are shown in Fig 5.2.

Table 5.12 Summary of Geophysical Survey Results and Exploration Drilling – Target B

Bh No.	Peg No.	Site Classification	Location	Structure Targeted	Blow out Yield m^3/hr	Comments on Geophysical Interpretation and Drilling Results
High Groundwater Potential Class						
10681	L28/9100	$\mathbf{1_B}$	Basalt-Ntane Contact within 250-450m block	Series of regional and local faults defined by EM/Mag	41	• Highly fractured and weathered basalt. • Several water strikes (167m) within the Stormberg Basalt. • Groundwater development potential proved for production drilling • Successful site
10686	L26/15370	$\mathbf{1_B}$	Basalt-Ntane contact 250m to 350m	Local fault structure defined by weak EM/Mag anomaly	25	• Minor fractures as evidenced by drill chips • Main water strike at the Basalt-Ntane contact • Predicted deep water strikes confirmed • Successful site
10688	L26/2140	$\mathbf{1_B}$	Basalt-Ntane contact 250m to 350m	Prominent regional fault defined by strong EM/Mag anomalies	51	• Fractures induced by faulting confirmed by drilling. • Deep water strikes as predicted. • Some water strikes within the basalt flow confirms the fractured basalt flow • Successful site
Moderate Groundwater Potential Class						
10682	L31/1110	$\mathbf{2_B}$	Basalt-Ntane contact 150m to 250m	Regional fault defined by strong EM/Mag anomalies	60	• Deep and extensive fracturing detected • Successful site, but the Ntane is thin (~40m thick) • The Ntane is highly fractured producing collapsing conditions when drilling. • High yields of 60m^3/hr
10685	L29/1290	$\mathbf{2_B}$	Middle of a hydrogeological block	Strong EM/Mag anomalies defining local fault	44	• thick basalt with minor fractures confirmed., • Successful site, with high (44m^3/hr) yield
10687	L27/3730	$\mathbf{2_B}$	Northern Zoetfontein fault Z2	Regional fault picked up by strong EM/Mag between two hydrogeological blocks	44	• Intense fractures of basalt • Water strikes within basalt • This structure very important • A successful site
Low To Marginal Groundwater Potential Class						

10683	L30/6210	**3_B**	Basalt-Ntane contact is less than 150m	Major regional fault system dividing two hydrogeological blocks 3_B and 1_B	0.85	• Site was initially graded as on class 2_B because of the thickness of the basalt-Ntane contact. • Deep highly fractured basalt and Ntane sandstone discovered during drilling • not a successful site • More exploration drilling along this structure should be tested to verify its actual potential.
10684	L29/6830	**3_B**	Basalt-Ntane contact is less than 150m	On a sub-regional fault lineaments	2.0	• Site was graded as on class 3_B because of the eroded thickness of the basalt. • thin highly fractured/ weathered basalt and Ntane sandstone not saturated discovered during drilling • not a successful site • More exploration is better to the east where basalt is thick & ntane is saturated

Target Area C

Only two boreholes were drilled within this Ecca aquifer target area. These were intended to test the same graben-horst hypothesis which was successful in Target A. There are regional structures and pseudo graben-horst structures which seem potentially ideal for exploration borehole drilling.

Bh10689 and Bh10690

Bh10689 was drilled on L35/710 on the edge of the Kweneng Dyke Swarm zone. The EM and magnetic profile data at this site suggest a graben-horst contact. However drilling results produced a dry borehole to a depth of more than 240m. The Boritse aquifer is very shallow to a depth of about 90m while the Kweneng sandstone and mudstones extend to a depth of 190m and overlie the Dwyka tillites. This suggests that this site is on a raised basement zone.

Borehole BH10690 was drilled to 251m and was dry despite the existence of fractures and thick medium to coarse grained sandstones which extend from 166 to 230m.

5.4.3 Comparison of Geophysical Survey and Drilling Results

The geophysical survey techniques applied during the Exploration Phase comprised magnetic profiling, Horizontal Loop Electromagnetic (HLEM) profiling, Time Domain (TDEM) electromagnetic sounding and Vertical Electrical Soundings (VES). All methods were applied along pegged traverse lines set out to examine the layered Karoo geological sequence and the influence of the structures/grabens that transect this sequence.

The exploration drilling results confirmed the existence of most structures/ grabens, delinated from both EMT, TDEM and aeromagnetic data as having profound influence in controlling groundwater occurrence and flow directions.

Structural features represented by inflection points and dykes appearing as local magnetic intensity highs along ground magnetic profiles also confirmed the structures interpreted from aeromagnetic data. Pre-Karoo dykes and sills are both depicted by magnetic intensity anomalous local highs, although the sills were much broader than the dykes. It is important to note that no post-Karoo sills or dykes were mapped in the project area.

Conductive zones were depicted by In phase (IP) over Out phase (OP) high ratios (at least over 1) along horizontal loop electromagnetic profiles. Unfortunately, HLEM data have not contributed much to the study because of poor penetration of less than 100m over much of the Project Area.

Overall there is a good to fair correlation between all interpreted resistivity probes (TDEM 200m loop, VES 400m half spread, TDEM 100 loops respectively) and exploration borehole drilling geologic logs, with a some few exceptions discussed below.

The TDEM200 and TDEM400 depicted the top of Boritse Formation aquifer all over the Project Area though with differing degrees of accuracy from place to place depending on the local sub cropping geology (Map 1). The implications of this observation are interesting in that resistivity soundings will remain an important tool in identifying groundwater targets over the sub-region rather than HLEM. HLEM rarely ‘sees” beyond 100m depth over the

Project Area. In particular, TDEM 200m loop with a more powerful transmitter provides better quality resistivity data. The TDEM and VES modelled resistivity were interpreted using the following criteria:

- Kalahari Formation (sand, calcrete/ silcrete and semi-consolidated clayey sands) resistivity ranges from around 100 to around 1000 ohm.m.
- Kwetla Formation (mudstone and shale) resistivity was around 10ohm.m or less.
- Ecca sandstone (Boritse Fm) resistivity with relatively fresh water is around 50 ohm.m whilst Ecca siltstone, coal and shale intercalations with or without saline water have around 20 ohm.m or less resistivity.
- The pre-Karoo basement, frequently represented by doleritic sills, has bulk resistivity of over 200 ohm.m.

Drilling results and modelled resistivity were compared on completion of the drilling programme. Individual point resistivity-depth interpretations along a profile were used to construct resistivity cross-sections and these were very useful in overall data interpretation. Various structural blocks were easily identified and these sections were much better where existing boreholes offered control as was the case along the main E- W BRGM survey line that passes through Malwelwe village (Figure 5.7).
In addition, the geophysical profiles aided the selection of the exploration drilling sites which were distributed to assess the extent and hydrogeological characteristics of the Ecca Aquifer.

It is clear that large loop TDEM soundings will remain an important tool in identifying groundwater targets over the sub-region, with the VES and TDEM 100m loop relatively redundant in this geological environment.

If additional work in this Target Area is contemplated in the future intensive exploration by use of TDEM/AMT methods is recommended so as to properly define the graben - horst edge.

5.5 Borehole Geophysical Logging

5.5.1 General

Borehole geophysical logging was performed on selected boreholes within the Project Area with the following specific objectives;

- Detailed identification of lithological units,
- Definition and characterisation of all aquiferous and non-aquiferous units for input data into the groundwater numerical model,
- Analysis of salinity of water with depth,
- Measure insitu rock properties.
- Correlation of lateral variations of lithology and water quality,
- Resolve stratigraphic ambiguities,
- Contribute to production borehole design,

5.5.2 Instrumentation

A Robertson Geologging Unit was used to log the selected boreholes. Two probes were used and these are described below;

Gamma Density – Probe 6673: Natural Gamma, caliper, long spaced density, high resolution density

This probe measures and outputs compensated formation densities (long spaced and high resolution densities), borehole diameter and natural gamma. It uses a Caesium 137 (137Cs) source which emits gamma rays which penetrate the formation and are scattered by the electrons present. The long spaced density was used to get the formation porosity log.

Apart from measuring the borehole diameter, the calliper is responsible for pressing the tool against the borehole wall to ensure that only gamma rays passing through the formation are detected.

Natural gamma logs were used to measure the naturally occurring gamma emissions from the formation surrounding the borehole and are very useful in delineating lithologies. For instance shales have higher radioactivity than sandstones.

Electrical Probe – Probe 6676: Long normal resistivity (64"N), short normal resistivity (16"N), single-point resistivity and self potential

Resistivity logs are the most usefully applied in groundwater exploration studies as they are vital in identifying the general geological/stratigraphic information. Resistivity values provide excellent information on two important hydro-geological aspects being aquifer location, aquifer shaliness and water quality. In sedimentary sequences consolidated aquifers are usually much more resistive than aquicludes such as clay layers and shales.

5.5.3 Geophysical Logging Results

Borehole geophysical logging formed an integral part of the exploration activities during the Stage 2A of the project. The logging was conducted when the drilling was completed because none of the exploration boreholes were cased except for the top loose Kalahari and weathered unstable upper formations. Three illustrative geophysical logs from the three Target Areas (BH10674, BH10687 and BH10689) are shown in Appendix B and the rest of the logs will be presented in the Technical Report No. 3, Geophysical Logging Report. Construction details of all the Exploration boreholes are given in Table 5.13 below although not all boreholes in the table were logged.

Table 5.13 Exploration Borehole Construction Details

BH No.	Depth (m)	UTM Coordinates (Cape Datum)		Drilling Details (m)			Casing Details (m)		
		Easting	Northing	12 inches	10 inches	8 inches	12 inches	10 inches	8 inches
10671	174	323656	7345931	30	70	74	2	30	100.5
10672	306	325782	7354685	30	71	205	3.58	30	102
10673	162	331615	7350901	30	43	89	3.1	30	74
10674	280	325897	7350849	30	59	191	5.67	30	90
10675	174	315968	7332801	30	40	104	6	30	70
10676	416	315122	7355245	30	67	319	7.2	30	98
10677	130	335502	7339311	30	41	89	12.12	30	72
10678	266	311966	7344877	30	96	140	6.12	30.2	127

10679	300	323127	7349325	30	106	164	4.77	30	137
10680	228	328714	7351537	30	41	157	4.5	30	72
10681	356	289750	7369191	25.35	16.21	258.44	6.12	25.35	41.56
10683	224	295503	7378174		66	158		12.36	67
10684	200	284324	7390209		55	145		9	56
10685	337	280866	7369911		72	265		10.34	73
10686	468	314234	7382261		72	396		10.35	73
10687	310	306490	7373066		65	245		6.12	66
10688	557	314426	7369115		54	503		12.19	55
10689	251	398371	7360934		81	170		12.22	81.4
10690	288	371492	7369960		171	117		8.15	172
Total	**5117**			**300.00**	**1205.21**	**982.00**	**61.18**	**406.28**	**1627.46**

A test borehole at WCS offices was used for calibration so as to check the data quality of the project exploration boreholes. This test borehole was logged before and after the project logging.

All logging data was processed and interpreted by the Consultant and it has been comprehensively reported in a separate Geophysical Logging Report. The various geophysical characteristics of the lithological units in the Project Area are summarized in Table 5.14, below and these were useful in the determination from the logs of most important lithological unit thicknesses.

Table 5.14 Summary Geophysical Characteristics of Main Lithological Units

Lithological Unit	Natural Gamma	Density	Resistivity	Porosity	Comment/Remarks
Kalahari sand and cretes	Always measured in cased sections	Always measured in cased sections	Always measured in cased sections	Always measured in cased sections	Always measured in cased sections
Karoo Basalt	Very low >50 API	High density values 2.5-2.7 g/cc	Weathered 30-100 ohm-m, fresh basalt 100-300 ohm-m	Low >18%	Highly distinct density contrast between Ntane and basalt was used to identify the contacts
Ntane Sandstone	>50 API	2.2-2.3 g/cc and always less than Karoo basalt	100-250 ohm-m	20-30%	Resistivity and density logs were critical to distinguish this layer
Mosolotsane	100-150 API	2.3-2.4 g/cc slightly more than Ntane sandstone	20-100 ohm-m	15-20 %	Resistivity and density logs were critical to distinguish this layer
Ecca mudstone	Variable from 150 to 200 API depending on the shale/siltstones	Slightly lower than sandstone (2.3-2.4 g/cc)	Very low 20-60ohm-m	20%	Very distinctive from surrounding layers except where they are carbonaceous
Shale	High 150 to 300 API	Slightly higher than coaly shale 2.3-2.5 g/cc	Very low 20-60 ohm-m	Very low 10-25 %	Resistivity logs identified these horizons clearly.

Coal	Very low for clean coal (>80API)	Clean coal very low 1.3 to 1.5g/cc.	Very high 200 – 600 ohm-m seems to depend on the cleanness or weathering	If weathered 50 and clean coal as high as 70%	Density log very critical to identify this unit
Coaly Shale	High counts 200 API	2.2-2.3 g/cc	Low 60-100 ohm-m	Less than 30 %	Density and resistivity logs very useful in identifying this unit
Ecca Sandstone clean, porous	Low counts 50 to 75 API for fine to coarse grained	Variable between 2.3-2.5 g/cc depending on amount of silts	Variable values 100-300ohm-m depending on the salinity of water and porosity values.	20-30%	Resistivity and natural gamma logs were very useful to identify these layers.
Ecca Siltstone	75 to 130 API	2.4-2.5 g/cc	Low between 50-100 ohm-m	Very low 18-25 %	Thin siltstone horizons were easily identified by use of resistivity logs.
Tillites	Less than 30 API	2.4-2.5 g/cc	Low resistivity values 60-70 ohm-m	Very low (>20%)	Only resistivity logs could be used to identify this unit since it has almost same density with sandstones.

From the information above it was possible to synthesis the geological and geophysical data sets and come up with stratigraphical interpretation composite logs. The use of drilling cutting logs was critical to the interpretation of the geophysical logs. The above table led to the delineation of thicknesses of individual formations as shown in Table 5.15 below.

Table 5.15 Summary Interpretations of Geophysical Logs

BH No.	**FORMATION THICKNESS**								
	Kalahari (m)	**Karoo Basalt (m)**	**Ntane (m)**	**Mosolotsane (m)**	**Kwetla (m)**	**Boritse (m)**	**Kweneng (m)**	**Bori (m)**	**Dwyka (m)**
BH10671	29	Na	Na	Na	38	31	72	0	Na
BH10672	23	Na	Na	Na	57	105	87	32+	-
BH10674	36	Na	Na	Na	27	114	89	120+	-
BH10676	25	Na	Na	Na	23	148	103	109+	-
BH10678	18	Na	Na	Na	50	118	51	18+	-
BH10681	6	280	67	9+	Nr	Nr	Nr	Nr	Nr
BH10682	14	136	26	9+	Nr	Nr	Nr	Nr	Nr
BH10683	25	99	43	40+	Nr	Nr	Nr	Nr	Nr
BH10685	15	212	76	6+	Nr	Nr	Nr	Nr	Nr
BH10686	64	321	81	Nr	Nr	Nr	Nr	Nr	Nr
BH10687	57	171	69	12+	Nr	Nr	Nr	Nr	Nr
BH10689	16	Na	Na	Na	0	74	100	0	54+

Na - not available
Nr – not reached

5.6 Exploration Borehole Aquifer Testing

Test pumping activities were undertaken by the Contractor, assisted by a sub-contractor. All borehole testing was undertaken using

- a positive displacement pumps powered by a hydraulic motor driven by a diesel engine.
- Water level measurements utilized an access conduit
- electric contract gauge 'dippers', and
- discharge was monitored with calibrated containers.

Testing schedules conformed to the normal DWA Approach of:

- calibration,
- step test and
- constant rate test (CRT) sequence,
- recovery monitored to within 95% after CRT.

A total of 19 boreholes (6 existing production boreholes and 13 project exploration boreholes) have been test pumped. Only one existing borehole Bh6830 was test pumped prior to the establishment of production boreholes.

Calibration tests were performed in order to determine suitable rates for the subsequent step tests, and consisted of 4 to 6 steps each of 15 minutes duration. Conductivity and/or TDS, pH and temperature were measured at the end of each calibration step. Often at low pumping levels no estimate of discharge was available for the first and sometimes subsequent steps due to filling up of the rising main and discharge hose during initial pumping. This was especially observed when testing the low airlift yield boreholes.

Variable discharge step tests comprised 4 to 6 steps, each step being 2 hours in duration. The main purposes of the step test were to determine a suitable rate for the constant rate test and to get a feel of borehole effeciency. Conductivity and/or TDS, pH and temperature were measured at the end of each step. Subsequent recovery, usually to at least 95%, was monitored for all the boreholes tested. In most cases the boreholes were allowed to recover overnight before the start of the constant discharge pumping the following morning.

Constant rate tests (CRT) varied in duration between 3 and 5 days depending on the pumping response. In cases where stabilization of the water level was attributed to under pumping, tests were usually restricted to shorter periods of 2 or 3 days. Reasons for under-pumping included:

- Gross under estimation of borehole capacity during the air-lifting process. This was most common with the existing production boreholes (Bh6824, 6825, 6826 and 6827). Yield estimation during drilling is mainly a function of several factors that include compressor performance, formation properties (transmissivity and porosity) and groundwater head.

- The excessively deep water strikes with a corresponding high heads were common in most boreholes Bh10681, 10682, 10685 10686 10687 and 10688) in the Ntane/Lebung aquifer north of the Zoetfontein Fault, and a consequent unavailability of proper test equipment for such deep water strike boreholes

Conductivity and/or TDS, pH and temperature were measured every 6 hours. Water samples were collected at 24 hours and at the end of each CRT, along with wellhead chemical analysis. Again recovery was monitored to at least 95% before the equipment was pulled out of the borehole.

A comparison of final airlift yields during drilling and CRT test pumping rates indicates that the blow-out yields usually, and sometimes quite significantly, underestimated the capacity of the boreholes. The project boreholes together with existing BRGM production boreholes data is shown in Table 5.16 and an attempt to show the relationship is better illustrated in Fig 5.8. The plot indicates three linear relationships. An Ecca low yield linear relationship is evident and appears to hold up yields of about 30m^3/hr and thereafter another less steep trend termed the 'High Yields Ecca' is quite clear. The only borehole that does not conform to any of the Ecca trends is Bh6825 with airlift of 15m^3/hr and was tested at 90m^3/hr with minimal drawdown of 16.2m after 72hrs of pumping. The 3rd trend is moderate yields (30-70m^3/hr) and is clearly defined within the Ntane/Lebung aquifer. The Ntane/Lebung trend has, however, been affected by the pumping discharge which has failed to adequately test these boreholes. The water strikes were deep and the available pumps could not be set at appropriate depths to stress the aquifer.

Table 5.16 Comparison of Airlift and CRT Yields

Borehole No.	Airlift Yield (m^3/h)	CRT Rate (m^3/h)	Borehole No.	Airlift Yield (m^3/h)	CRT Rate (m^3/h)
6824	36	65.1	10678	dry	Not tested
6825	15	90.4	10679	65	110
6826	30	50.8	10680	0.46	Not tested
6827	45	100.4	10681	41	20
6828	18	30.1	10682	59.4	40
6829	12	8	10683	0.8	Not tested
6830	18	120	10684	1.8	Not tested
10671	16.7	20	10685	43.92	30
10672	30.5	50	10686	25	10
10673	20.19	25.1	10687	44	25
10674	89	110.2	10688	51	30
10675	2.0	Not tested	10689	dry	
10676	6.6	5	10690	1.0	
10677	2.3	3.5			

5.6.1 Ecca Boreholes - Test Pumping Results

Step Tests

A summary of the production boreholes step test results is provided in Table 5.17. Step test graphs are included in Appendix C. No significant temporal trends during pumping with respect to conductivity or TDS were noticed. Generally all the boreholes, except for Bh6827, show low efficiencies of less than 60%. Borehole Bh6827 shows values that range from 84% to 43% with a mid range of about 60%. Fall in borehole efficiency over the duration of the step test was largest in Bh6824 and Bh6828, at around 30%. The smallest fall was in Bh6827.

However the drawdown interval over which the efficiency fall occurs is important in estimating the efficiency of a borehole.

Table 5.17 Production Boreholes - Step Test Results

Borehole	Available Drawdown (m)	Step No.	Discharge (m^3/h)	Drawdown (m)	Conductivity (µS/cm)	Efficiency (%)	CRT Rate (m^3/h)
6824	90.2	1	15.11	0.65	500	41.3	110
		2	30.1	1.89	520	26.1	
		3	45.09	3.67	530	19.1	
		4	55.13	5.44	570	16.2	
		5	60.12	7.25	560	15.0	
		6	70.34	7.40	560	13.1	
6825	118.2	1	20.1	3.66	558	-	90
		2	40.1	5.63	561		
		3	60.2	7.09	516		
		4	70.1	8.22	558		
		5	75.21	9.22	528		
6826	9.3	1	20.1	3.09	590	60.6	50.8
		2	30.1	5.80	610	50.7	
		3	40.13	9.21	640	43.5	
		4	50.21	12.26	610	38.1	
		5	55.64	15.01	600	35.7	
6827	63	1	15.	2.41	653	84.8	100.4
		2	30	6.52	464	73.8	
		3	45	11.88	578	65.1	
		4	60	17.95	541	58.3	
		5	75	23.20	630	52.8	
		6	90	30.05	625	48.3	
		7	110	38.35		43.3	
6828	74.6	1	5	1.31	310	60.0	30.1
		2	15	6.23	275	33.3	
		3	25	17.47	275	23.1	
		4	35	31.32	280	17.6	
		5	45	46.85	281	14.3	
6829	79.4	1	4.01	1.90	360	-	8
		2	8.02	9.33	356		
		3	12.03	83.96	327		
6830	97.7	1	60	1.64	935	98.5	120
		2	80	2.31	959	98.0	
		3	90	2.60	763	97.7	
		4	100	2.88	775	97.5	
		5	105	3.33	758		

The exploration boreholes steps results are tabulated in Table 5.18 and the graphs are included in Appendix C. As was the case with the old production boreholes in the area no significant temporal trends during pumping with respect to conductivity or TDS were noticed. Generally all the exploration boreholes show better efficiencies than the production boreholes above. Borehole Bh10671 show values that range from 87% to 59% with a mid range of about 72%. The high values shown by the low yielding borehole Bh10676 are a result of very low pumping rates that precluded any meaningful results. Fall in borehole efficiency over the duration of the step test was largest in Bh6824 and Bh6828, at around 30%. The smallest fall was in Bh6827.

Table 5.18 Exploration Boreholes - Step Test Results

Borehole No.	Available Drawdown (m)	Step	Discharge (m^3/h)	Drawdown (m)	Conductivity (µS/cm)	Efficiency (%)	CRT Rate (m^3/h)
10671	82.3	1 2 3 4 5	5.0 10.08 15.05 20.10 25.04	5.18 10.58 17.89 27.58 36.90	462 450 440 446 440	87.9 78.2 70.6 64.3 59.1	20
10672	97.42	1 2 3 4 5	10.02 20.07 30.10 40.07 50.18	2.57 10.62 18.39 32.95 44.83	540 528 588 530 560	49.4 32.8 24.5 19.6 16.3	50
10673	84.03	1 2 3 4 5	8.0 16.0 24.0 32.0 40.0	7.79 18.75 33.82 51.96 Pump suction	340 349 351 345	77.4 63.1 53.3 46.1	25
10674	57.05	1 2 3 4 5	40.0 60.0 80.0 100.0 120.0	2.41 6.52 11.88 17.95 23.20	397 394 391 394 398	77.1 69.1 62.7 57.3 52.8	110.2
10676	124.95	1 2 3 4	3 5 7 9	37.46 65.07 102.75 Pump suction	328 325 330	90.1 84.6 79.6	5
10677	124.9539.6	1 2 3	3 5 6	13.42 31.85 Pump suction	328 335	36.4 25.6	5
10679	55.9	1 2 3 4 5	40.0 60.0 80.0 100.0 120.0	5.28 9.80 14.86 21.09 27.09	400 385 390 379 380	65.1 55.4 48.2 42.7 38.3	110

Constant Discharge Rate Tests

Most production boreholes except for Bh6830 were pumped for constant rate and the pumping duration ranged from 72 hrs to 96 hrs depending on the aquifer response to the abstraction. Field data collected during CRT is tabulated in Table 5.19 below

Table 5.19 Production Boreholes - Constant Rate Pumping Field Test Details

Bh No.	Observation Bh no.	Rest Water Level (m)	Pump Intake (m)	Pumping Rate (m^3/hr)	Pumping Duration (hrs)	Max Drawdown (m)	Water Quality (TDS mg/l)	Comments
6824	6741	59.80	180 150	65 110	74	8.95	520	Minimal drawdown
6825	6759	61.8	180	70 90	50 72	7.46 11.62	600 600	Minimal drawdown
6826	6764	60.74	151	51	96	12.05	508	Minimal drawdown
6827	6767		120	110	96	42.44	637	
6828	6761	75.44	150	30	97	30.01	269	
6829	6736	71.55	150	8	72	32.04	445	Malwelwe Production borehole
6830	6743	50.27	103	120	71	4.10	682	

Seven successful exploration boreholes drilled in the same Malwelwe area were also tested in similar manner and the field test details are tabulated in Table 5.20.

Table 5.20 Exploration Boreholes - Constant Rate Pumping Field Test Details

Bh No.	Rest water Level (m)	Pump Intake (m)	Pumping Rate (m^3/hr)	Pumping Duration (hrs)	Max Drawdown (m)	Water quality (TDS mg/l)	Comments
10671	67.70	150	20	120	26.69	445	
10672	56.58	151	50	75	50.35	406	Minimal drawdown
10673	66.97	151	25	72	89.51	316	
10674	62.95	120	110	102	14.54	394	
10676	52.55	177.5	5	50	78.48	494	
10677	72.40	112	3.5	24	35.59	640	
10679	64.10	120	110	73	25.39	379	Minimal drawdown

The drawdown data for each of the CRTs are included in Appendix C. Included on these graphs are the Jacob straight line analyses in determining transmissivities. Similar graphs for the recovery data are also included. The transmissivity values are tabulated in Table 5.21 below. In addition, the CRT data has been analysed using the DWA Test Curve programme. The Test Curve plots are also included in Appendix C.

Transmissivity values from existing BRGM Ecca production boreholes in the Malwelwe area generally range between 8m^2/day and 850m^2/day. These values are similar to values determined for exploration boreholes in the area as presented in Table 5.21. The corresponding transmissivity values determined by BRGM some 20 years ago are presented in Table 5.21 and show similar trends. The project exploration boreholes also show the same trend.

This data interpretation suggests a high transmissivity area within the central portion of Target Area A centred around Bh6827 - Bh6825 - Bh10679 - Bh10674, with transmissivity on the upper end of the range around 600 m^2/day. High values seem to occur where the Ecca aquifer is thickest, as at Bh10674 and Bh10679. The area around Bh6829, located on the steep edge of the Main Graben, seems to be a low transmissivity area, probably due to a reduced thickness of the aquifer. A similar trend is also observed at Bh10671 some 3.7km west with an intercepted basement at 172m depth. This low transmissivity trend related to reduced Ecca aquifer thickness is also evident at Bh6828 to the south and the recently drilled project borehole Bh10677 with an airlift yield of only 2.3m^3/hr.

Specific capacities at different times during the CRT were also analysed and the data is tabulated in Table 5.21 below.

Table 5.21 Ecca Constant Rate Test Results and Transmissivity Values

Bh No.	**Duration**	**Rate**	**Drawdown**	**Transmissivity (m^2/d)**			
	(hrs)	**(m^3/h)**	**(m)**	**Test Curv**	**Pumping[1]**	**Recovery[1]**	**Adopted Value**
6824	74	110	8.95	250	280	140	**270**
6741					220	70	**220**
6825	72	90.4	11.62	850	860	620	**855**
6759					761	620	**650**
6826	96	50.8	13.15	165	180	64	**50**
6764					40	40	**40**
6827	48	100.4	41.1	112	270	130	**160**
6767					86	86	**86**
6828	95	30.1	30.01	35	51	7	**35**
6761							**not tested**
6829	72	8.0	32.04	8	2.01	1.6	**2**
6736							**not tested**
6830	342	53	2.67	-	501	-	**500**
6743	120	70	4.98		389		**390**
10671	120	20	26.69	22	130	40	**22**
10672	75	50	50.35	35	24	80	**30**
10673	48	25.1	38.34	13	14	11	**13**
10674	102	110.2	14.54	255	24	430	**350**
10676	48	5	78.34	2.3	8.1	0.73	**3.5**
10677	24	3.5	35.59	0.11	0.8	3.5	**1.5**
10679	73	110	25.39	304	400	33	**350**

[1] Jacob straight line method of analysis

Borehole Efficiency Analysis

The assessment of both old and new test pumping data (steps and CRT), has revealed that 6 of the existing BGRM boreholes Bh6824, 6825,6826,6827,6828 and 6830 have the potential to be utilised for production purposes.

However, analysis of individual borehole step test performance of these BRGM sites has revealed both efficient and considerably less efficient boreholes, almost certainly as a result of borehole construction (screens). Table 5.22 below gives a breakdown of efficiency over the discharge rate that was used.

Table 5.22 Production Borehole Efficiency Comparison

Borehole No.	Steps Pumping Range (m^3/hr)	Efficiency % Max - min	CRT Rate (m^3/hr)	Comments
6824	15 – 70	41 - 13	110	minimal drawdown
6825	20 - 75	-	90	Bh developing during test
6826	20 - 56	60 - 36	50	minimal drawdown
6827	15 - 110	85 - 43	100	
6828	5 - 45	60 - 14	30	
6829	3 - 16	90 - 63	8	
6830	16 - 50	97 - 99	53	

The most efficient borehole Bh6829 is a low yielding borehole that could be pumped only at 8m^3/hr after yield assessment during step testing. High efficiency values were possible at very low (3-9m^3/hr) discharge rates when linear well losses are dominant. In high yielding borehole non-linear losses tend to be dominant as the flow is centralized by the pump. The size of the borehole also plays critical role.

Exploration borehole step test data was also analysed in a similar manner and the results are tabulated in Table 5.23 below. The results show a similar trend although Bh10677 is an anomaly in that it registered very low efficiency at low discharge rates, but this borehole was essentially a dry hole and only 2 steps could be completed (Table 5.18).

As may be expected, it is apparent that the unscreened exploration boreholes show higher efficiency that the screened BRGM production boreholes. This is illustrated by borehole Bh6828 and Bh10673 which are comparable in that they display very similar yield characteristics. The unscreened exploration borehole Bh10673 indicates much better efficient (77to 46%) than the screened production borehole Bh6828 with a range of 60-14%.

Table 5.23 Exploration Borehole Efficiency Comparison

Borehole No.	Steps Pumping Range (m^3/hr)	Efficiency % Max - min	CRT Rate (m^3/hr)	Comments
10671	5 – 25	87 - 59	20	
10672	10 - 50	49 - 16	50	
10673	8 - 40	77 - 46	25	
10674	40 - 120	77 - 79	110	minimal drawdown
10676	3 - 6	90 - 25	5	pump suction during test
10677	3 - 6	36 - 25	3.5	pump suction during test
10679	40 - 120	65 - 38	110	minimal drawdown

Specific Capacity Evaluation

Despite known drawbacks in the use of specific capacity in the estimation of yield potential of a borehole, an evaluation was made on all Ecca boreholes. The potential pitfalls of using specific capacity to project possible productivity include:

- pumping time,
- pumping rate and

- well construction
- hydraulic boundary effects

The specific capacity S_c is the ratio of discharging (Q) to steady drawdown (S_w).

$$S_c = Q/S_w$$

For a given discharge a well is often assumed to have a constant specific capacity. Any significant decline in the specific capacity of a well can be attributed either to a reduction in transmissivity due to a lowering of the groundwater level in an aquifer or to an increase in well loss associated with clogging or deterioration of the well screen or productive zones.

For individual borehole comparison purposes capacities at 24hr, 48hr and 72hrs were calculated and theses are tabulated in Table 5.24 for existing BRGM production boreholes and Table 5.25 for Project Exploration boreholes. It is evident that the high yielding (>50m^3/hr) boreholes have high specific capacities with a range of 2-9m^2/hr. Most boreholes have indicated fairly constant specific capacities across the three time periods except for the low yielding borehole like Bh6829, 10676 and 10677.

The influence of hydraulic boundaries is evident in almost all the test pumping data in the Project Area. Both positive and negative boundaries are present. Bh6824 shows recovery tendencies when pumped at 70m^3/hr and again at 90m^3/hr. The structural set up in the area (Inception Report, March 2009) displays significant hydraulic barriers and boundaries and these come into play during pumping. Negative boundaries tend to reduce specific capacities and this effect will be further highlighted when calculating abstraction rates for production borehole.

Table 5.24 Production Borehole Specific Capacities

Bh no.	Pumping Rate (m^3/hr)	Pumping Duration (Hrs)	Final Drawdown (m)	Final specific Capacity	Spec Capacity 24 hrs (m^2/hr)	Spec Capacity 48 hrs (m^2/hr)	Spec Capacity 72 hrs (m^2/hr)
6824	65	74	8.95	7.263	9.5029	8.075	7.336
6824	110	48	12.72	8.648	9.6661	8.648	-
6825	70	50	7.46	9.383	9.3834	9.383	-
6825	90	72	11.62	7.745	8.1374	7.826	7.745
6826	50	96	13.15	3.802	3.9809	4.227	4.181
6827	100	48	41.1	2.433	7.9491	7.943	7.937
6828	30	95	30.01	1.000	1.0526	1.032	1.015
6829	8	72	32.04	0.250	0.2756	0.267	0.250
6830	120	71	4.07	0.0334	0.0307	0.032	0.0334

Table 5.25 Exploration Boreholes Specific Capacities

Bh no.	Pumping Rate (m^3/hr)	Pumping Duration (Hrs)	Final Drawdown (m)	Final specific Capacity	Spec Capacity 24 hrs (m^2/hr)	Spec Capacity 48 hrs (m^2/hr)	Spec Capacity 72 hrs (m^2/hr)
10671	20	120	26.69	0.749	0.756	0.7513	0.7496
10672	50	75	50.35	0.993	1.089	1.0314	0.9956
10673	25	48	38.34	0.652	0.693	0.6521	-
10674	110	102	14.54	7.565	8.475	8.3019	7.9595
10676	5	48	78.34	0.064	0.078	0.0638	-
10677	3.5	24	35.59	0.098	0.098	-	-
10679	110	73	25.39	4.332	4.435	4.339	4.332

The spatial distribution of the specific capacities is very similar to the distribution defined by test yield distribution, with higher values within the Main Graben area and the associated satellite smaller grabens as shown in Figure 5.7.

A north - south cross section across the Main Graben through Malwelwe village is shown in Fig 3.7 and it shows the extent of this potentially more productive aquiferous zone. This zone as marked does not extend much to the south due to the up-lifted basement represented by the Malwelwe Horst in the centre, Dipuo Horst to the south west and the Sethunya Horst to the south east. The area between the Mopipi Graben and the Main Graben, where Bh6828 is located, has arenaceous sandstone but the thickness is reduced by the uplifted basement represented by the Botlhapatlou High that terminates the aquifer completely to the east. Bh10673 is typical borehole with a reduction in aquiferous Ecca aquifer. The less steep pre-Karoo basement uplift (Fig 3.7) to the north of the Main Graben extends this high potential aquiferous zone to the north and boreholes like Bh6830, 10672 have indicated good resources in the northern fringes of the Main Graben.

5.6.2 Ntane/ Lebung Boreholes - Test Pumping Results

Step Tests

A summary of the Ntane/Lebung borehole step test results are provided in Table 5.26. Step test graphs are included in Appendix D. No significant temporal trends during pumping with respect to conductivity or TDS were noticed. Generally all the boreholes, except for Bh6827, show high efficiencies of less than 60%. Borehole Bh 6827 show values that range from 84% to 43% with a mid range of greater than 50% at initial stages of test. Fall in borehole efficiency over the duration of the step test were largest in Bh10681 at around 36%. The smallest fall was in Bh10685. However the drawdown interval over which the efficiency fall occurs is important in estimating the efficiency of a borehole.

Boreholes Bh10686 and 10687 show negative slopes and these were interpreted to indicate borehole development during pumping.

Table 5.26 Ntane/ Lebung Boreholes - Step Test Results

Borehole No.	Step	Discharge (m^3/h)	Drawdown (m)	Conductivity (µS/cm)	Efficiency (%)	CRT Rate (m^3/h)
10681	1	10	21.76	553	60.5	20
	2	15.1	30.8	555	50.4	
	3	20	46.27	566	43.4	
	4	25	83.42	564	38.0	
	5	30	Pump suction	560		
10682	1	10	8.22	-	96	40
	2	20	18.88		92.2	
	3	30	31.94		88.8	
	4	50	49.76		82.6	
	5	60	63.36		79.8	
10685	1	5	14.14	570	97.5	25
	2	10	16.15	560	95.2	
	3	15	22.80	565	92.9	
	4	20	38.02	560	90.8	
	5	30	55.26	568	86.8	
	6	40	71.83	570	83.1	
10686	1	5	43.38	270		10
	2	10	68.62	290		
	3	15	94.47	293		
	4	20	118.09	281		
	5	25	128.9	284		
	6	30	38.35	285		
10687	1	5	13.37	549		30.1
	2	10	20.83	561		
	3	15.1	28.59	570		
	4	25.05	44.21	560		
	5	35.2	58.47	540		
10688	1	10	9.32	363	72.7	30
	2	15	20.75	365	63.9	
	3	20	30.47	358	62.5	
	4	30	48.85	355	52.6	
	5	35	64.19	358	48.8	

Constant Discharge Rate Tests

Field data collected during CRT is tabulated in Table 5.27 below and it highlights the shallow pump setting when compare to the Ntane/ Lebung water strikes.

Table 5.27 Ntane/ Lebung Boreholes - Constant Rate Test Data

Bh No.	Ntane Water Strike (mbgl)	Rest water Level (mbgl)	Pump Intake (m)	Pumping Rate (m^3/hr)	Pumping Duration (hrs)	Max Drawdown (m)	Water quality (TDS mg/l)
10681	290	59.80	160	20	72	78.03	600
10682	152	61.8	160	40	75	83.03	532
10685	228	76.52	196	30	96	55.53	1000
10686	388	78.70	210	10	72	66.82	561
10687	226	94.30	150	25	56	52.22	533
10688	522	94.63	150	30	48	90.15	1200

The drawdown data for each of the CRTs are included in Appendix C. Included on these graphs are the Jacob straight line analyses in determining transmissivities. Similar graphs for the recovery data are also included. The transmissivity values are tabulated in Table 5.28 below. In addition, the CRT data has been analysed using the DWA Test Curve programme. The Test Curve plots are also included in Appendix C.

Table 5.28 Ntane/ Lebung- Constant Rate Test Results and Transmissivity Values

BH	Duration	Rate	Drawdown	Transmissivity (m^2/day)			
	(hrs)	(m^3/h)	(m)	Test Curv	Pumping[1]	Recovery[1]	Adopted Value
10681	72	20	78.03	4.5	3	9.7	**4.5**
10682	75	40	83.06	6.4			
10685	96	30	55.53	15	28	25	**25**
10686	72	10	66.82	7.5	1.8	8.3	**7**
10687	56	25	52.22	14.5	13	18	**14**
10688	48	30	90.15	6	5.7	11	**6**

[1] Jacob straight line method of analysis

Transmissivity values from the Ntane/Lebung boreholes generally range between 4 m^2/day and 25 m^2/day within the Sorilatholo area but it is important to note that these values are definitely not a true reflection of the properties of the Ntane/Lebung aquifer due to test pumping problems encountered. The boreholes were under pumped due to equipment limitations. As a result of the testing limitations no borehole efficiency analyses have been attempted.

However, the data interpretation suggests a high transmissivity area within the fractured areas immediately north of the Zoetfontein Fault as indicated by boreholes Bh10681, Bh10685, Bh10687 and Bh10688. The aquifer thickness has also proved to be important. Bh10683 and 10684 were almost certainly dry because of reduced aquifer thickness and to the west towards Salajwe the yields are also low because of reduced thickness of Ntane Sandstone aquifer as in borehole Bh9344 and Bh9346.

Specific Capacity Evaluation

Specific capacities at different times during the CRT were also analysed for the Ntane/Lebung aquifer exploration boreholes and the data is tabulated in Table 5.29 below. The values are generally lower than those determined in the Ecca south of the Zoetfontein Fault and these values show a distinct reduction of specific capacities with time. This is attributed to the pumping set up where the pumping rates were low, the pumps were set up well above the aquifer and much of the contribution to initial drawdown could be attributed to borehole storage.

Table 5.29 Ntane/Lebung Exploration Boreholes Specific Capacities

Bh No.	Pumping Rate (m^3/hr)	Pumping Duration (Hrs)	Final Drawdown (m)	Final Specific Capacity	Specific Capacity 24 hr	Specific Capacity 48hr	Specific Capacity 72hr
10681	20	72	78.03	0.256	0.325	0.265	0.2563
10682	40	75	83.06	0.482	0.670	0.648	0.4820
10685	30	96	55.53	0.540	0.559	0.550	0.5458
10686	10	72	66.82	0.150	0.176	0.158	0.1499
10687	25	56	52.22	0.479	0.578	0.503	-
10688	30	48	90.15	0.333	0.352	0.333	-

The analysis of test pumping data both old and new, steps and CRT, has revealed that 6 of the existing boreholes Bh6824, 6825,6826,6827,6828 and 6830 have the potential to be pumped as production purposes. Analysis of individual borehole steps test performance has revealed both efficient and less efficient screened boreholes. Table 5.30 below gives a breakdown of efficiency over the discharge rate that were used and an attempt is made to rank these boreholes on basis of performance. The comparison across boreholes might be difficult to appreciate but it gives a sense of individual borehole efficiency against pumping rates.

Table 5.30 Production Borehole Efficiency Comparison

Borehole No.	Steps Pumping Range (m3/hr)	Efficiency % Max - min	Efficiency Ranking	CRT Rate (m3/hr)	Comments
6824	15 – 70	41 - 13	6	110	minimal drawdown
6825	20 - 75	-	7	90	Bh developing during test
6826	20 - 56	60 - 36	4	50	minimal drawdown
6827	15 - 110	85 - 43	3	100	
6828	5 - 45	60 - 14	5	30	
6829	3 - 16	90 - 63	2	8	
6830	60 - 100	97 - 99	1	120	

The most efficient borehole Bh6829 is a low yielding borehole that could be pumped only at $8m^3$/hr after yield assessment during step testing. High efficiency values were possible at very low ($3\text{-}9m^3$/hr) discharge rates when linear well losses are dominant. In high yielding boreholes non-linear losses tend to be dominant as the flow is centralized by the pump. The diameter size of the borehole also plays critical role.

Exploration borehole step test data was also analysed in a similar manner and the results are in Table 5.31 below. The results show a similar trend although Bh10677 is an anomaly in that it registered very low efficiency at low discharge rates, but this borehole was essentially a dry hole and only 2 steps could be completed (Table 5.18). In general it is apparent that the unscreened boreholes show higher efficiency that the screened boreholes. Borehole Bh6828 and Bh10673 compare well as they display very close yield characteristics. The open hole Bh10673 indicates slightly better efficient (77-46%) than the screened borehole Bh6828 with a range of 60-14%. An attempt to rank the exploration boreholes efficiency does not show any useful trends but it is apparent that boreholes Bh10671, 10672, 10673, 10674 and Bh10679 show good potential.

Table 5.31 Exploration Borehole Efficiency Comparison

Borehole No.	Steps Pumping Range (m3/hr)	Efficiency % Max - min	Efficiency Ranking	CRT Rate (m3/hr)	Comments
10671	5 – 25	87 - 59	2	20	
10672	10 - 50	49 - 16	6	50	
10673	8 - 40	77 - 46	4	25	
10674	40 - 120	77 - 79	3	110	minimal drawdown
10676	3 - 6	90 - 25	1	5	pump suction during test
10677	3 - 6	36 - 25	7	3.5	pump suction during test
10679	40 - 120	65 - 38	5	110	minimal drawdown

5.7 Production Target Zone Selection

At the end of the Explorantion work the Consultant assessed and set out the production parameters of the existing BRGM production boreholes that are available in Target Area A, since these holes will form the core of the proposed new Malwelwe Wellfield and equipping parameters are required by the delivery system design engineers.

Also under this task the Consultant has described the selection of zones (and specific sites) that fromed the results of the exploration programme have been identified as having high potential for the development of production boreholes.

5.7.1 Existing BRGM Production Boreholes

Seven production boreholes (Table 5.32) drilled by BRGM in Malwelwe Area form the core of the proposed wellfield development in Target Area A. These boreholes lie within a zone of the Ecca aquifer that has good groundwater potential delineated in Figure 5.7. *Additional production boreholes were proposed in the same zone as a result of project exploration activities.*

Table 5.32 Malwelwe Production Boreholes - Construction Details

BH No.	UTM X	UTM Y	Depth (mbgl)	Optimum Pump Setting (m)	Drilling Details (Interval(m)/ Diameter (mm)	Steel Casing Details (Interval(m)/ Diameter (mm)	Steel Screen Details (Interval(m)/ Diameter (mm)
6824	318997	7345934	246	98	0-104 m / 356 mm 104- 246 m / 305 mm	0 - 104 m / 356 mm 0 - 99 m / 219 mm 110 - 156 m / 219 mm 214 - 246 m / 219 mm	99 - 110 m / 219 mm 156 - 214 m / 219 mm
6825	321370	7346340	245.37	100	0 - 96 m / 381 mm 96 - 245 m 203 mm	0 - 96 m / 356 mm 0 - 102 m / 219 mm 136 - 197 m / 219 mm 186 - 214 m 219 mm 233 - 245 m / 219mm	102 - 136 m / 219 mm 173 - 186 m / 219 mm 214 - 233 m / 219 mm
6826	317896	7345895	242.06	140	0 - 81 m / 381 mm 81 - 242 m / 305 mm	0 - 81 m / 356 mm 0 - 141 m / 219 mm 156 - 200 m / 219 mm 236 - 242 m / 219 mm	141 - 156 m / 219 mm 155 - 236 m / 219 mm
6827	314841	7345521	235	105	0 - 93 m / 381 mm 93 - 235 m / 305 mm	0 - 93 m / 356 mm 0 - 108 m / 219 mm 135 - 155 m / 219 mm 228 - 235 m / 219 mm	108 - 135 m / 219 mm 155 - 228 m / 219 mm

6828	331851	7341522	210	125	0 - 82 m / 381 mm 82 - 210 m / 305 mm	0 - 82 m / 356 mm 0 - 127 m / 219 mm 197 - 210 m / 219 mm	127 - 197 m / 219 mm
6829	327360	7345991	217.66	115	0 - 88 m / 381 mm 88 - 218 m / 305 mm	0 - 88 m / 356 mm 0 - 118 m / 219 mm 209 - 218 m / 254 mm	118 - 209 m / 219 mm
6830	322964	7358486	192.64	140	0 - 67 m / 381 mm 67 - 193 m / 305 mm	0 - 67 m / 356 mm 0 - 68 m / 219 mm 125 - 142 m / 219 mm 163 - 177 m / 219 mm 186 - 193 m / 219 mm	68 - 125 m / 219 mm 142 - 163 m / 219 mm 177 - 186 m / 219 mm

Since the existing BRGM boreholes are some 19 years old and have never been used it was agreed that they should be cleaned and test pumped before use for production purposes. Borehole Bh6830 was tested during the establishment of addional production boreholes.

BRGM borehole construction details are tabulated in Table 5.32 above. From this information it was possible to determine the optimum pump setting which are also included in the table. In most boreholes the production pumps are to be set above the first screens. Borehole Bh6830 has shallow screens at 67m depth which leaves only 15m of available drawdown. In this instance it is suggested that the pump should be set at 140m depth within a plain section of the screen assemblage and the resultant available drawdown will be about 85m

For the production abstraction rate determination two different approaches were used. The DWA approach based on Rural Water Design Manual (RWDM) DWA 1989 was used and 10 year pumping horizon and boundaries are taken into account. Values calculated from this approach are tabulated in Table 5.33.

The second approach is based on specific capacities. The specific capacity S_c of borehole is the ratio of discharge (Q) to steady drawdown (S_w).

$$S_c = Q/S_w$$

For a given discharge a well is often assumed to have a constant specific capacity. Any significant decline in the specific capacity of a well can be attributed either to a reduction in transmissivity due to a lowering of the groundwater level in an aquifer or to an increase in well loss associated with clogging or deterioration of the well screen or productive zones or a boundary influences.

Specific capacities calculated during constant rate tests are listed in Tables 5.24 and 5.25 where the 24hr, 48hr and 72hr values are tabulated. In boreholes where longer tests were carried out the final values are also calculated and included in these tables.

Borehole yield estimation is calculated by reversing the above equation

$$Q = S_c * S_w$$

In the existing BRGM production boreholes, available drawdown (or S_w as indicated above) was calculated as the difference between the top screens and the rest water level and these are tabulated in Table 5.33 below. The production yields as calculated by the specific capacity method together with yield values derived from DWA RWDM approach are also tabulated in Table 5.33.The values calculated from specific capacity were divided by 2 as factor to accommodate boundary effects.

$$Q = (S_c * S_{w)}\ ) / 2$$

A comparison of these two sets of calculated values indicate very close values at low yields but at high yields the specific capacity calculations tend to give higher values.

Table 5.33 Production Borehole Abstraction Calculations

Bh No.	Depth (m)	SWL (m)	Calculated Available drawdown (m)	Adopted Specific Capacity (m^2/hr)	Sp. Capacity Calculated Abstraction Rate (m^3/hr)	DWA WDM Calculated Abstraction Rate (m^3/hr)	Proposed Abstraction Rate (m^3/hr)
6824	246	60	33	7.336	121	70	75
6825	235	62	33	7.460	123	76	80
6826	242	61	82	4.181	171	38	40
6827	235	57	40	7.937	158	80	80
6828	210	73	47	1.015	24	23	25
6829	218	71	38	0.250	5	4	5
6830	193	50	15	14.0	105	80	100
Total abstraction (m^3/hr)							**400**

5.7.2 Potential New Production Sites

Target Area A (Malwelwe Wellfield)

From the studies carried out during the Construction Stage 2A five exploration boreholes (Bh10671, Bh10672, Bh10673, Bh10674, and Bh10679) were selected for re-development by production drilling because they were high yielding boreholes with excellent abstraction characteristics (as determined from test pumping analysis).

From the overall results of the exploration activities, in particular the geophysical surveying, it was also been concluded that an additional five or six more production boreholes can be located within the Target area A and in the vicinity of the Malwelwe Wellfield as defined by the original BRGM production boreholes. BRGM recommended a distance of 1.5 km as minimal distance between production boreholes and a distance of 1.8 km production borehole separation in the final distribution of boreholes is envisaged.

In order to locate the specific sites for these additional 5-6 production boreholes supplementary geophysical surveys was undertaken during Construction Stage 2B, utilising the optimised techniques applied during the exploration stage.

A total of 7 sites were selected for supplementary surface geophysical investigations in Malwelwe Wellfield (Figure 5.10). The criteria used to select the sites are illustrated in Table 5.34. Three of the sites for investigations are positioned on exploration geophysical lines L4, L20 and L22. Additional lines L36, L37, L38 and L39 were selected at prime areas within the wellfield delineated area.

Table 5.34 Potential Additional Production Sites in Target Area A (Malwelwe Wellfield)

Line No.	Line Length (km)	Survey Methods	Reasons For Line Selection
L4	1	EM, TDEM	This is at the centre of the Main Graben about 3 km north of BH6825. Anomalous EM results from first survey surveys confirmed the extension of a fault on which a high yielding BH10679 about 1.8km east of this site. Two short (500m) lines are proposed for geophysics.
L20	1	EM, TDEM	The site is centred on L20/1670 within the Main Graben and is very identical toBH10679 2km west. Groundwater potential is excellent on this site.
L22	3	EM, TDEM, Magnetics	Site L22/1400 has exceptionally good anomalies from EM/Mag and they need to be resolved further by closely spaced lines so that a similar borehole to BH6830 can be developed. It is on the Demonstration Ranch.
L36	3	EM, TDEM, Magnetics	Within the Main Graben at the intersection of two regional faults **F10** and A-A'.
L37	3	EM, TDEM, Magnetics	This site has identical conditions where BH10674 was drilled and proved to be high yielding. It is on the contact between Main Graben and Ranch Horst.
L38	3	EM, TDEM, Magnetics	Site is within the Main Graben on a local fault. Low potential site.
L39	3	EM, TDEM, Magnetics	On the edge of the Main Graben and Ranch Horst where a regional fault passes through. BH10672 is along this same fault and it is hoped that same hydrogeological conditions prevail.

Target Area B (Sorilatholo Wellfield)

The proposed 'Sorilatholo Wellfield' is a relatively large area in Target Area B which extends from Tshatshane cattle-post in the west to the Bh10686 (Fig 5.11). This proposed wellfield zone is about 45 km across and 20 km wide. Although areas further east can be developed, the seriously limiting factors are the thick basalt and thus the associated high costs of drilling and pumping from deep boreholes.

Within Target Area B successful exploration boreholes Bh10681, Bh10682, Bh10685 and Bh10687 are regarded as 5 potential production borehole sites within the proposed Sorilathoro Wellfield. An additional seven sites are proposed for further ground geophysics with the intention of drilling 5 more additional production boreholes.

The 7 additional potential production sites selected for supplementary geophysical surveys are shown in Table 5.35 below. The selection of additional sites was primarily to increase the number of production boreholes within the delineated 'Sorilatholo Wellfield' area to 10.

Table 5.35 Potential Additional Production Sites in Target Area B (Sorilatholo Wellfield)

Line No.	Line Length (km)	Survey Methods	Reasons For Line Selection
L40	3	EM, TDEM, Magnetics	On a regional fault dividing two blocks hydrogeological (**Class** $\mathbf{2_B}$ and **Class** $\mathbf{1_B}$).
L41	3	EM, TDEM, Magnetics	Similar to L40. Depth to Basalt-Ntane contact is ~150 m - 200 m.
L42	3	EM, TDEM, Magnetics	The site is characterized by high density of regional and local fault patterns. Depth to Basalt-Ntane contact is ~250 m.
L43	3	EM, TDEM, Magnetics	Along the **Z2** fault zone which separates two blocks with contrasting basalt thicknesses. Depth to Basalt-Ntane contact is ~250 m – 300 m.
L44	3	EM, TDEM, Magnetics	Within block with thin basalt flow and deep fractures of basalts expected. Depth to Basalt-Ntane contact is ~150 m – 200 m. Ntane sandstone is expected to be thin (>50m)
L45	3	EM, TDEM, Magnetics	Intended to tape groundwater resource from intense fractures associated with regional and local faults. Depth to Basalt-Ntane contact is ~150 m - 250m.
L46	3	EM, TDEM, Magnetics	Depth to Basalt-Ntane contact is ~100 m - 200 m while the Ntane sandstone is probably thin (>50m).

Summary Conclusions

From detailed examination of previous geophysical work in the region the following general conclusions and comments can be made.

- The HLEM is the most efficient method of determining sub-vertical to vertical conductive zones interpreted as fractures. However, the application of the method could be improved by selecting the correct frequencies within a range 1760Hz to 110Hz depending on the properties of the area of interest derived from existing resistivity data or calibration data or both. The HLEM technique is most effectively applied in a profiling mode and large separations between the transmitter and receiver coils will be necessary to enhance signal to noise ratio. However, depth penetration limitations of this technique in the current Project Area may prove to be a huge drawback, especially in the northwest corner of the Project Area where the aquifer was anticipated to be very deep.

- Direct current techniques have big limitations in the current project environment as there will be problems with current injection into the very dry, resistive soils and sands as well as the overall shallow depth of penetration of the method (less than 1/6 of the current electrode spread is common). However, direct current resistivity work was attempted at a minimum half spread length of 400m and a better effort was made to collect the data but penetration was hindered insufficient cuurent input.

- Ground magnetic profiling is a good tool for locating short wavelength shallow magnetic sources such as dolerite dykes, sills and map out discontinuities, which can enhance the aquifer permeability on a local scale. Deeper structures with long wavelength are best interpreted from the regional aeromagnetic surveys but it may be necessary to locate them on the ground through ground surveys.

- Resistivity (direct current) and electromagnetic (both time and frequency domain) techniques differ in survey productivity, costs, depth of penetration and resolution. The HLEM (horizontal loop EM) technique appear to be most cost effective. However, although TDEM (time domain EM) is time consuming and costly, it is a deeper penetrating technique and has a better layer resolution at depth.

- It is the Consultant’s opinion that a well-balanced and appropriately spread combination of both EM techniques may prove to be technically and economically the best exploration option for the current project. Magnetic profiling is always necessary to support the interpretations.

6. HYDROGEOLOGICAL EVALUATION

The hydrogeological regime of the region is characterised by the basin margin sedimentary environment of the Central Kalahari Karoo Basin in which the principal Ecca Group sedimentary units are diachronous onto the Pre-Karoo basement and irregularly spatially distributed and variable in thickness and lithological composition. Such an environment is considered to be an active groundwater system with both recharge and possibly discharge zones. However, this system largely 'truncated' to the north by the transcontinental Zoetfontein Fault zone which brings the northern Upper Karoo strata into juxtaposition against the principal Ecca aquifers to the south. To the north of this structure the Upper Karoo Lebung Group Ntane Sandstone Formation appears much more uniform in character both in lithological composition and presumably also in hydrogeological properties.

6.1 Groundwater Occurrence

Groundwater occurs in all geological units present in the Project Area, but only the sandstones of the Karoo Lebung and the Karoo Ecca Groups constitute major productive aquifers.

In other geological units groundwater quantity and quality preclude their serious consideration as aquifers and it is unlikely that they constitute extensive sources of groundwater. Some comments are, however, made on the 'Kalahari Aquifer' and the the basalt as they may play some roles in potential recharge processes for the underlying aquifers.

The most important aquifer in the project area, and as implied in the Terms of Reference for the study, the particular focus of this investigation, is the Ecca Group sandstones of the Malwelwe area. However, other important aquifer almost certainly also exist in the Stormberg basalt and especially the Ntane Sandstone strata in the north and northwest, to the north of the Zoetfontein Fault.

Other geological units of the Karoo largely comprise relatively impermeable mudstones and shales which have only small and very limited aquifer potential. Similarly, the pre-Karoo Proterozoic sedimentary rocks of the Waterberg and Transvaal Supergroups have been slightly metamorphosed and have negligible inherent permeability, with the result that their aquifer potential is represented by fracture flow systems with limited storage.

The Kalahari deposits of the project area are generally relatively thin (<40m) and lie above the regional piezometric surface, and thus have no aquifer potential. Exceptions to this do exist along the fairly deeply incised fossil drainage channels of the Meratswe and Kohiye valleys, where Kalahari and more recent alluvial deposits may constitute shallow (possible perched) aquifers for highly localised supply.

The lower-most Karoo Dwyka Group will not be discussed as an aquifer as no details of its hydrogeological characteristics in the area are available and project drilling revealed very little additional hydrogeological information.

6.2 Aquifer Distribution

Within the Project Area two geological units that have significance with respect to regional groundwater resources have been identified and these are the Lebung Group and the Ecca Group

Aquifers, and the distribution and hydrogeological properties of each as established from the previous and the work undertaken during the this current programme are detailed below.

As noted above, no significant aquifers exist in the other geological units in the Project Area, although localised resources occur both in the Kalahari and in the basalt. However, to complete the hydrogeological ‘picture’ comments are also made on these two minor aquifers.

Kalahari Aquifer

The geology of the aquiferous Kalahari Group deposits in the fossil river valleys comprises loose to poorly consolidated sand, silcrete and calcrete intercalations of variable proportions. The uppermost aeolian deposits of the Kalahari sequence are represented by loose to poorly consolidated fine sands and silts and the underlying crete deposits predominantly comprise silcrete and subordinate calcrete with minor ferricrete. The basal Kalahari gravels have been found to constitute an aquifer in some places elsewhere in the country (eg Werda) but so far no borehole in the project area has intercepted any Kalahari gravels.

There are no known boreholes specifically drilled into the Kalahari Group deposits except for a few wells (Table 6.1) located at various localities during the Reconnaissance Survey carried out early in the project. Existing water level records indicate that the Meratswe fossil river valley has shallow (< 20m) borehole water levels. During GRES II it was postulated that these shallow water levels are an indication that the valley is a groundwater discharge zone. A similar thinking was also extended to other fossil valleys like Kohiye and Dikgonnyane located to the west of Meratswe valley.

During the survey only one fresh water well at Kgesakwe (TDS-610mg/l) was identified in the Meratswe Valley. The other productive wells are located in a tributary valley at Mestibothoko and these are reported to be saline (>10,000mg/l).

A dry well was also noted down the valley from the Gaotlhobogwe Wellfield but this has been dry since the wellfield was established in 1990. Elsewhere the Kalahari deposits rarely exhibit any water bearing potential.

Table 6.1 Shallow Kalahari Aquifer Boreholes in the Project area

Well No	X coord.	Y coord.	Location	Depth	SWL	TDS(mg/l)	Comments
BGPA27	293613	7345692	Kgesakwe	40	15.5	610	Never dry up
BGP 152	196022	7235077	Letlhakeng		14.85		
BGPA76	310228	7330679	Gaotlhobogwe	6	n/a	n/a	dry
BGP144	283272	7340625	Metsibotlhoko		3.40	salty	No Hand pump
BGP145	283044	7340711	Metsibotlhoko		3.80	salty	No Hand pump
BGP146	283035	7340739	Metsibotlhoko		3.96	salty	No Hand pump
BGP147	283068	7340703	Metsibotlhoko		2.68	salty	No Hand pump
BGP148	283236	7340642	Metsibotlhoko		3.48	salty	No Hand pump
BGP150	283272	7340625	Metsibotlhoko		3.67	salty	No Hand pump

Basalt Aquifer

This minor aquifer occurs largely to the north of the Zoetfontein Fault (ZF), although the aeromagnetic interpretation indicates that the Stormberg basalt may not be distributed as indicated on the published geological maps, with a significant basalt-free, Ntane Sandstone apparent in the north-west portion of the project area. Stormberg basalt does however appear to always exist in a zone of varying width adjacent to the Zoetfontein Fault Zone.

Within the project area there is clearly a considerable local variation in basalt thickness and degree of dislocation as a result of structural movement. In the eastern portion of the project area previous drilling work has indicated basalt thicknesses of up to 560 metres to the north of several of the principal E-W structures marking the Zoetfontein Fault and complete absence of basalt immediately to the south of these same structures. The throw on the ZF must thus be of the order of 500m to the north in this zone. In general the thickness of the basalt decreases considerably from east to the west across the project area north of the Zoetfontein Fault. As noted previously, a basalt thickness of 560m was recorded at BH9234 near Diphuduhudu, 568m at BH10788 and whereas around Salajwe very little basalt has been intercepted. In the deep basalt area very few boreholes have been drilled due to poor groundwater success rates and subsequently almost no hydrogeological or aquifer properties information is available.

A number of existing boreholes intercepted basalt at various depths but the current data set indicates that only one borehole (BH 4803) struck a substantial amount of water within the basalt at 76m depth with an airlift yield of 60m^3/hr. Unfortunately no water quality details are available for this borehole. The rest of the productive boreholes intercepted groundwater just below the basalt/ Ntane Sandstone interface or well below the basalt in the Karoo Lebung sediments. Farr et al (1981) indicated that the occurrence of groundwater within the basalt is related to the presence of horizontal inter-flow horizons (palaeo-soils, inter flow deposits) and adjacent weathered and fractured horizons connected by fractures. Generally, yields are generally small and water quality is often brackish (1000mg/l<TDS>10,000mg/l). In the project area yields recorded from basalt boreholes range from dry to 20m^3/hr (BGRM 1991) in the project area. Project borehole BH10681 recorded an airlift yield of 13 m^3/hr in the basalt and the quality was at TDS 780mg/l.

To the south of the Zoetfontein Fault only 3 boreholes (S42, S43 and borehole Z4803) stuck water in the basalt. A high groundwater head (1975/6) was noted (BGRM 1991) in boreholes S42 and S43, when compared to boreholes in the Ecca south of the Zoetfontein Fault.

In the areas of thin basalt around Khudumelapye-Salajwe the basalt is well above the regional piezometric surface and is thus unsaturated. However, within the Zoetfontein Fault zone, and as a result of the down faulted blocks, it is evident that the basalt is in hydraulic continuity with the Lebung Ntane Sandstone aquifer and the quality is similar to that in the Ntane Sandstone as was the case in Bh10681, 10685 and Bh10687.

Water strikes, rest water level depths and quality are quite variable as indicated in Table 6.2 below. The table data is derived only from project boreholes.

Table 6.2 Basalt Aquifer Hydrogeological Details

BH No.	BH depth (m)	Kalahari base (m)	Basalt base (m)	W/strike (m)	Rest Water Level (m)	Blow out yield at strike (m^3/hr)	TDS at water strike (mg/l)	Aquifer Basalt	Water type
10681	365	7	290	45, 85, 118, 167	38.95	seepage 6.7 13.0	780	1st w/strike 4th w/strike	Na- HCO3-Cl
10682	198	16	152	106, 125,	65.96	0.3 6.6	420 394	1st w/strike 2nd w/strike	Na- HCO3-Cl
10688	557	46	522	177	96.01	5.4	291	1st water strike	Na- HCO3-Cl
10741	282		282+					Seepage in basalt	Na- HCO3-Cl

Most private boreholes north of the Zoetfontein Fault have no records and it is difficult to know if they intercepted the Ntane Sandstone below the basalt and as a result only project borehole have been used in the table above.

An attempt on site at borehole BH 10681 was made to differentiate the basalt and the Ntane Sandstone water and the results in Table 6.3 are only indicative. A slight mineralization was noted in the basalt as noted in changes in total dissolved solids.

Table 6.3 BH 10681 Water Strike Details

Depth (m)	Blow out Yield (m3/hr)	pH	Conductivity (u/cm)	TDS (mg/l)	Comments
45	no yield				1st water strike - basalt
85	6.7				2nd water strike - basalt
92	12.96	8.74	1520	780	
162	9.8	8.45	1720	850	
167	13	8.74	1520	780	38.95 swl - basalt
293	10.5	7.87	950	470	1st water strike - Ntane
302	22.3	8.68	840	420	
305	27.4	8.6	730	360	
311	40	8.12	760	380	
321	41	8.53	940	470	
343	44	7.5	740	370	
349	44			300	
358	44	8.45	800	400	
365	44	8.31	770	380	42.92 swl - composite

In general basalt groundwater as indicated in Table 6.2 above is of type Na-Ca-HCO_3 indicating a mixture of recent and old water. The recent water is thought to reflect the direct recharge and the old water is thought to be from the Ntane Sandstone below. When plotted on a Piper plot diagram (Figure 6.1) it shows a similar water signature as the Ntane, indicating hydraulic continuity between the two systems.

Lebung Aquifer

The Lebung Ntane Sandstone is the most widespread and consistent aquifer (in terms of properties, yields and water quality) in Botswana.

In the Project Area the Ntane Sandstone aquifer occurs predominantly to the north of the Zoetfontein Fault, mostly beneath the Stormberg Basalt cover of varying thickness, although in the north-west of the area between Salajwe and Khudumelapye the Ntane Sandstone occurs to the south of the ZF as a direct sub-crop beneath the Kalahari deposits. The geological map also indicates a block of Ntane Sandstone in the east of the project area, but little evidence can be found for its existence and it is not considered significant.

To the north of the Zoetfontein Fault (ZF1) the structural interpretation reveals considerable block faulting (Fig 5.3), especially immediately to the north of the ZF1 where thick basalt and the underlying Ntane Sandstone have been preserved on a down faulted block (see N-S cross-section 2.1). Because of variation in the thickness of the basalt resultant on this block faulting (and possibly also depositional variation) the Ntane Sandstone aquifer occurs at depths that range from 560m in Phuduhudu at Bh 9234 and Bh 10688 to only 3m of basalt in the Salajwe area at Bh 8362 and Bh 8363.

Within the Ntane Sandstone unit groundwater is mostly encountered immediately at the junction with the Stormberg basalt but less usually several metres below this point as a result of a reduction in porosity due to very low grade metamorphism or ‘baking’ of the sandstone during basalt deposition. However, in the deep basalt areas around Phuduhudu-Malengwane, water strikes are recorded at the basalt/Lebung contact zone and the hydraulic heads are usually high. Heads in excess of 500m have been recorded (Table 6.1 and Table 6.2). Groundwater yield below this first water strike generally increases gradually with depth, indicating that the whole Ntane Sandstone unit is relatively permeable, although distinct water inflows related to fractures or in some cases to more highly permeable and somewhat coarser and uncemented horizons do occur. These lithological variations are easily appreciated in borehole Bh 10681, 10682, 10683, 10685, 10686 and Bh 10687 that were geophysically logged (Technical Report No. 3, Geophysical Logging Report).

Work carried out, by Hydrogeo (DWA, 2000) indicates yield ranges from dry boreholes to about $60m^3$/hr at Z4803 and similar Project results are tabulated in Table 6.2. Table 3.30 summarizes the details of the few existing boreholes in the project area that tap the Ntane Sandstone aquifer, the majority of which are in the Salajwe area. Very few boreholes appear to penetrate the full Lebung sequence, although three boreholes (BH 9344, BH 9346 and BH 9347) indicate an average thickness of about 90m which from evidence from elsewhere is considered to be near to the full thickness of the Ntane Sandstone sequence (Table 6.4).

Table 6.4 Existing Selected Lebung Borehole Details

BH No	Depth (m)	W/strike (mbgl)	Yield (m^3/hr)	SWL (m)	TDS (mg/l)
9344	106	55	17	37.5	515
9345	353	78	< 1.0	58.6	9200
9346	160	59	5	58.6	477
9347	131	70	3.5	58	444
9234	655	605	20	83.75	735
9235	604	548	70	83.6	615
9133	381.5	359	9	66	305
589	77	59	120	49	738
646	117	58	0.45	52	-
8361	150	48	.02	-	-
8362	146	dry	-	-	-
8365	216	dry	-	-	-
8366	354	dry	-	-	-

As a result of the poor spatial density and distribution of the Ntane Sandstone borehole data the definition of a reliable piezometric surface for the Ntane Sandstone aquifer has not been possible, but indications are that groundwater flow paths trend to the northwest, conforming to the regional Ecca system.

The Mosolotsane Formation which is a transitional unit below the base of the Ntane Sandstone is predominantly argillaceous (mudstone and siltstone) but also has relatively thin and often isolated sandstone horizons that form aquifers. Evidence from other areas in Botswana indicates that the yield from the sandstone members of the Mosolotsane Formation may be reasonable (~ 15-30 m^3/hr) but water quality is frequently brackish or saline, presumably because of the dominantly argillaceous environment. This unit has, however, not been widely drilled or noted in the project area due to its (generally) great depth below the higher Lebung formations.

Three of the eight ‘Lebung’ boreholes (Bh10681, 10682 and 10688) encountered groundwater in the basalt although major water strikes were struck within the Ntane Sandstone Formation. The contact zone between the basalt and the Ntane Sandstone was always the first water strike in the Ntane Sandstone and thereafter the yield increased with depth as more aquifer was penetrated.

Table 6.5 below illustrates the changes in blow out yield and water hydrochemical signatures between the Stormberg Basalt and the Ntane Sandstone as monitored during the drilling of Bh 10681. Elevated TDS and conductivity values are evident in the basalt. The composite head is at 42.92m where as the basalt head before the Ntane was struck is at 38.95m depth. In general the Ntane Sandstone aquifer is confined as shown in **Table 6.5**

Table 6.5 Bh 10681 Water Strike Details

Depth (m)	Blow out Yield (m3/hr)	pH	Conductivity (u/cm)	TDS (mg/l)	Comments
45	no yield				1st water strike - basalt
85	6.7				2nd water strike - basalt
92	12.96	8.74	1520	780	
107	19				
162	9.8	8.45	1720	850	
167	13	8.74	1520	780	38.95 swl - basalt
233	8.6				
293	10.5	7.87	950	470	1st water strike - Ntane
302	22.3	8.68	840	420	
303	22.39				
305	27.4	8.6	730	360	
307	10.6				
311	40	8.12	760	380	
321	41	8.53	940	470	
331	43				
343	44	7.5	740	370	
349	44			300	
358	44	8.45	800	400	
365	44	8.31	770	380	42.92 swl - composite

Hydrogeological details for the last boreholes (Bh10689, 10690) are limited as the boreholes were essentially dry and only sizeable seepage yield could be recorded in Bh10690.

The relationship between saturated thickness and blow out yield is not that difficult to appreciate because the blow out yields were significantly affected by the ground water head (Table 6.6) and does not reflect the true borehole yield. It is probably best to compare aquifer thickness with test pumping results rather than blow-out yields.

Table 6.6 Lebung Boreholes - Confining Heads

Bh No.	Ntane - Base Depth (mbgl)	Ntane 1st Water strike (mbgl)	SWL (mbgl)	Ntane Confining Head (m)	Saturated. Ntane (m)
10681	340	300	42.92	257.08	40
10682	194	152	65.96	83.04	42
10683	198	125	66.93	58.07	73
10684	158	115	65.96	49.04	43
10685	308	228	76.90	151.1	80
10686	468	388	79.90	308.10	80
10687	292	226	96.28	129.72	66
10688	557	522	92.45	429.55	35+

Results from the hydrochemistry analyses available to date indicate that the Ntane/Lebung Aquifer contains very fresh groundwater, with TDS values ranging between 500-1000mg/l.

Groundwater in the Ntane/Lebung is of the Na-HCO_3-Cl type. The presence of high Na percentage ratio in the Ntane/Lebung groundwater is an indication of possible lengthy residence time.

A comparative groundwater analysis data for each aquifer in the project area is illustrated in Table 6.7 below. Complete individual borehole analysis data is tabulated in the Technical Report No. 5, Hydrochemistry and Recharge Report. A Trilinear diagram plot (Fig 6.2) clearly highlights the hydrochemical signature of the Ntane / Lebung aquifer.

Table 6.7 Aquifer Comparisons - Hydrochemical Data

Stage	Borehole No.	Lab Cond (µS/cm)	Lab TDS (mg/l)	Na (mg/l)	Ca (mg/l)	HCO_3 (mg/l)	Cl (mg/l)	NO3 (mg/l)
Basalt	10682	1130	600	103	79.6	295.24	153.97	15.64
Ntane/ Lebung	10684	1230	500	171	26.4	274.5	178.2	11.57
Ecca	10674	910	500	46	91.2	330.62	91.23	2.816

In Target Area B the TDS levels are slightly elevated to the northwest where the basalt has been intensively fracture (Bh10681, 10685). In the absence of a deep borehole to investigate the Ecca below the Lebung sequence to north of the Zoetfontein Fault, it can only be speculated that the saline water in the Ecca may be ‘up-coning’ by virtue of greater hydraulic head through these fractures.

It should also be noted that Ntane borehole Bh10686 to the north east of Target Area B bears relatively fresher water with a TDS value of 300mg/l and the nitrates are significantly lower at 0.6 mg/l or less. This is in sharp contrast with nitrate values recorded in the rest of the Ntane/Lebung aquifer that show elevated values that are as high as 42mg/l (Bh10685) as shown in Table 6.8 below. However, although the nitrates in the Ntane/Lebung aquifer are elevated compared to the levels in the Ecca, all values recorded so far are within the BOBS standard upper limit of 50mg/l.

Table 6.8 Ntane/ Lebung Nitrate - Iron and Nitrate Concentrations

Bh No.	W/S1 TDS (mg/l)	Dev TDS (mg/l)	W/S1 NO3 (mg/l)	Dev NO3 (mg/l)	W/S1 Fe(mg/l)	Dev Fe (mg/l)
10681	600	400	12.21	15.33	2.39	0.71
10682	600	800	15.64	26.27	0.46	0.22
10683	500	900	10.87	0.29	8.93	0.34
10684	500	500	0.37	11.57	0.18	4.49
10685	1000?	1000?	0.20	42.79	1.53	1.20
10686	300	300	0.64	0.14	11.88	2.39
10687	400	500	5.46	9.64	6.50	1.19
10688	400	400	0.35	3.34	2.37	0.27

W/S1 - 1st water strike
Dev - development

6.2.1 Kwetla Aquifer

The Kwetla Fm predominantly comprises a thick non-aquiferous sequence of non-carbonaceous mudstone and shale groundwater does occasionally occur in relatively thin and probably discontinuous arenaceous siltstone and sandy mudstone horizons and occasional sandstone layers. However, due to the predominantly argillaceous nature of the Kwetla Formation individual groundwater yields are very low. In the project area no borehole has been recorded as drawing water from the Kwetla Formation.

It should be noted that there is difficulty in positively demarcating the contact between the Kwetla Fm and the Boritse Fm where the uppermost carbonaceous Ecca mudstones are absent and thus water strikes encountered within a few meters of the interpreted base of the Kwetla Fm may well be within the Ecca.

6.2.2 Ecca Aquifers

The Ecca Group contains the most prolific aquifers and is believed to be present throughout out the whole Project Area south of the Zoetfontien Fault zone

The principal Ecca aquifer units are the medium to coarse grained sandstones of the middle Ecca Boritse and Kweneng Formations, which constitute lithologically variable, basin margin depositional facies whose areal distribution and thickness has clearly been influenced by pre-Karoo topography and syn-Karoo structural movements (BRGM, 1991). Within such a mixed sequence, it would appear that both primary as well as secondary (fracture) porosity are significant, and re-activated pre-and post Karoo faults appear to have a considerable influence on the yields of boreholes in the area. All evidence, both from previous and current re-evaluation work strongly suggests a double porosity, fracture dominated hydrogeological regime. This was clearly illustrated during aquifer testing in the Gaotlhobogwe Wellfield itself, (Phase I and Phase II Final Reports, DWA, 1995; 1996a), where a number of observation boreholes clearly indicated fracture responses.

It is also considered that the presence or absence of the mudstone comprising the Kwetla Formation (and possibly the uppermost Boritse Formation) almost certainly plays a critical role in the recharge potential of the underlying aquifers, since a thick mudstone cover, even when fractured, can not be conducive to any significant direct percolation from the surface to the underlying aquifer. However, the presence of good quality, low TDS(<750 mg/l) groundwater in the Boritse and Kweneng Formations over most of the area, even below a thick mudstone sequence (Bh10751, 10746 and Bh10754), would tend to indicate appreciable groundwater through flow, derived from recharge mainly in the south, east, and from other areas with little or no mudstone capping.

As a result of their very mixed lithological character, the principal aquifer units invariably exhibit confined groundwater conditions, even in the absence of a clearly defined confining layer. Water strikes are generally relatively shallow (around 50-60 m below ground level in Gaotlhobogwe valley and 80-95 m elsewhere including Malwelwe) and groundwater quality is most usually potable, although in general terms salinity increases down gradient to the northwest and could esily be influenced by the argillaceous nature of the aquifer further in to the basin..

With respect to regional piezometry (Map 4 groundwater gradients trend from southeast to northwest, becoming more northerly as flow approaches the sub-continental Zoetfontein Fault. Gradients are generally steeper in the southeast, as may be expected where general recharge potential is greater in this zone.

Piezometry

The piezometry map for the Ecca aquifer (Map 4) appears to indicate three distinct general groundwater flow systems, referred to as the eastern and western flow systems separated by a central dominant flow system.

The central flow system extends from Botlhapatlou to Letlhakeng and has a dominant northwesterly flow direction. Essentially this flow is controlled by the NW-SE trending structural domain which is dominated by the faulting system (F1 to F7). Structurally the central flow system appears to be limited by structure F3 to the east and by structure F6 to the west. The main Zoetfontein Fault (Z1) to the north-west appears to have minimal effect implying continuation of flow across the regional Zoetfontein fault structure; although to the extreme north-west of the Project Area the subsidiary Zoetfontein Fault (Z2) appears to have some influence. The northwesterly central flow pattern is rather disrupted in the south by the abstraction within the Gaotlhobogwe Wellfield area, where it is interesting to note that the wellfield cone of depression also appears to conform to the same NW-SE structural trend. To the south west the Jwaneng Northern Wellfield shows very little NE-SE similar effect.

Two distinct low hydraulic gradient areas are defined within the central flow system. The area between F3 and F4 with a sight extension west of F4 has low gradient. This area appears to receive flows from the major eastern groundwater divide that is centred between F2 and F3. The other flow from the west into this low gradient area is from a minor groundwater divide located to east of Gaotlhobogwe Wellfield.

The second low hydraulic gradient area is located at the extreme north-west of the project area, beginning around Khudumelapye and extending to Salajwe. The Khudumelapye- Salajwe trend appears to be centred on structure F5 and partly on F6 which both define the NW-SE trend. The groundwater flows into this area are from localised piezometric ‘highs’ to the north and south.

The eastern and the western flow systems are relatively minor and they appear not to conform to the dominant NW-SE structural domain. Project borehole Bh10689 and 10690 drilled in the eastern area were low yielding.

The eastern flow system is located in the Eastern Structural Zone and has a general easterly flow direction, but the trend is ill defined due to poor data density. The groundwater flow direction conforms to the NE-SW, structural domain that is defined in the Project Area by F9, F10, F11 and to some extend by the Zoetfontein Fault Zone. Groundwater gradients are fairly unformed and in this area the Zoetfontein Fault zone appears to act as a barrier suggesting that the Zoetfontein Fault zone most probably exhibits different hydrogeological characteristics at different locations.

The western flow system that is to the west of the Gaotlhobogwe Wellfield, trends towards the Jwaneng Northern Wellfield and does not appear to be influenced by the NW-SE trending faulting system. However, this flow regime is poorly defined in the extreme southwest margin of the project area and structural influence cannot be ruled out. It is possible that the groundwater divide centred on structure F6 controls the western flow system and the flow conforms to the NE-SW structural domain. However, in this domain the natural system has been clearly affected by the Jwaneng Northern Wellfield abstraction.

Aquifer Properties

Geological cross sections Figures 2.1, 2.2 and 2.3 trending north-south and east-west across the Project Area indicate variations in pre - Karoo topography. The line of these geological sections is shown on Map 1, the Geology Map.

The lithological profiles of boreholes drilled within the project area have indicated the presence of an Ecca lithology comprising a very mixed sequence of both arenaceous and argillaceous units, providing very variable borehole yields, which are apparently not necessarily related in magnitude to the occurrence of thicker horizons of coarser Karoo sandstones. In this respect, it has been observed that even boreholes drilled into favourable arenaceous units on apparent fault zones or depositional graben structures determined from geophysical data, such as borehole BH 10671, 10681, 10676, 8199, BH 6734, BH 6735 are not necessarily guaranteed to have high borehole yields. Table 6.9 gives an indication of aquifer (Boritse& Kweneng Fm) thickness and the respective encountered yields. The formation thicknesses were derived from the logging results

Table 6.9 Summary Formation Thicknesses – Yield Relationship

Bh No.	Kalahari (m)	Kwetla (m)	Boritse (m)	Kweneng (m)	Water strike (m)	Blow out yield (m3/hr)
BH10671	29	38	31	72	101	20
BH10672	23	57	105	87	111	50
BH10674	36	27	114	89	100	110
BH10676	25	23	148	103	145	5
BH10678	18	50	118	51	dry	0

The thickness of the various lithological aquifer units, namely the Boritse and the Kweneng Formations, is variable and this variability is also enhanced by structures and grabens that have generated partially separated ‘compartments’ (DWA, 1998).

Transmissivity Distribution

Test pumping data compilation and analysis of both past and present projects has revealed highly variable transmissivity values throughout the area. The average Ecca aquifer transmissivity values in Gaotlhobogwe and Malwelwe wellfield areas range between 180 – 200 m^2/day. In the Malwelwe area relatively high transmissivities values have been linked to steep edges of the grabens that appear to display significant structural control and the southern edge of the Main Graben is well defined. Available test pumping data along this edge suggests a high transmissivity (600m^2/day). The area is centred around Bh6827 – Bh6826, Bh6824 and Bh6825 and it would appear also that other smaller grabens/ host structures exhibit a similar trend and some successful boreholes Bh6830 and Bh10672 are locate off the Main Graben. Careful delineation of these edges is important in that a borehole placed on the host like Bh10671 will have a reduced yield due to a reduced aquifer thickness. In the middle of the Main Graben where aquifer thickness is substantial the transmissivities values are higher. Boreholes Bh10679 and Bh10674 in middle of the Main Graben are on the upper end of the range around 600m^2/day. The extension of this high

T value zone appears to be controlled by the NW-SE structural trend. Although further to the north west of Malwelwe Bh10676 intercepted thick argillaceous Ecca sequence with low T value of 3.5m^2/day and the borehole yield was only 5m^3/hr.

There is clearly a recognizable zone of high transmissivity values around the Jwaneng Wellfield with an average value of about 560m^2/day. It appears that around the Jwaneng Wellfield both primary as well as secondary (fracture) porosity are significant, and re-activated pre-and post Karoo faults appear to have a considerable influence on the yields of boreholes in the area.

The transmissivity and storativity values compiled by both WCS, 1998 and by BRGM 1991 in the project area are highly variable and show a wide range of values

In the project area the Ecca aquifer exhibits confined aquifer conditions, even in areas where the overlying Kwetla/ Dibete mudstone unit is absent. This is attributed to the 'self-confining' effect of the various mudstone/siltstone horizons on the different sandstone aquifer units within the Ecca sequence. Such 'self-confining' behaviour has also been noted in the Ecca aquifer on other WCS projects elsewhere e.g. Kang; Werda; Hunhukwe-Lokalane. Illustrative confining heads are listed in Table 6.10 below.

Table 6.10 Confining Heads in the Ecca Aquifer

BH No.	Aquifer Base (m)	First Water Strike (FWS) (mbgl)	SWL (mbgl)	Confining Head (m)	Sat. Thick FWS (m)	Sat. Thick SWL (m)
10671	170	101	58.00	43.00	69	84
10672	278	111	56.59	54.41	167	33
10673	162+	106	69.04	36.96	56+	135
10674	280+	100	81.08	18.92	80+	71
10675	151	106	63.40	42.60	23	42
10676	-	145	52.00	93.00		
10677		112	76.60	35.40		
10678		dry	76.30	-		
10679	294	147	67.00	80.00	147	-
10680	112	115	89.95	25.05	0	

Within the Botlhapatlou project area the confining head values ranges between 0 to 95m and on average the value is about 40m. Only one borehole in the project area is reported to show unconfined conditions (GRES II, 1994). Localized groundwater flow systems were also sited during the GRES II project. Figure 6.3 indicates trends in the distribution of the confining Ecca heads. The Malwelwe area has the highest confining heads and head values are much less in Gaotlhobogwe Wellfield area. Confining head values are also less in both an easterly and westerly direction.

6.3 Hydrochemistry

6.3.1 Overview

Existing data on groundwater chemistry and isotopes was compiled from various sources. This data set was then supplemented with analysis data from water samples collected during the reconnaissance sampling. The preliminary interpretations at the end of Inception Phase were summarised and presented in the Inception Report [DWA, 2004]. Additional hydrochemistry and environmental isotope data was subsequently gathered during the Exploration and the Production Phases drilling and test pumping with the aim of achieving the following.

- delineating areas of fresh water
- identifying various hydrochemical water types both laterally and vertically
- identifying possible recharge areas
- contributing to the conceptual groundwater model of the area.

For further characterization of the groundwater resources environmental isotopes were used to identify groundwater from different sources. It is also believed that isotopes (^{18}O and ^{2}H) could reveal indications of any possible recharge to the Kalahari aquifers and possibly the underlying Karoo bedrock aquifers. The full integration and interpretation of isotope, hydrochemistry and other hydrogeological information such as head distribution and flow patterns has contributed to a more comprehensive understanding of the groundwater system(s) in the Project Area.

Limited environmental isotopes sampling was carried out during the project as area has been subjected to a number of recharge studies (GRES I and II.) Data from these past studies was to be used for the resources evaluation in the Project. The full integration and interpretation of isotope, hydrochemistry and other hydrogeological information such as head distribution and flow patterns has contributed to a more comprehensive understanding of the groundwater system(s) in the Project area.

The paucity of reliable hydrochemistry data north of the Zoetfontein Fault revealed during the Inception Phase was partially addressed during the Exploration and Production Phases, which allowed for additional water sampling of new boreholes.

Samples collected during the course of the project were analysed for in the Consultants in-door laboratory for standard hydrochemical parameters and selected samples of Ntane Sandstone were analysed for environmental isotopes (^{18}O, ^{2}H, ^{13}C, ^{14}C and ^{3}H) by the private laboratory, Environmental Isotope Laboratory in South Africa.

The general quality of the hydrochemical data was verified by calculating an ionic balance check

The hydrochemistry data was entered to an Aqua Chem database for chemical analysis and spatial analysis was carried out using ArcView and Surfer.

6.3.2 Regional Synopsis

The project area has low water table gradients and natural groundwater movement is slow or virtually stagnant in some areas. The low hydraulic gradients limit large-scale regional groundwater flow in the hydrogeological system as a whole. It would seem unlikely that significant quantities of groundwater would be entering or leaving the study area. Locally, groundwater flow may be enhanced, e.g. near areas where natural recharge may take place. Generally flow patterns in the area are influenced by through flow, the two wellfield abstractions and possibly by isolated cattle post abstractions.

The project area has relatively deep water strikes and the presence of overlying Kwetla mudstones and Stormberg basalts in many places strongly suggest that direct rainfall recharge in the area is limited. In addition, the rainfall recharge process and quantity will be governed by the thickness and the nature of the sand cover. Recharge to the system is likely to be solely by the inflow from the south-east and aerial recharge in places where the Kwetla mudstones or basalts are absent or minimal in thickness

A regional spatial understanding of hydrochemical system has been derived by the assessment of parameters in relation to other important controlling factors such as groundwater flow (Geology Map 1 and Piezometry Map 4) and chemical parameters listed below were considered in detail:

- Water Type (Map 5)
- Total Dissolved Solids (TDS, Map 6)
- Bicarbonate (HCO3)
- Chloride (Cl-)

The Project area is large and encompasses two distinctly different aquifers and a prominent hydrogeological barrier, the Zoetfontien Fault, which exert some influences on the diversity of the hydrochemistry regime. This is well illustrated in the range of concentrations of few selected hydrochemical parameters shown in Table 6.11 below.

Table 6.11 Range of Hydrochemical Parameters Illustrating Diverse Hydrochemical Environments

Parameter	Minimum (mg/l)	Maximum (mg/l)	Average Value (mg/l)
Basalt Aquifer			
TDS	400	600	500
Cl	116	238	177
Na	103	200	150
HCO_3	66	256	160
Lebung Sandstone Aquifer			
TDS	400	1000	580
Cl	64	447	170
Na	114	286	180
HCO_3	65	563	250
Ecca Sandstone Aquifer			
TDS	313	730	475
Cl	11	112	60
Na	34	343	190
HCO_3	100	520	300

6.3.3 Chemistry of Different Aquifers

Kalahari Aquifer

The Kalahari Group comprises of mainly loose to poorly consolidated sand, silcrete and calcrete intercalations of variable proportions in fossils river valleys. There are no known boreholes drilled in Kalahari in the project area except for few wells at various localities (Table 6.12) Existing water level records indicate that the Meratswe fossil river valley has shallow (< 20m) borehole water levels, this shallow water in the valley is postulated as an indication that the valley is a groundwater discharge zone.

During a Project Reconnaissance Survey only one fresh water well at Kgesakwe (TDS-610mg/l) was identified in the Meratswe Valley. The other productive wells are located in a tributary valley at Mestibothoko and these are reported to be saline (>10,000mg/l).

Table 6.12 Shallow Kalahari Aquifer Boreholes in the Project Area

Well No	X coord.	Y coord.	Location	Depth	SWL	TDS(mg/l)	Comments
BGPA27	293613	7345692	Kgesakwe	40	15.5	610	Never dry up
BGP 152	196022	7235077	Letlhakeng		14.85		
BGPA76	310228	7330679	Gaotlhobogwe	6	n/a	n/a	dry
BGP144	283272	7340625	Metsibotlhoko		3.40	salty	No Hand pump
BGP145	283044	7340711	Metsibotlhoko		3.80	salty	No Hand pump
BGP146	283035	7340739	Metsibotlhoko		3.96	salty	No Hand pump
BGP147	283068	7340703	Metsibotlhoko		2.68	salty	No Hand pump
BGP148	283236	7340642	Metsibotlhoko		3.48	salty	No Hand pump
BGP150	283272	7340625	Metsibotlhoko		3.67	salty	No Hand pump

Basalt Aquifer

The minor basalt aquifer is restricted mainly to the north of Zoetfontein Fault. Stormberg basalt does however appear to always occur in a zone of varying width adjacent to the Zoetfontein Fault Zone. The degree of dislocation and local variation in basalt thickness is evident in the project area. Data from the drilling has confirmed various thicknesses. Basalt thickness of up to 560m have been recorded at BH 9234 near Diphuduhudu and project borehole Bh10688 has 522m whereas around Salajwe very little basalt has been intercepted

The basalt aquifer yields are generally small with often brackish water (1000mg/l<TDS>10,000mg/l). Borehole yields drawing water form basalt ranges from dry to 20m^3/hr with project borehole BH 10681 recording airlift of 13m^3/hr with TDS value of 780mg/l

Water strikes, rest water level depths and quality are quite variable as indicated in Table 6.13 below. The table data is derived only from project boreholes because private boreholes north of Zoetfontein Fault have no records and it is difficult to know if they intercepted the Ntane Sandstone below the basalt.

Table 6.13 Basalt Aquifer Hydrogeological Details

BH No.	BH depth (m)	Kalahari base (m)	Basalt base (m)	W/strike (m)	Rest Water Level (m)	Blow out yield at strike (m^3/hr)	TDS at water strike (mg/l)	Aquifer Basalt	Water type
10681	365	7	290	45, 85, 118, 167	38.95	seepage 6.7 13.0	780	1st w/strike 4th w/strike	Na- HCO3-Cl
10682	198	16	152	106, 125,	65.96	0.3 6.6	420 394	1st w/strike 2nd w/strike	Na- HCO3-Cl
10688	557	46	522	177	96.01	5.4	291	1st water strike	Na- HCO3-Cl
10741	282		282+					Seepage in basalt	Na- HCO3-Cl

In general basalt groundwater noted in Table 6.13 above is of type Na- HCO_3- Cl indicating a mixture of recent and old water. The recent water is thought to reflect the direct recharge and the old water is thought to be from the Ntane Sandstone below. When plotted on a Piper plot diagram (Figure 6.1) it shows a similar water signature as the Ntane, indicating hydraulic continuity between the two systems.

Ntane/ Lebung Aquifer

The Lebung aquifer is restricted to the northern part of the Project area and aquifer distribution data suggests that the Lebung aquifer may only be significant north of the Zoetfontein faulted blocks, although the geological map suggests the presents of the Lebung to the east of the project area. The Lebung aquifer is well developed in the north of the Project area where a saturated thickness averaging about 60m has been recorded during the current project.

Table 6.14 Lebung Aquifer Hydrogeological Details

BH No.	UTM Coordinates (Cape Datum)		BH Depth (m)	Blow out Yield (m^3/hr)	Water Strikes (mbgl)	Rest Water Level (mbgl)	TDS Water Quality (mg/l)	Water type
	Easting	Northing						
BH 10681	289750	7369191	365	41	45, 85, 118, 167,	42.92	380	Na- HCO3-Cl
BH 10682	295503	7378174	198	59.4	106, 125, 152	65.96	510	Na- HCO3-Cl
BH 10683	284324	7390209	224	0.8	125	**?**	352	Na- HCO3-Cl
BH 10684	280869	7374594	200	1.8	115	65.96	415	Na- HCO3-Cl
BH 10685	279366	7369911	337	43.92	191, 228	76.9	930	Na- HCO3-Cl
BH 10686	314234	7382261	468	25	388	79.90	240	Na- HCO3-Cl
BH 10687	306490	7373066	310	44	226	96.28	454	Na- HCO3-Cl
BH 10688	314426	7369115	557	51	177,522	79.30	390	Na- HCO3-Cl
BH 10740	297493	7375249	222	7	123	57.3	442	Na- HCO3-Cl
BH 10742	303987	7372839	315	25	191, 216	93.7	384	Na- HCO3-Cl
BH 10743	294118	7373350	281	119	168	49.15	510	Na- HCO3-Cl
BH 10744	302736	7379995	280	100	178	63.4	365	Na- HCO3-Cl
BH 10745	285584	7367781	416	33	232	52.0	430	Na- HCO3-Cl

A total of 21 boreholes were found drawing water solely from the Lebung Group and 4 boreholes (Bh 10681, Bh 10682 and Bh 10688) are drawing water from both the basalt and the Ntane Sandstone. The salinity (TDS) of the groundwater in these boreholes is shown in Table 6.14 and these are slightly elevated to the northwest where the basalt has been intensively fractured (Bh10681, 10685, 9345, 9344, 9347). In the absence of a deep borehole to investigate the Ecca below the Lebung sequence to north of the Zoetfontein Fault, it can only be speculated that the saline water in the Ecca may be ‘up-coning’ by virtue of greater hydraulic head through these fractures.

Fig. 6.4 indicates a simplified piezometric head in the Ntane Sandstone aquifer. It is evident that the salinity in the Lebung aquifer has a narrow water quality variation range (350 mg/l - 1,000 mg/l) and does not show any obvious pattern in line with the piezometric flow trend.

It should also be noted that Bh10686 to the north of Target Area B bears relatively fresher water with a TDS value of 300mg/l and the nitrates are significantly lower at 0.6 mg/l or less. This is in sharp contrast with nitrate values recorded in the rest of the Ntane/Lebung aquifer that show elevated values that are as high as 42mg/l (BH10685) as shown in Table 6.15 below. However, although the nitrates in the Ntane/Lebung aquifer are elevated compared to the levels in the Ecca, all values recorded so far are within the BOBS 32:2009 standard upper limit of 50mg/l.

Table 6.15 Ntane/ Lebung Aquifer - Iron and Nitrate Values

BH No.	W/S1 TDS (mg/l)	Dev TDS (mg/l)	W/S1 NO_3 (mg/l)	Dev NO_3 (mg/l)	W/S1 Fe(mg/l)	Dev Fe (mg/l)
10681	600	400	12.21	15.33	2.39	0.71
10682	600	800	15.64	26.27	0.46	0.22
10683	500	900	10.87	0.29	8.93	0.34
10684	500	500	0.37	11.57	0.18	4.49
10685	1000?	1000?	0.20	42.79	1.53	1.20
10686	300	300	0.64	0.14	11.88	2.39
10687	400	500	5.46	9.64	6.50	1.19
10688	400	400	0.35	3.34	2.37	0.27

W/S1 - 1st water strike

Dev - development

In an effort to get a better understanding of the nitrate values changes at water strike and at the end of borehole development, both the TDS and iron vales were included in the Table 6.15 above. It is apparent that both TDS and nitrates concentrations show no obvious pattern and the changes appear random. The iron values show a definite decreasing trend with development or pumping.

A Salajwe supply borehole BH 589 show very little hydrochemical changes over a period of 13 years between 1982 and 1995 as shown in Table 6.16 below. More monitoring data is imperative to get a better understanding of this aquifer.

Table 6.16 BH 589 Time Series Hydrochemical Data

BH No.	Date	conductivity (m/cm)	TDS (mg/l)	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)	Cl (mg/l)	SO4 (mg/l)	F (mg/l)	HCO3 (mg/l)	Fe (mg/l)
589	10/5/1982	150.5	942.0	148.0	72.0	59.0	9.0	201.0	62.0	0.1	425.0	-1.0
589	12/6/1986	164.0	952.0	68.0	68.0	45.0	3.4	204.0	33.0	0.4	405.0	0.0
589	12/9/1986	139.7	840.0	135.0	70.0	40.0	4.2	184.0	64.6	0.5	403.0	-1.0
589	01/1/1990	150.0	906.0	99.0	66.0	43.0	3.4	185.0	60.0	0.3	341.0	-1.0
589	08/8/1993	147.0	860.0	13.2	109.2	50.0	4.7	219.8	32.9	0.5	259.0	0.0
589	26/04/1995	114.7	738.0	128.9	22.3	41.3	3.5	35.4	46.1	0.5	400.0	0.1

Data distribution limitations are thought to be a hindrance in any meaningful interpretation of the Lebung hydrochemistry data set.

Groundwater in the Ntane /Lebung is of the Na- HCO_3- Cl type and the presence of the Na is an indication of lengthy residence time.

The hydrochemical evolution in the Lebung Group aquifer is shown in the trilinear diagram in Fig 6.2. In the case of borehole Bh 589, the analyses were carried out over the period from 1982 to 1995 and the minor difference in the relative chemical composition of the water is noteworthy.

6.3.4 Major Ion Chemistry

All these water types have been noted to have gone through significant ion exchange as reflected by high sodium percentages (Table6.17).

Table 6.17 Lebung Boreholes -Sodium Percentages

Bh No.	Sample type	pH	EC uS/cm	TDS mg/l	Ratio Ca/ Na	Na %
10681	W/S 1	7.83	1130	600	0.19	79.02
10681	Development	8.39	890	400	0.20	81.28
10682	W/S1	7.78	1130	600	0.77	50.09
10682	Development	7.88	1470	800	0.17	79.93
10683	W/S1	7.81	950	500	0.27	69.29
10683	Development	8.28	1790	900	0.06	92.35
10684	W/S	8.15	1230	500	0.15	78.21
10684	Development	8.39	1140	500	0.18	78.47
10685	W/S	8.09	2170	1000	0.22	80.89
10685	Development	8.04	2210	1000	0.19	76.72
10686	W/S 1	8.12	550	300	0.09	82.23
10686	Development	8.06	543	300	0.07	89.32
10687	W/S 1	8.23	780	400	0.12	82.63
10687	Development	7.7	976	500	0.20	76.12
10688	W/S 1	8.02	665	400	0.13	86.25
10688	Development	7.99	700	400	0.21	78.07

The sodium concentration expressed as percentage of the cations provides an indication of the hydrochemical evolution in the aquifer. The data for the Lebung Group aquifers are presented in Table 6.17. From this figure it is evident that the groundwater in the Lebung Group aquifer has already reached an advanced stage of evolution in the northern parts of the Project area and in the east. Boreholes Bh10681 10682 and 10688 had 1st water strikes in basalt.

One distinct water type is evident in the Lebung aquifer, namely:

Na – HCO_3/Cl Water Type C

The salinity in the Lebung aquifers is most likely to be a result of hydrogeological entrapment. The rate of flushing or groundwater flow will determine in part the rate removal of resident groundwater, the strength of diffusion influences and dissolution rates (Lloyd, 1985). In this context, within these Lebung aquifers, the regional structural setting has been shown to be dominated by the Zoetfontien Faults. This has compartmentalised the aquifers and thus impacted upon, and probably reduced, sub-regional groundwater flow rates. This structural control is also evidenced by rather subdued and “confused” flow patterns as well as the distribution of the major ions in the Lebung aquifer close to the Zoetfontein Fault zone where the project exploration was focused.

Ecca Group Aquifer

The Ecca Group aquifer is mainly restricted to the south of the Zoetfontien Fault, occurring beneath and partly confined by the Kwetla Fm. Both the Boritse and Kweneng aquiferous Fms are the targets for groundwater resources within the Project area. Water types and quality within the Ecca aquifers appear to be determined by two major factor namely structural control (graben and horsts) and formation inter-layering (particularly coal/ mudstones horizons). In the Project area groundwater in the Ecca Group aquifer show low mineralization (<1000mg/l).

The Ecca hydrochemical setting of the groundwater of the Project area has been extensively discussed in previous groundwater resources projects (DWA, 1995, BRGM, 1991), and has been investigated in detail by the DGS GRES II Project (GRES II, 1995). Existing hydrochemical data and water samples collected during the course of the project were analysed in order to develop regional groundwater chemistry synopsis of the project area.

Given the occurrence of relatively fresh and very little saline groundwater in the project area, a primary objective of the hydrochemical study was to address the issue of the hydrochemical composition of water types and to discuss their possible origin and evolution.

The dominant cations in the Ecca group aquifer are Ca^{2+}, Na^{+} and Mg^{2+} and dominant anions are HCO_3^- and Cl^-. Concentration findings of these parameters confirm previous studies where investigations in the area revealed fresh groundwater (Table 6.18).

Table 6.18 Range of Hydrochemical Parameters for the Ecca Aquifer

Parameter	Unit	Minimum	Maximum	Average
TDS	mg/l	116	1986	470
Conductivity	uS/cm	230	3340	799
Ca	mg/l	1	456	60
Na	mg/l	10	660	50
Mg	mg/l	1	54	22
NO_3	mg/l	0.5	102	2.7
Cl	mg/l	28	485	86
HCO3	mg/l	31	1500	312
F	mg/l	0.05	0.2	19

(Adapted from BRGM (DGS, 1991)

Total Dissolved Solids (TDS)

Total Dissolved Solids map (Map 6) generated during the course of the project shows a very strong correlation between piezometry/groundwater flow and groundwater quality.There is also a strong correlation between water quality and the Zoetfontein Fault structure. The Zoetfontein Fault structural control is demonstrated by the termination of Na-HCO_3 water type against the Na-HCO_3-Cl along the fault zone exerting an east - west control.

The Ecca Group aquifer has TDS values ranging from 200-850mg/l with average value of 450mg/l. Low TDS value of 300mg/l are recorded in the central part of the aquifer while higher values (>800mg/l) are recorded to the east and south east. The northern part of the project area which is regarded as discharge zone (BRGM) also recorded higher TDS values.

Vertical and Temporal Hydrochemical Variations

Project exploration drilling has revealed some vertical variation in groundwater, with a general increase in TDS with depth. There are also indications of water quality changes as a result of multi-layered nature of the Ecca aquifers although this was partially masked by the restrictions on water sampling and the “mixing” that occurs as a result of the drilling process that was used.

It has generally been observed that the Boritse Fm constitutes the predominantly fresh water aquifer within the project area with the underlying Kweneng Fm aquifer usually yielding slightly mineralised water (Bh10746, 10751). However, importantly this general observation does not hold for some boreholes (Bh10754) which revealed constant water quality to terminal depth even after penetrating both the Boritse and the Kweneng aquifers. Table 6.18 shows minor water quality changes observed in borehole Bh10751.

Table 6.18 BH 10751 Minor Water Quality Variations with Depth

Bh No.	Depth (m)	TDS (mg/l)	Conductivity (µS/ cm)	pH	Yield (m^3/hr)
10751	119	423	845	5.48	water strike
10751	143	424	853	5.14	44
10751	161	430	853	5.02	51.42
10751	185	426	852	7.47	54.36
10751	209	439	875	6.90	80.35
10751	233	430	862	6.10	84.56
10751	257	436	870	5.24	88.92
10751	281	437	865	7.87	112.66

Temporal groundwater hydrochemical variations are minor within the project area; this has been noticed over years as well as short periods of test pumping and also at some production sites. A borehole in Letlhakeng Bh 1314 has been pumping since 1970 and there has been very little water chemistry changes as indicated in Table 6.19 below.

Table 6.19 Bh 1341 Time Series Data

Bh No.	Date	TDS (mg/l)	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)	Cl (mg/l)	SO4 (mg/l)	F (mg/l)	CO_3 (mg/l)	HCO_3 (mg/l)
1341	1/25/1970	720	4	10	190	3	36	13	3	26	440
1341	8/4/1973	486	10	44	128	3	36	20	0.5	18	432
1341	3/9/1984	526	7	6	190	5.9	58	20	1.73	19	387
1341	11/10/1990	520	9.4	4.2	156	3.5	48	19	2	31	343
1341	10/10/1995	512	4.4	9	192	2	24.5	9	1.29	67	342

There is little time series changes for Gaotlhobogwe Wellfield production boreholes as well as Jwaneng Wellfield that has been operating since 1981. Data from Jwaneng Northern Wellfield shows around 10% variation (Table 6.20) and the wellfield has remained Ca/Mg HCO_3 water type A from 1981-2010. TDS values have been fairly stable around 600mg/l.

Table 6.20 Jwaneng Wellfield Water Conductivity Time Series Data (illustrative values only)

BH No.	March 1983	Dec 1983	Aug 1990	Jan 1991	Dec 2006
A1	902	800	843	866	916
A2	870	660	795	877	853
B1	940	820	844	925	965
B2	931	810	870		
C1	921	928	832	918	942

Structure/ Groundwater Flow (Piezometry)

The Ecca regional piezometric map indicates natural groundwater flow from the south-east with a dived centred on F4 that generates a southeast-ward and a west-ward flow. The divide also has ‘apparent’ separation of Ca/Mg-HCO_3 and the Na-HCO_3 water types. The northwest flow component in the Kudumelapye area assumes a Na-HCO_3 water type character.

The Lebung and Ecca aquifer have hydraulic continuity but on the northern side of the Zoetfontein Fault the groundwater character is Na- HCO_3- Cl with a high (>75%) Na percentage ratio.

In general the hydraulic gradients are low and water type boundaries are diffuse and difficult. No head differences have been observed across any of the major Zoetfontien Faults series groundwater flow controlling structures and this is confirmed by the Ecca piezometric surface (Map 2). Some hydraulic boundary influences were observed during test pumping.

6.3.5 Hydrochemical Facies

The hydrochemical facies in the Project area are governed by both the structures and the flow regime as is illustrated by the Ecca piezometric surface (Map 4).

In general, over much of the project area groundwater is low in mineralization and the few relatively elevated cases are mostly associated with deep water strikes or contributions from the Kwetla Formation mudstones. The Ecca groundwater in the project area can generally be classified into two main groups although there are a few exceptions to this generalized classification.

- Ca-Mg - HCO_3	Water Type A
- Na - HCO_3	Water Type B
- Na – HCO_3/Cl	Water Type C (mostly Lebung groundwater)

Other less important water types noted include Ca-Na-HCO_3, Ca/ Na- Cl and Na – HCO_3/Cl. It must be noted that with the exception of the first water strike, all other samples represent mixed samples from various levels of the boreholes. This has undoubtedly influenced water typing.

Water Type A is mostly found in the Gaotlhobogwe area and extends northwards to Malwelwe and all the way to the Government Ranch next to the Zoetfontein Fault zone. Southwards the Water Type A zone extends west and south-west to the Jwaneng Northern Wellfield. Very little data is available in the eastern portion of the project area but indications are that Water Type A is dominant as indicated by borehole Bh 300 and Project borehole Bh 10690.

The Na-HCO_3 Water Type B is dominant in the area north of Letlhakeng and extends into Kudumelapye area and partly to the north of the Zoetfontein Fault. This water type zone is ill defined as some isolated boreholes within the zone show Water Type A. It is generally believed that this water type is a result of ion exchange promoted by the presence of the argillaceous units within the Ecca as a result of groundwater evolution down the hydraulic gradient (GRES II, 1997). The Kwetla mudstones and other similar horizons within the Boritse and the Kweneng formations are argillaceous in nature

Water Type C, Na-HCO_3/Cl, is not common in the project area and isolated occurences of it have been identified in some localities like Molengwane (BH 6310, 6375, 6309) north of Serilatholo, Kudumelapye-Salajwe area (BH2869,Z6090). Different water types mixing could also explain this type of water.

In the Ecca, south of the Zoetfontein Fault, groundwater flow is towards the north and north-west and the water mineralization slightly changes down the groundwater gradient. This trend probably reflects the principal cation exchange reaction ($Ca^{2+} > 2Na^{+}$) that can normally be followed as the groundwater moves down gradient through an aquifer. Older, stagnant or slow moving water tends to be more Na^{+} dominant due to interaction with cations in clay minerals. Highly soluble minerals are commonly present in this slow flow zone because little groundwater flushing occurs. In zones of more active flow recharge, fresh Ca^{2+} dominant water enters the system. Therefore as the water moves down gradient, an evolution sequence from Ca^{2+} dominant water to Na^{+} dominant water occurs.

In all high yielding Gaotlhobogwe Wellfield boreholes (BH8132, BH8189, BH8133, BH6830, BH6827 and BH8226), the predominant cation is Ca^{2}+. Evidently most low yielding boreholes (Bh8191, Bh8237 and Bh8238) in the same area have Na^{+} as the dominant cations. It is postulated from this hydrochemical evidence that low yielding boreholes may be located in isolated blocks of fairly stagnant or slow-flow groundwater zones.

Within the Malwelwe Wellfield area Ca/ Na rations have indicated that boreholes within the Main Graben have ratios of less than 0.5 (BH 10674, 10750, 10679, 10752, 10755) as compared to those boreholes (BH 10671, located on the graben edges (BH 6759, 10747, 10754) and those located on the horsts (BH 683, 6742). The Water Type A area in general has Ca/ Na ratios of less than 2. Similar trend is quite evident sodium concentration expressed as percentage of the cations is considered it provides an indication of the hydrochemical evolution in the aquifer. The data for the Ecca aquifer are presented in Figure 6.5. From this figure it is evident that the groundwater in the Ecca aquifer is generally in the early stages of evolution except for the discharge zone centered on the Meratswe fossil valley and the eastern Ecca aquifer as indicated by borehole BH 10690 and 10691 which indicate Na percentage values in access of 75%. Boreholes BH 10675 and BH 10677 drilled on the edges of minor garbens have values of 74% and 91% respectively.

This project central zone centered on Malwelwe has Na percentage values ranging between 17% and 30%. This recent water observation supports the thinking that there is some active recharge within the project area.

Previous studies (DWA, WCS, 1998) suggest that in zones of the Project area where the Ecca sandstones are not covered by large thicknesses of Kwetla Formation mudstones there may be improved potential for active recharge of the groundwater, leading to predominantly a Ca- Mg - HCO_3 Water Type A. Boreholes with Na^+ as the predominant cation (Water Type B) are considered to be located in area overlain by thick Kwetla mudstones or are located in more isolated areas in which groundwater flow is much reduced, thereby promoting ion exchange processes noted above.

6.4 Groundwater Potability snd Water Quality

Despite noted differences in the hydrochemistry in the various aquifers (Kalahari, Basalt, Ntane Sandstone and the Ecca), at any particular point, the hydrochemical parameters determining the suitability of the groundwater for specific purposes are generally the same.

Available water quality data show that many of the boreholes are within the BOS 32:2009 Drinking Water Specifications. In the case of iron less than half of the existing boreholes in the project area exceed the specifications (Table 6.21). Coupled with biofouling problems, it is evident that iron is a key portability factor for the region. Potable, low TDS (<1000mg/l), groundwater is common in the area.

Table 6.21 BOBS 32 : 2009 Water Quality Standards

Determinants	Class I (acceptable)	Class II (Max. allowable)
Conductivity (uS/cm)	1500	3100
Dissolved solids (mg/l)	1000	2000
Calcium (mg/l)	150	200
Chloride (mg/l)	200	600
Fluoride (mg/l)	1.0	1.5
Magnesium (mg/l)	70	100
Nitrate (mg/l)	50	50
Nitrite (mg/l)	3.0	3.0
Potassium (mg/l)	50	100
Sodium (mg/l)	200	400
Sulphate (mg/l)	250	400
Iron (mg/l)	300	2000
Manganese (mg/l)	100	500

(adapted from BOBS 32:2009)

6.4.1 Specific Parameters

Total Dissolved Solids (TDS)

Within the Project area, as per the Ecca TDS map, potable water inflow appears to be from the south east and flows to the north and northwest.

The TDS values range from 200-850mg/l, with an average value of 450 mg/l. A contour plot of the TDS values is presented in Map 6. A significant low TDS area is evident in the centre of the project area and higher values are located to the east and south east. To the north-west the TDS is also slightly elevated (>800mg/l). This area was regarded as groundwater discharge area (BRGM, 1991) and is centred on the Meratswe fossil river valley. In the Jwaneng Northern Wellfield TDS values ranges 500 - 1000mg/l and in Gaotlhobogwe Wellfield the range is 500-800mg/l.

With respect to temporal variations in groundwater composition there is very little time series water quality data variations from a number of Gaotlhobogwe Wellfield production. Simillary there is also little changes in the Jwaneng Wellfield that has been operating since 1981. Illustrative data (Table 6.20) from Jwaneng Northern Wellfield show at most some 10 % variation is evident.

On a seasonal basis minimal hydrochemical changes have been observed despite an attempt to collect data during the GRES II project which yielded inconclusive results.

A borehole in Letlhakeng BH 1314 has been pumping since 1970 and there has been very little water chemistry changes as indicated in Table 6.19 but no recent hydrochemistry data has been found.

Water quality variations with depth are commonly observed but the magnitude of the changes is minimal. For example during drilling at BH 6763 1st water strike was Water Type A, but at depth the water type changed to Water Type B. Other changes noted with depth include Ca/Na and Ca/Mg rations changes.

When it became apparent that the nitrates in the Lebung were slightly elevated, important parameters, TDS, Fe and NO_3 were continuously monitored during drilling and the data is shown in Table 6.15. There is no obvious pattern evident on the TDS and the nitrates although the iron values show a definite decreasing trend with depth.

Iron

Iron is essential to human body and the recommended limits (BOBS 32:2009) placed on it is essentially for the purpose of avoiding problems in household water associated with precipitates and stains that form because of oxides of these metals are relatively insoluble (Freeze and Cherry, 1979).

In general, the water from the Ecca aquifers of the project area can be classified as being very hard, which would suggest the encrustation of pipes, water heaters and the components of the delivery system could occur (DWA, 1998).

With respect to existing and future production boreholes themselves, iron encrustation and the presence and growth of iron bacteria within the borehole, the screens and the immediately adjacent aquifer will (and has!!) over time gradually blocked screens and aquifer fissures and cause reduced yields.

6.4.2 Biofouling and Groundwater Resource Degradation

Over the life of the Gaotlhobogwe Wellfield is has become apparent that the Ecca aquifer, at least in the immediate vicinity of the individual production boreholes, is ‘polluted’ by iron/sulphate reducing Gallionela Ferruginea and Sphaerotilus type bacteria. These bacteria form colonies and grow as clumps on the inside of the well screens as well as in the immediate area in the aquifer, and in the correct hydrochemical conditions, is responsible for the slime deposits that have seriously blocked both boreholes and the abstraction pumps in both the Jwaneng Northern Wellfield and the Gaotlhobogwe wellfields. This biofouling has in turn almost certainly had significant negative impact on the two wellfield yields since inception in 1981 and 1991 respectively.

As a result of this biofouling problem a number of studies and rehabilitation attempts have been conducted in Gaotlhobogwe Wellfield by DWA [T. Reikel, DWA, 2001; WCS, DWA 2003; Roscoe Moss, 2007-8].

- The first attempt to rehabilitate some of the Gaotlhobogwe Wellfield production boreholes was a chemical treatement was carried out by DWA at BH’s 7864 and 7914 when ‘Anolyte Solution’ was used. The exercise was reported successful (T. Reikel, DWA, 2001) as the yields were reported to have increased by 25%.

- Work done by Wellfield (DWA,2003) was never followed up by a borehole rehabilitation process but the presence of Gallionela Ferruginea, an aligotrophic organism that grows in a low carbon environment but requires organic substrate was confirmed. During this investigation the boreholes that were tested pumped (BH 7858, 7860, 7864, 7914, 7931, 7966, 6875 and 9379) indicated serious bacterial growth and biofouling and had specific capacities well below 50% of their initial values.

- Recent work also carried out by DWA under the guidance of Roscoe Moss company experts also confirmed the presence of the iron bacteria during the Water Well Inspection and Rehabilitation Project (WWIRP) in 2006 - 2007. The project was a collaborative effort between the government of Botswana (DWA), U.S. Trade and Development Agency (USTDA) and Roscoe Moss Company improve the yield and operation of DWA production boreholes, develop a borehole rehabilitation schedule and procedures for borehole rehabilitation, and trained the DWA cleaning crews on rehabilitation techniques.

- A total of 35 boreholes were selected in six wellfields in different hydrogeological environments around Botswana were investigated and rehabilitated in accordance with a standard borehole rehabilitation plan comprising water sampling and down the hole video inspections, pre-rehabilitation performance step tests, mechanical development, chemical treatment, and post-rehabilitation performance step tests. Five boreholes at Gaotlhobogwe Wellfield (BH 7860, BH 7864, BH 7914, BH 7931, and BH 7966) were included in the study; however, none could be succesfully redeveloped because of the downhole conditions that were found (eg broken screens, dropped pipes, collapsed hole).

Examination of the results of these activities and other literature has revealed the following;

- Iron bacteria are micro - organisms which obtain energy by directly oxidising iron into iron oxides or hydroxides, or oxidize ferrous iron in solution to the ferric state and effect the precipitation of ferric hydroxide (Fe (OH_3). This energy is used to promote the growth of thread - like slimes which, together with the ferric iron (and in conjunction with carbonate precipitates), form voluminous mass.
- *Gallionella ferruginea* is a bean-shaped and iron-oxidizing bacterium that produces a twisted stalk, and is often heavily incrusted with precipitated iron. It was first described by Ehrenberg in 1836 and has been placed among the "iron bacteria".
- Iron bacteria include both heterotrophs as well as chemoantrophs organisms and they catalyze the oxidation of ferrous ($Fe^{2+)}$ and can use CO_2 as source of carbon. The process by which the bacteria proliferate is kinetically controlled and is largely a function of redox conditions, water chemistry and availability of nutrients like dissolved oxygen and carbon.
- The preferred optimum environment for the Gallionela aligotrophs is noted below (Driscoll 1986):
  - requires low dissolved oxygen (0.1-1.0mg/l)
  - near neutral pH (6.0-7.6)
  - redox potential (200-320m/l)
  - temperature (4 -25.6°C)
  - low iron content (1-25mg/l)
  - traces of organic matter (carbon source)
  - grows best in potable groundwater
- Iron bacteria are found in all parts of the world, and occur naturally in dams, swamps, watercourses, lakes and ground water. The reported occurrence of iron bacteria in bores has increased rapidly in recent years (ref T. Reikel, DWA)
- When iron bacteria infect a bore, the resultant growths may either suspend in solution or tuberculate (deposit growth) onto the bore casing, screens or the aquifer itself. Tubercles, which are usually firmly adherent to any metal surface, may set up an oxygen concentration cell leading to accelerated corrosion at the bottom of the tubercle. The problem is often aggravated by the fact that the anaerobic region at the base of the tubercle also provides a suitable habitat for sulphate-reducing micro-organisms; they proliferate in this region and add their own contribution to the total corrosion.
- Tuberculation may also occur in pumping equipment and reticulation systems. As a result, restrictions, or even complete blockages of free entry of ground water into the bore and through the reticulation system, may occur. Decreased pumping efficiency and increased pumping costs are the likely outcomes.
- In fixing to metallic fittings the bacteria are thought to secrete an acidic substance which increases metal corrosion resulting in deterioration of bore casing, screen, pump, column and reticulation system.
- Iron bacteria may cause a decrease in the standard of water quality with adverse effects on taste, colour and odour, and lead to undesirable staining, usually of a reddish nature.

The above listed conditions and detrimental outcomes are common in all the boreholes in Gaotlhobogwe Valley as per sample listing generated by Wellfield Consulting Services in 2003 (DWA, 2003).

Table 6.22 below lists some of the relevant hydrochemical parameters pertaining to bacterial growth from the Gaotlhobogwe Wellfield production boreholes.

Table 6.22 Gaotlhobogwe Production Boreholes-Selected Hydrochemistry Details

BH No.	pH	Temperature °C	Redox (milli volts)	Dissolved O_2 (mg/l)	Dissolved CO_2 (mg/l)
7858	7.36	25.8	-18	1.7	11
7860	6.68	25.5	18	2.5	24
7864	6.64	25.3	22	2.3	28
7914	7.56	27.0	-29	2.3	9
7931	6.79	26.7	13	6.7	24
7966	6.58	24.9	24	2.4	28
6875	6.71	26.1	20	4.0	65
9379	6.19	26.4	18	4.5	51

These hydrochemical conditions are similar to those in Jwaneng Northern Wellfield where similar bacterial growth problems have been reported. Since both wellfields are tapping the same Ecca aquifer that has abundant carbon as a nutrient it is not unreasonable to assume that any future wellfields abstracting from this aquifer (eg Malwelwe) will suffer from the same problem.

During the project, production borehole, BH 6824, 6825, 6826, 6827 and 6829 established by BRGM some 20 years are were inspected by a camera and no biofouling was observed. These boreholes have not been pumping, supporting the conclusion that bacteria biofouling is also promoted by pumping. The bacteria proliferation is kinetically controlled and is largely a function of redox conditions, water chemistry and availability of nutrients like dissolved oxygen and carbon.

As per current developments it appears that the only solution to the problem lies with systematic regular borehole rehabilitation which will disrupt extensive bacterial growth. So far it is not clear that construction materials play a significant role but there are possibilities that they contribute. The recent study by DWA has not been very conclusive.

6.4.3 The Nitrate Phenomena

Elevated nitrate concentrations have a long-term effect on the teeth and joints of man and animal. Such effects may take several years to manifest themselves depending on the concentrations in groundwater.

The BOBS standard for nitrate of 50.0 mg/l is not exceeded by any boreholes in the area but there is an obvious pattern related to the two main different aquifers in the Project area. The Lebung aquifer to the north of the Zoetfontein Fault has elevated nitrates when compare to the values recorded in the Ecca south of the Fault. The TDS values were also noted to be elevated as shown in the illustrative Table 6.23 below.

Table 6.23 Aquifer Comparisons - Hydrochemical Data

Aquifer Type	Borehole No.	Lab Cond (µS/cm)	Lab TDS (mg/l)	Na (mg/l)	Ca (mg/l)	HCO_3 (mg/l)	Cl (mg/l)	NO3 (mg/l)
Basalt	10682	1130	600	103	79.6	295.24	153.97	15.64
Ntane/ Lebung	10684	1230	500	171	26.4	274.5	178.2	11.57
Ecca	10674	910	500	46	91.2	330.62	91.23	2.816

In Target Area B the TDS levels are slightly elevated to the northwest where the basalt has been intensively fracture (BH10681, 10685). In the absence of a deep borehole to investigate the Ecca below the Lebung sequence to north of the Zoetfontein Fault, it can only be speculated that the saline water in the Ecca may be ‘up-coning’ by virtue of greater hydraulic head through the NNW-SSE trending fracture system.

It should also be noted that BH10686 to the north of Target Area B bears relatively fresher water with a TDS value of 300 and the nitrates are significantly lower at 0.6 mg/l or less. This is in sharp contrast with nitrate values recorded in the rest of the Ntane/Lebung aquifer that show elevated values that are as high as 42mg/l (BH10685) as shown in Table 2.8. However, although the nitrates in the Ntane/Lebung aquifer are elevated compared to the levels in the Ecca, all values recorded so far are within the BOBS standard upper limit of 50mg/l.

6.5 Groundwater Recharge

6.5.1 Previous Recharge Mothodologies Applied in the Region

Recharge in the Kalahari has been a contentious issue but is of great importance for groundwater resource evaluation. There is evidence that the thick Kalahari sand cover will prevent any movement of soil moisture beyond the zone of evapo-transpiration (Foster et al 1982). The existence of groundwater in the aquifers underlying Kalahari sands was explained as recharge during prolonged (few 1000’s years) pluvial periods in the past (de Vries (1984). The advent of isotope hydrology has changed this concept radically. Groundwater containing tritium was found in some areas in the Kalahari, thereby indicating recent (few decades) recharge (Verhagen et al 1974). Tritium was found in soil moisture at great depth (Beekman et al 1999). Variations in soil moisture content in response to rainfall were measured down to 4 meters depth (Selaolo 1998). These all produce evidence that rain can penetrate deep in the Kalahari sands enabling recharge to continue to take place in some localities. Stable isotope data support the idea that extreme rainfalls form the major components of recharge through the Kalahari sands because they wet the soils deep enough to be beyond the reach of most of the tree roots. This is in addition to preferential pathways ‘short-circuiting’ vertical water flow (Selaolo 1998, Beekman et al 1999).

Recharge determination methods differ widely in the time scale involved (months to millennia), the distance involved (meters to 100 kilometers), depth (below root zone towards the water table) and nature of the soil/outcrop material (Xu and Beekman 2003). The results therefore differ widely and the hydrogeologist using these data for resource evaluation needs to interpret them carefully. In particular a distinction needs to be made between the micropore recharge (i.e. the recharge through the unsaturated zone) which is dependent on evapotranspiration, macropore recharge (directly through outcrops into the aquifer) without any evaporation enrichment of ions and isotopes, which then sum-up to the total recharge contributing to the aquifer. The different methods that are available cater for each of these components.

Chloride Mass Balance

Micropore recharge through the unsaturated zone will inevitably result in the loss of water through evapotranspiration through the soil and plant causing enrichment of anions and cations and the stable isotopes in the water. Chloride is the most conservative of the common chemical species and in the absence of additional Cl sources, the input of chloride from precipitation plus dry deposition can be equated to the mass of chloride in soil water or in groundwater. The Chloride Mass Balance (CMB) may therefore be used to estimate recharge under assumptions that the mass of chloride lost by surface runoff, adsorption or reaction with mineral phases is negligibly small. But the method is limited to quantifying micropore recharge in a localized area.

The chloride concentration in groundwater reflects the degree to which the chloride in the precipitation is concentrated by evaporation. Knowing the total amount of chloride deposited annually (from precipitation and dry deposition), it is possible to calculate the annual recharge to an aquifer. Eriksson and Khunakasem (1969) calculate the groundwater recharge flux from equation below:

$$R*Cl_{gw} \quad = \quad P*Cl_{wap} + D \quad = \; T_D \qquad (1)$$

where

R = groundwater recharge flux (mm/a)
Cl_{gw} = chloride concentration in groundwater (mg/L)
Cl_{wap} = total chloride deposition (wet and dry deposition) (mg/L)
P = precipitation (mm/a)
D = dry deposition of chloride (mg/m^2/a)
T_D = total (wet and dry) chloride deposition (mg/m^2/a)

It must be stressed that the fact that a calculation by this equation yields sensible recharge numbers does not prove that recharge actually exists.

There are two ways of estimating Cl_{gw}, the chloride concentration in groundwater. One method is to analyse the chloride content in soil moisture with depth. In general, chloride concentrations in soil moisture increase with depth until the soil moisture is beyond the reach of trees (Gieske 1992, Wrabel 1999). The stable portion of the chloride profile represents the chloride content of groundwater that can be used in the above equation. The other method is to use the chloride concentration in groundwater directly. This is applicable in areas where the water table is deep enough to exclude the influence of water withdrawal by trees and where the chloride concentration of water is unaffected by leaching of aquifer material. Sampling of groundwater right at the water table would be ideal but is not feasible in the confined fracture aquifer environment of the present project. To accommodate the fact that additional salinisation frequently occurs in the saturated zone and that variations occur from place to place, some mean value of the lower chloride levels in an aquifer needs to be found. The harmonic mean of Cl (of different boreholes in an area) or the arithmetical mean of individual recharge values is frequently used to represent the areal ‘average’ condition. In the case of small data sets a median value of the individual recharge values seems more appropriate for comparison purposes since it is not influenced by extreme (low or high) values.

Calculation of recharge rates based on the groundwater chloride content does not prove that recharge is actually occurring. The calculation merely indicates the recharge rate if the vadose zone recharge were to take place over the presumed time scale. A calculation based on the chloride content of soil moisture is a better indication that vadose zone recharge is actually occurring in a given locality. This method of soil profiling approach was applied with reasonable success during the Palla Road Project (DWA, 1993) as a supplementary recharge evaluation approach. It serves as an alternative method to obtain the chloride content of groundwater from the region between the root zone and the water table.

Radiocarbon

Radiocarbon is used to date groundwater in a range from several hundred years to about 40 000 years. ^{14}C is continuously produced in the upper atmosphere by nuclear reaction between cosmic radiation and nitrogen in the stratosphere. This process maintains the ^{14}C concentration in the atmosphere at a specific concentration level. This background level is expressed as 100 pmc (percent modern carbon) at a $^{14}C/^{12}C$ ratio of about 10^{-12}. Once dissolved ^{14}C reaches the groundwater table, the water is isolated from the atmosphere and the ^{14}C level decreases by radioactive decay with a half-life of 5730 years.

The radiocarbon content of a sample pumped from a borehole reflects the flow, recharge and mixing processes in an aquifer and in the sampled borehole. It is seldom that these processes can all be quantified. One is therefore reliant on models as simplistic expressions of the real situation (see e.g. Mook 2000, Talma and Weaver 2002).

The simplest flow model is to assume that all the water in the study area originated from the same source or has the same initial properties. This is typically the case in artesian aquifers, at least in the part of the aquifer away from the recharge zone. This type of flow is simulated by water flowing like a piston through a pipe and called the ‘piston-flow’ model. Conceptually it is similar to the dating of an archaeological object by ^{14}C. In this case an ‘age’ for a water sample can be calculated which represents the single travel time through the aquifer. The age of the water, or its travel time, can be calculated from:

$$\text{Age} = 8270*\ln(^{14}C_i/^{14}C_o) \qquad (2)$$

where $^{14}C_i$ = initial ^{14}C concentration in pmc, and
$^{14}C_o$ = measured ^{14}C concentration of the sample.

The initial ^{14}C content of the water depends on the amount of dilution of the living carbon (from vegetation) by solution of ‘dead’ carbon (from soil or aquifer carbonate). For each aquifer there has to be some evaluation of the dilution factor applicable and in the Ecca the presence of coals is important. This effect is handled in the calculation by correcting the initial ^{14}C content of water by dividing by a dilution factor, Q, which usually varies between 0.5 and 1 (Clark & Fritz 1997).

Equation (2) then becomes:

$$\text{Age} = 8270 *\ln(100*Q/^{14}C_o) \qquad (3)$$

Various approaches to determine a realistic value of Q for different situations can be employed, for example (Clark & Fritz 1997). These rely on a good understanding of the water chemistry and isotope behaviour in the water, or, more empirically by viewing the relation between modern 14C and tritium. The usual practice in this region where there is seldom sufficient knowledge of the carbon chemistry is to assume a value of 0.85 for Q. Should there be evidence of carbonate precipitation or solution along the flow path (for instance from ^{13}C and/or chemical changes along flow lines) appropriate chemical mass balance reaction models (e.g. NETPATH and PHREEQC) exist to account for these processes (Beekman and Selaolo 1997).

The calculated age differences in locations of clearly confined flow yield local flow rates of groundwater down-dip. In those cases where water flows through a simple geometric structure, then the water mass balance requires that

$$R*A = 1000*X*H*U*\Phi \qquad (4)$$

where

R = groundwater recharge flux (mm/a),
A = recharge area supplying the confined aquifer (km^2),
X = width of the confined aquifer perpendicular to the flow direction (km),
H = average thickness of the confined aquifer (m),
U = flow velocity determined from age differences (m/yr), and
Φ = average total porosity of the confined aquifer.

Recharge can then be calculated based on estimates of the other parameters. In most real situations the geometry will be more complex (Beekman and Selaolo 1997).

The more common flow model (the exponential flow model) considers the groundwater pumped from a borehole as a mixture of water that has flowed through different pathways and represents different recharge events. This model is often used to interpret flow in phreatic aquifers and has been used in many local aquifers (Talma and Weaver 2003, Beekman and Selaolo 1997, Gieske 1995). The Mean Residence Time (MRT) of the groundwater is given for a borehole producing mixed groundwater derived from all water strikes by the equation (Gieske 1995):

$$MRT = 8270\,(Q*{}^{14}C_i/{}^{14}C_o - 1) \qquad (5)$$

MRT, as calculated above, can be seen as the ratio of water volume to recharge. On the vertical scale this transforms to:

$$R = 1000*H*\Phi/MRT \qquad (6)$$

where: H = thickness of the saturated aquifer (m),
Φ = total porosity
R = mean annual recharge (mm/a)

Estimates of H and Φ can therefore be used to assess the recharge of an aquifer on a regional scale.

Tritium

Natural tritium (^3H) is similar to radiocarbon and is formed in the stratosphere and finds its way as water throughout the globe. The background concentration in the local rainfall is 3 to 4 TU (1 tritium unit is $^3H/^1H$ of 10^{-18}). After recharge, the water supply is closed and tritium decays with a half-life of 12.4 years. In principle, this should enable tritium to be used as a dating tool back to about 50 years. The atmospheric nuclear weapon tests between 1954 and 1961 produced large amounts of tritium of which some have found their way to the southern hemisphere and caused the tritium content of local rainfall to rise to a maximum of 60 TU in the early 1960s. Since then, tritium levels in rainfall have declined to the pre-bomb levels. The bomb tritium peak was reduced by radioactive decay to a flat input curve of 3 to 13 TU in 1993 (when data in the present project area by GRES II and BRGM were obtained). At the present time (2008) the input curve has decayed to levels between 2 and 4 TU.

Groundwater samples taken at the present time with tritium levels >2 TU are interpreted as being mainly post-1950 recharge water. Usually such waters also show high ^{14}C (>80pmc) content. Recharge of groundwater with tritium level below 1 TU would be of pre-1950 age or some mixture of water from these different periods.

Stable isotopes: Oxygen-18 and Deuterium

Isotope ratios of oxygen ($^{18}O/^{16}O$) and hydrogen ($^2H/^1H$) are ideal geochemical tracers of the water cycle as they form an integral part of the water molecule and their ratios do not alter by interaction with aquifer material under normal (low temperature) hydrological conditions. Once underground and removed from zones of evaporation, the isotope ratios remain preserved and are only affected by mixing of waters having different isotopic signatures. The ^{18}O and D composition (as they are colloquially called) of the groundwater can thus be used to identify recharge sources as well as chemical and physical processes in which the groundwater occurs.

Stable isotope ratios are expressed as differences (δ) of the relative ratios of sample and some standard. The parameters $\delta^{18}O$ and δD are therefore used to express these isotope ratios relative to a universally used standard (SMOW) in per mille (‰) (see for example Clark and Fritz 1999, Mook 2000).

The most important physical process causing variation of the ratios $^{18}O/^{16}O$ and $^2H/^1H$ in water is vapour-liquid fractionation during evaporation and condensation. The vapour pressure of water containing the light isotopes (^1H and ^{16}O) is lower than that of water containing the heavier isotopes deuterium and ^{18}O. When water and water vapour are in equilibrium, the vapour is isotopically lighter with respect to both $^2H/^1H$ and $^{18}O/^{16}O$. Hence, water vapour from the ocean is depleted by 10 to 15 ‰ in $\delta^{18}O$ and by 80 to 120‰ in deuterium (Clark and Fritz 1997, Mook 2000).

When water vapour, carried inland, condenses to form rain, fractionation takes place in the reverse direction, with the liquid being isotopically heavier than the vapour. The fractionation during evaporation is thus largely reversed during condensation and the first rain to fall from water vapour over the ocean would have an isotopic composition of about -3‰ (Clark and Fritz 1997, Mook 2000). Precipitation of rainwater selectively removes ^{18}O from the atmospheric vapour phase and $\delta^{18}O$ of subsequent rainfalls becomes lower. By this depletion process, rainfall becomes progressively lighter in ^{18}O as it rains out further from the ocean source. For deuterium the process is rather similar. A plot of δD and $\delta^{18}0$ values in precipitation yields a straight line known as the "Global Meteoric Water Line" (GMWL) with the equation:

$$\delta D \quad = \quad 8*\delta^{18}0 + 10 \qquad (7)$$

The slope of the GMWL (8) is a general constant determined by the physical properties of the isotopes. The intercept (10) on the deuterium axis, usually called the 'deuterium excess' of a water sample, is applicable to most of the world's rainfall from temperate coastal areas. Water with an isotopic composition along the GMWL is almost certain to have originated from the atmosphere and to be unaffected by other isotopic processes. Local variations of slope and deuterium-excess due to specific meteorological conditions and recharge mechanisms are quite common. A Local Meteoric Water Line (LMWL) can be calculated from ^{18}O and deuterium data of rainwater from local stations, generally based on cumulative monthly rainfall samples or on event based rainfall samples (Gieske 1992, Clark and Fritz 1997, Selaolo 1998).

Evaporation from open water surfaces introduces deviations from the meteoric water line caused by isotopic fractionation resulting in enrichment of the heavier isotopes in the remaining water. The ratio of evaporative enrichment of the two isotope pairs is different from that of condensation and the MWL relationship does not hold anymore. Lower slopes of the evaporation line are characteristic of more arid climates. The slope of the deuterium versus $\delta^{18}O$ plot for evaporation from open water bodies in southern Africa generally ranges between 4 and 6. Water loss by transpiration through plants does not produce isotope enrichment. The mixing of isotopically enriched soil moisture in the unsaturated zone with rainfall recharged groundwater causes the ^{18}O and deuterium to plot parallel to, but displaced from the LMWL and this is used to quantify recharge rates

Allison et al. (1984) developed an empirical method of estimating groundwater recharge from precipitation in semi-arid to arid regions in Australia (rainfall 100 to 710 mm/a and recharge rates 1 to 140 mm/a) where a uniform sandy, unsaturated cover is usually present (i.e. similar to the present study area). Under these conditions they observed that the ^{18}O-D analyses of groundwater from such areas plot below, but parallel to the local meteoric water line. This phenomenon is interpreted as the result of mixing of infiltrating rainwater with soil moisture that has undergone some evaporation in the unsaturated zone. If recharge conditions remain uniform through time the groundwater ^{18}O and deuterium data would plot along a line parallel to, but displaced from, the local meteoric line. The extent of this displacement is proportional to the evaporative enrichment of infiltrating water in the upper layers of the soil and dilution by recharging groundwater. Recharge values estimated in this manner are generally more accurate for lower values of recharge, typically less than 10mm/a (Selaolo, 1998).

For a uniform soil it has been shown empirically that the enrichment in ^{18}O and D is related to the recharge by the following equation (Allison et al 1994):

$$\Delta\delta D \quad = \quad C_1/\sqrt{R} \qquad (8)$$

where $\Delta\delta D$ is the displacement of δD
$C_1 = 22$, estimated constant
R = mean annual recharge in mm/a

Groundwater Level Time Series

Variations in groundwater levels can be used as indicators for recharge in its response to high rainfall events. Recharge techniques suitable in the region (SVF, CRD) have been reviewed by Bredenkamp et al (1995) and Beekman and Xu (2003). Modelling of soil moisture variations has been done in the study area during the BRGM project (BRGM 1991).

Groundwater Numerical Modelling

Numerical modelling of the piezometric surface is frequently used to estimate recharge. In essence this method relies on the balancing of fluxes when inflows, out flows and other critical aquifer parameters are optimized. This approach is mostly used to refine values of recharge determined by other methods and provides an assessment and evaluation of the variation of these values. Similar approach is presented in the Resources Quantification Capter 8 of this report.

6.5.2 Review of Specific Recharge Investigations in the Project area

The region of the present project area has seen three major recharge investigations during the past two decades (BRGM 1991, Beekman et al 1999, Verhagen 1993, Verhagen and Butler 2006). These form the basis for any evaluation of data for the project and are discussed below.

BRGM

During the Letlhakeng-Botlhapatlou Project (DGS, 1991) a range of recharge determination activities were carried out that culminated in different recharge estimates covering the study area, which now forms the central block of the present project area. The various activities are outlined below and the recharge estimates are highlighted.

Soil moisture measurements were undertaken for two rainy seasons, 1990/1, and evaluated with the GARDENSOL software which simulates a rainfall-evaporation-recharge process (DGS, 1991). The results show recharge beyond 9m depth of 5.0 mm in 1990 and 3.5 mm in 1991. This period includes a major flooding episode which is bound to affect the extrapolation of this data sets to a long-term average values.

Chloride mass balance calculations were done, based on the chloride content of groundwater found in the study area (DGS, 1991). A chloride deposition rate, TD, of 410 mm/a (NWMP 1990, cited in DGS, 1991) was used. The Cl distribution in groundwater was used and recharge values were calculated based on 25%, 50% and 75% percentiles in the Cl frequency distribution. Restricting the evaluation to groundwater samples with conductivity values less than 750µS/cm the recharge range was 5.2 to 9.8 mm/a.

Soil profile samples were taken and analysed for chloride. The resultant data were considered unreliable and as a result no recharge evaluation was possible

Analyses of 4 borehole samples were done for tritium by BRGM (DGS, 1991) and these are included to the analysis list and tritium was found only in one sample (Ngware, BH 285). This borehole is located in the presumed recharge area and it indicates the presence of rain-water not more than 40 years old.

16 radiocarbon samples were obtained from boreholes in the study area with 14C contents ranging between 4 and 81pmc (DGS, 1991). These cover the full range from young to old (~25 000 years) in the flow direction from the assumed recharge zone to the confined area and also varied in

sampling depths. Recharge was calculated based on an aquifer thickness of 150 m, initial 14C content of 100 pmc, porosity of 1 and 2% and an average 14C content of the water in the aquifer of 50 pmc. This approach produced recharge values of 0.175 to 0.35 mm/a (DGS, 1991). These values are questionable because the total porosity, and not the much lower kinematic porosity should have been used in the calculations. The assumption of 50 pmc as average 14C level for the entire unconfined part of the aquifer is not well justified. The follow-up evaluation by GRES II (Beekman and Selaolo 1997, discussed below) produced better results.

Groundwater modelling over 2826km^2 was also carried out using piezometry (DGS,1991) and overall mean recharge of 4.3mm/a was optimized. Infiltration studies carried out at five stations and the resulting outcome indicated recharge values of 2 to 7 mm/a.

The 18O and deuterium data for groundwater obtained in the BRGM project area indicate lower values than the rainfall that was sampled by them. This supports the notion that the groundwater is only recharged during the past wetter periods and/or during exceptional rainfalls during present times (DGS, 1991).

GRES II

The GRES II project was a multi-pronged approach to the determination of recharge in Botswana (Beekman et al 1999, Selaolo 1998) of which the main activities centred in the Letlhakeng-Botlhapatlou area.

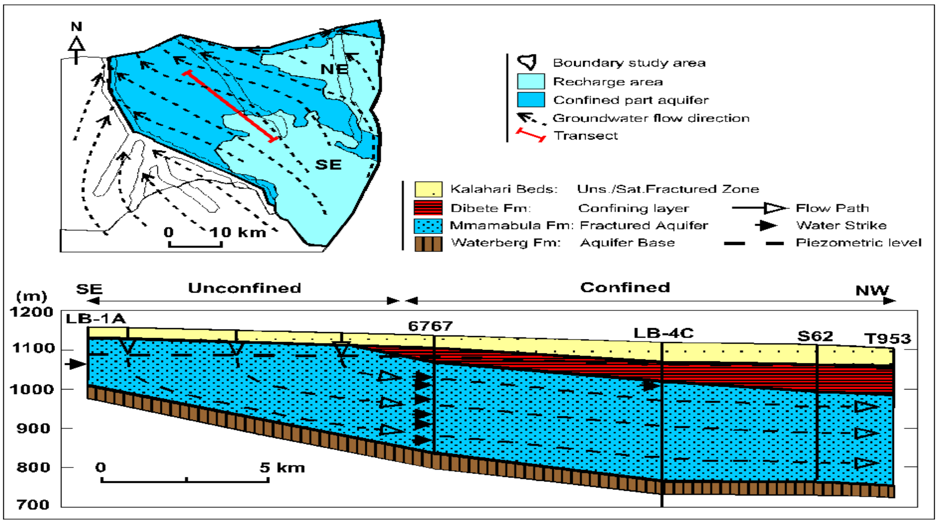
The present day rain-water chemical analyses yielded a chloride deposition rate in the Letlhakeng-Botlhapatlou area of 500±200 mg/m2/yr (Beekman et al 1997, Selaolo 1998). This quantity was based on a long-term sampling of rain-water for chemistry and isotopes that was initiated by Gieske (Gieske, 1992). Based on the harmonic means of the chloride contents of the groundwater in the south-eastern part of their study area (east of Letlhakeng), a mean recharge of 10 mm/yr was calculated. For the northeastern part the recharge was estimated at 5 mm/yr. However, due to the great age (>10 000 years) of this groundwater, the assumptions underlying this calculation are less certain. The possibility (more likely probability) of pluvial events in the past, imply that TD values of the present time do not necessarily reflect conditions 10 000 years or more ago.

Soil profiling, also in the south eastern part of their project area, provided an alternative means to obtain the chloride enrichment of recharge water. Vertical water fluxes range between 1 and 10 mm/yr and are very much locality dependent (Beekman et al 1997, Selaolo 1998). The chloride profiles also provided evidence for bypass flow which complicates the modelling of chloride and water movement. **These variations between individual sites demonstrate the difficulty of integrating a range of spot measurements to achieve an areal or regional value that can be integrated into resource estimation of an aquifer.** The deuterium offset method from these soil profile samples gave similar recharge values and were eventually used to validate the Allison et al (1984) method for the Kalahari (Beekman et al 1997). Tritium from soil profiles was also reported but at the low recharge values in this area, vapour flux dominates the recharge process and the method yields abnormally high recharge values (Beekman et al 1997).

A finite element model utilizing water levels was set up for the GRES II study area (slightly different from that used by BRGM earlier) located south of the Zoetfontein fault and including the Jwaneng Northern Wellfield (Nijsten and Beekman 1997). This area consists of Ecca sandstone aquifer partly overlain by Kewtla mudstones. There are therefore clear potential recharge and confined areas. Discharge localities along the fossil valleys, along the western part of the

Zoetfontein Fault and to the west of Jwaneng Northern Wellfield were defined. Water level data from 1975/76 were used to avoid the effects of exploitation of the Jwaneng Northern Wellfield which started in 1979 onwards. The calibrated areal recharge rates that were obtained from this modelling exercise were 3 mm/yr in the northeast and 7 mm/yr in the southeast. Averaged over 48% of the project area, the recharge rate amounts to 5.7 mm/yr. The present project area is not significantly different from that used for the GRES II flow model. The Jwaneng Northern Wellfield however has been excluded, while areas to the northeast and northwest were added.

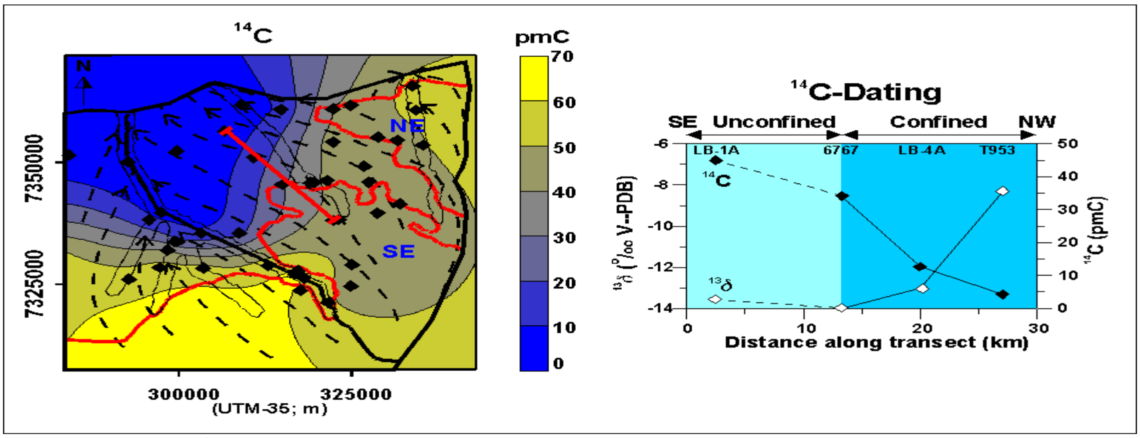
Beekman and Selaolo (GRES II, 1997; Selaolo 1998) have integrated the hydrochemical and isotopic (14C and 13C) changes in a part of the study area in order to determine flow rates of the groundwater. They used the earlier BRGM (DGS, 1991) data in addition to newer data obtained during the GRES II project. They viewed the area south of the Zoetfontein fault, west and north of Bothlapatlou that was also used for finite element modelling as discussed above (Figure 6.7). The 14C and 13C data from the Mmamabula (=upper Ecca) wre interpreted to suggest flow towards the north-west that corresponds to the water levels (Figure 6.8). 14C values decreased sharply where the Mmamabula is overlain by Dibete (= Kwetla mudstones and siltstones). This indicates that flow slows down under confined situations and that great water ages can be attained there (Figure 6.7). A quantitative evaluation of the carbon isotopes together with chemical changes (using NETPATH software) accounts for the flow times within the confined part of the aquifer as well as solution/precipitation reactions along the way (Figure 6.9). Taking the geometry of the aquifer into account this indicates a recharge value of 1.2 mm/yr valid over a period of the last 20 000 years. The helium isotope data for the same part of the aquifer, when used as dating tools, suggested shorter flow rates and therefore somewhat higher recharge rates: in the range of 2.2 to 3.1 mm/yr (Selaolo 1998).



(adapted from Selaolo -1998)

Figure 6.7 GRES II –Illustration of a Finite Element Flow Model

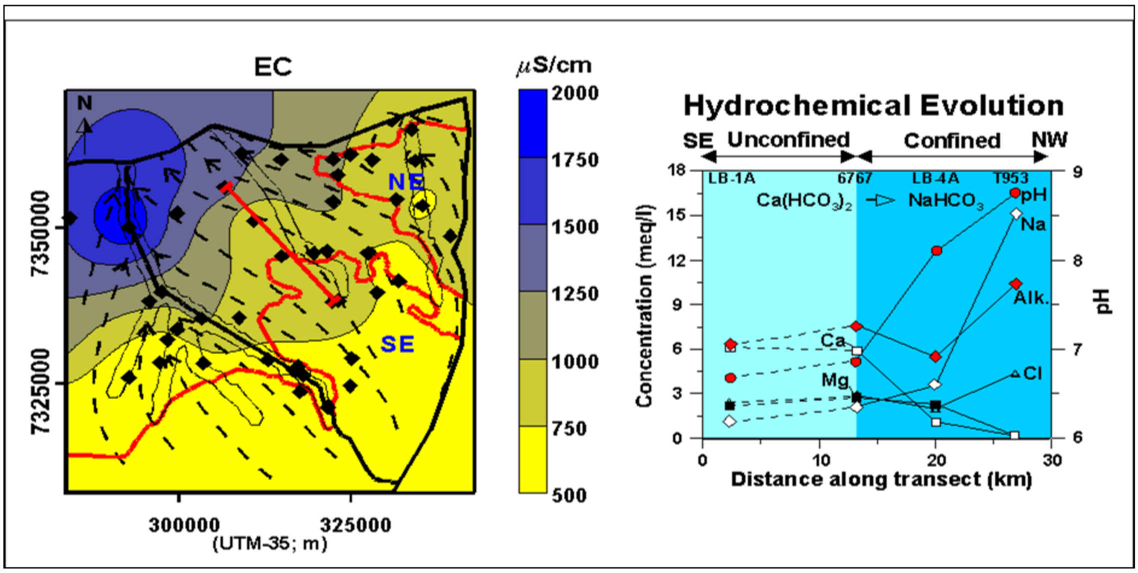
The Upper section in Figure 6.7 shows the area used by GRES II for finite element flow and carbon isotope modelling. The presumed recharge areas are those parts where the Ecca sandstone is not covered by Kwetla and the Lower section shows the Conceptualised flow from the Ecca sandstone recharge area towards the confined part of the aquifer.



(adapted from Selaolo -1998)

Figure 6.8 GRES II - Flow Pattern Derived from Finite Element Modelling Superimposed on Contour Mapping of the 14Carbon

The Left section in Figure 6.8 shows flow pattern derived from finite element modelling superimposed on contour mapping of the 14C data from the Ecca sandstone. The red curve indicates the extent of aquiclude coverage. The red line shows the transect line used for NETPATH modelling purposes during the GRES II project. The right section shows the decrease of 14C and increase of 13C along the transect.



(adapted from Selaolo -1998)

Figure 6.9 GRES II - Flow pattern derived from finite element modelling superimposed on contour mapping of the EC

The left section of Figure 6.9 shows the contour mapping of the EC data from the Mmamabula. The red curve indicates the extent of aquiclude coverage and the red line shows the transect line used for NETPATH modeling. Right section shows the increase of pH, Na, alkalinity, Cl and concomitant decrease of Ca and Mg.

Jwaneng Northern Wellfield

The Jwaneng Northern Wellfield is located just beyond the borders of the present project area, towards the south-west. The aquifer consists of a fluviatile Ecca sandstone partially capped by mudstones. The wellfield has been exploited since 1979. 14C values in the groundwater range from 75 pmc in the centre to 55 pmc along the margins of the wellfield. Verhagen and Brook (1989, cited in Verhagen 2003), calculated recharge rates of 3 - 8 mm/yr in the wellfield area based on these 14C levels and porosity of 0.15. A later evaluation of the same data yielded 3.7 to 4.7 mm/a recharge (Verhagen 1993, 2003). Re-sampling the very same boreholes twenty years later showed very similar 14C values and indicates that the aquifer is not under stress and that some return flow from the aquitard does take place (Verhagen and Butler 2006).

An analysis of a 12–year hydrograph of average groundwater levels in the Jwaneng Northern Wellfield yielded recharge values between 3.0 and 4.9 mm/a (Van Rensburg and Bush 1994, cited by Verhagen 2003).

Chloride mass balance calculations have been done based on the chloride content of groundwater samples in the study area (DGS, 1991). A chloride deposition rate, TD, of 330 mm/a was used and produced a median recharge rate of 4 mm/a.

6.5.3 Summary of Recharge Data

The assembled recharge data are summarized in Table 6.24. When sorted by method it is clear that systematic differences exist. The local methods derived from profiles and individual groundwater samples show large variations. The CMB methods show higher recharge values than the other techniques. The recharge values over millennia do not differ significantly from those with shorter time span even though the longer time span of the oldest water in the aquifer (5000 to 40 000 years) includes both wet and dry periods (Thomas and Shaw 2002). It must be noted that even though the CMB methods include samples with great ages, the estimate of TD is only based on data collected over not more than ten years (Selaolo 1998).

Table 6.24 Summary of Past Recharge Assessments done in the Project area

Project	Method	Recharge (mm/a)	local/areal	Time scale	Reference
BRGM	^{14}C model	1.8-3.5 [1]	areal	millenia	DGS (1991)
GRES II	^{14}C model-MBR	1.2	areal	millenia	Beekman & Selaolo (1997)
Jwaneng	^{14}C model	3.7-4.7	areal	millenia	Verhagen (1993)
BRGM	CMB-GW	6.2-11.8 [2]	areal	millenia	DGS (1991)
GRES II	CMB-GW	5-10	areal	millenia	Beekman & Selaolo (1997)
Jwaneng	CMB-GW	6 [2]	areal	millenia	DGS (1991)
GRES II	He model	2.2-3.1	areal	millenia	Beekman & Selaolo (1997)
GRES II	CMB-soil profile	1-10	local	centuries	Beekman et al (1997)
GRES II	Deuterium offset	1-10	local	centuries	Beekman & Selaolo (1997)
BRGM	Flow model	2 - 7	areal	decades/years	DGS (1991)
GRES II	Flow model	3-7	areal	decades/years	Nijsten & Beekman (1997)
Jwaneng	Flow model	3.0-4.9	areal	decades/years	Van Rensburg & Bush

					(1994)
BRGM	Soil moisture balance	3.5-5.0	local	months	DGS (1991)

1. Recharge values re-calculated with a porosity of 0.1
2. Recharge values re-calculated with the more recent T_D = 500 $mg/m^2/a$

6.5.4 Isotope Data Base

The available isotope data from boreholes sampled during past projects and the three samples collected during the present project are presented indetail inthe Technical Report No. 5, Chemistry and Recharge

Stable isotope patterning

The distribution of 18O and deuterium in the groundwater within the study area conforms to what is found elsewhere (Figure 6.10). Most of the samples arrange along the Global Meteoric Water line at the low end, with some evaporated water at higher values below the line. Kulongowski et al (2004) have shown that groundwater in the area dated to older than 10 000 years will have higher 18O and D content than recent recharge. This pattern is probably due to more evaporative recharge conditions in the past and is likely to explain much of the variation shown in Figure 6.10. There is no evidence to suggest the existence of different water bodies in different parts of the study area.

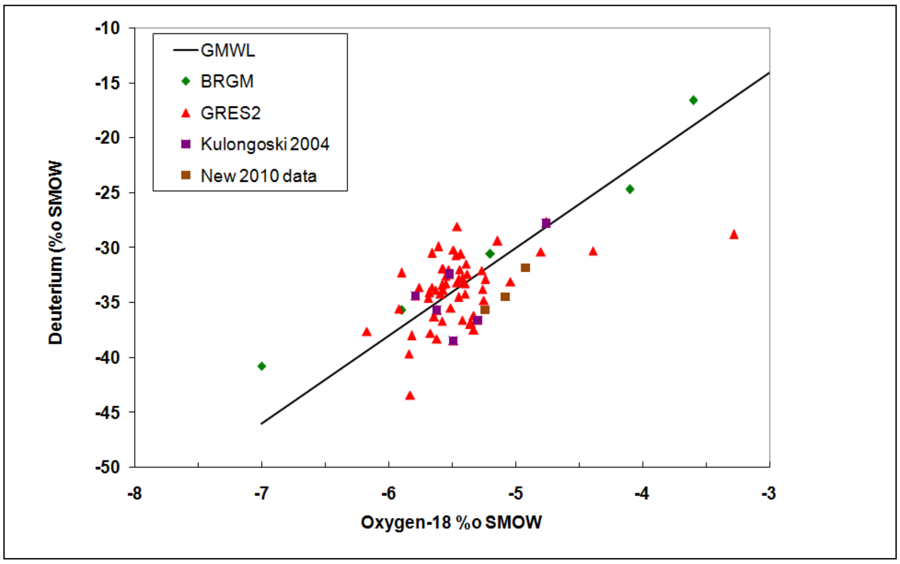


Figure 6.10 Plot of deuterium (2H) against 18O of the Project

Data obtained during the GRES II project indicated a reasonable explanation for the large differences of radiocarbon in the groundwater in the area (GRES II 1997, Selaolo 1998). It was shown that recharge occurs directly to the Ecca aquifer (Boritse and the Kweneng Formations) where they are not overlain by the Kwetla and then proceeds in a northerly direction under the Kwetla (Figure 6.7 to 6.9). Because of the low flow rate underneath the confining Kwetla, the modelled 14C contours indicate low 14C contents in the Ecca from boreholes close to the southern edge of the Zoetfontein fault (Figure 6.11). At the same time, however, there are boreholes along the line of the Meratswe valley with high 14C contents indicating recent recharge (Table 6.25). The data indicate that even though there are confining conditions in general in this area, there are occurrences of local recharge that are characterised by high 14C values, in some boreholes supported by elevated tritium. It is important to note that there are some data that reflect isolated shallow Kalahari perched that are not related to the deep Ecca aquifer.

Table 6.25 Meratswe Valley Isotope Data

Borehole	^{14}C (pmc)	Tritium (TU)	Aquifer	Depth (m)	Water Level (m)
702	2	0 ± 0.1	Ecca confined	76.2	3.05
Well I	109	3.25 ± 0.15	Ecca unconfined		
744	114	-	Ecca unconfined	57.61	6.1
5489	97	1.35 ± 0.25	Ecca unconfined	112	14.3
T972	91	0.05 ± 0.35	Ntane unconfined	-	
Zoetfontein Fault					
708	95	0.65 ± 0.2	Ntane nconfined	60.96	29.53
6310	44	0.15 ± 0.12	Ntane nconfined	200	49.99

During the present project, three of the newly drilled exploration boreholes were sampled for isotope analysis. These were selected in order to present a range of increasing basalt thickness as aquiclude (Figure 6.11). The data indicate that this old groundwater is associated with thick basalt cover although some mixing of young and old water in borehole 10682 cannot be excluded. A similar GRES II evaluation of the area immediately south of the Zoetfontein Fault (Figure 6.7) suggests that the deeper boreholes could well be fed from elsewhere and thereby produce the old age water pumped from these boreholes. There are too few data set from the north of the fault to be more specific about the extent of this observation. In general the groundwater flow in the Lebung north of the Zoetfontein Fault is northwards.Table 6.26 below lists properties of the three boreholes north of the Zoetfontein fault from which isotope data were obtained in the present project. The boreholes provide an east - west isotope cross section and the basalt is thicker in the east.

Table 6.26 Project - Lebung Isotope Data

Borehole	14C (pmc)	Tritium (TU)	Kalahari thickness	Basalt thickness	Ntane thickness
10685	4	0.1 ± 0.2	15	213	80
10682	33	0.2 ± 0.2	16	136	10
10688	9	0 ± 0.2	46	476	35

7. GROUNDWATER RESOURCES DEVELOPMENT

7.1 Overview

The main objectives of the Production Phase of the Boatlhapatlou Groundwater Exploration and Development Project as indicated in the Terms of Reference for the project were to provide increased quantity and improved reliability of water supply to the principal population centres in the Project Area and the major villages of Molepolole, Thmaga and the BDF Telephatshwa Air Base. Current groundwater sources within the project area comprise the Gaotlhobogwe Wellfield that supplies Molepolole/Thamaga and the Air base, whilst individual smaller villages are supplied by smaller wellfields established adjacent to the villages. The Jwaneng Northern Wellfield located to the south-west of the Project area supplies Jwaneng mine some 52km to the south.

These objectives were achieved by the establishment of additional production boreholes within the Malwelwe and Sorilatholo areas.

Specifically, production boreholes were sited, drilled, optimally constructed and properly tested in order to provide a reliable and adequate long term (2020) supply to the various demand centres.

The total projected demand at the design horizon for all the villages stands at approximately 20400m^3/day (derived from Table 1.8). This is significantly more than what the existing wellfields of Gaotlhobogwe, Suping and Ramapatlhe can produce as per current abstraction shown in Table 7.1 below.

Table 7.1 Current Production Boreholes

Borehole No.	Recommended Abstraction Rate (m^3/hr)	Day Pumping period (hrs)	Actual Abstraction (m^3/day)	Wellfield
Gaotlhobogwe Wellfield				
10551	15	24	360	Gaotlhobogwe
7864	12	24	288	Gaotlhobogwe
10553	57	24	1368	Gaotlhobogwe
8132	60	24	1440	Gaotlhobogwe
9574	12	24	288	Gaotlhobogwe
10550	62	24	1488	Gaotlhobogwe
9572	18	24	432	Gaotlhobogwe
9571	18	24	432	Gaotlhobogwe
7966	42	24	1008	Gaotlhobogwe
10549	24	24	576	Gaotlhobogwe
6875	98	24	2352	Gaotlhobogwe
9379	100	24	2400	Gaotlhobogwe
10343	20		Not pumping	Gaotlhobogwe
10344	15		Not pumping	Gaotlhobogwe
Gaotlhobogwe total supply	**553**		**12432**	
Suping Wellfield				
6769	10	24	240	Suping
6744	49	24	1176	Suping
4296	14	24	336	Suping
6785	14	24	336	Suping
6786	34	24	816	Suping
6864	30	24	720	Suping
Suping total supply	**151**		**3624**	
Ramaphatle Wellfield				
4402	18	12	220	Ramaphatle
3029	6	12	77	Ramaphatle

6077	32	12	382	Ramaphatle
Ramaphatle total supply	**56**		**672**	

7.2 Production Geophysical Surveys

The main objective of ground geophysical surveys in the Production Phase of the project was to assist in siting additional production boreholes for further development of the existing groundwater resources within the Ecca and Lebung aquifers in the vicinity of the Malwelwe and Sorilatholo.

In this context, proposed Groundwater Production Areas were delineated both on the basis of the analysis of all the existing information, as well as on the findings of the completed Exploration Phase of the project. The Groundwater Production Areas are shown on Figure 5.10 and Figure 5.11 together with the prospective individual production zones. The prospective production zones were selected on the basis of a full evaluation of all structural and hydrogeological information derived from the preceding phases of the project, with special cognisance taken of the potential aquifer depth and thickness, structural controls and water quality.

It is important to note that in the Malwelwe Wellfield area both the NW/SSE and E/W as well as the host and graben structures have a dominant influence, whilst in the Sorilatholo Wellfield the E – W related to the Zoetfontein Fault structures are the most important structures. Also in the Sorilatholo Wellfield the influence of the NW-SE structural trend is evident but difficult to appreciate within the wellfield area. However, both structures ZF1 and ZF2 constitute boundaries to the south. [For more details the reader is referred to Technical report No. 5, Groundwater Resources Modelling Report.

Prospective production zones (Fig. 5.10 and Fig 5.11) in the Malwelwe and Sorilatholo Wellfield have been further prioritized as production zone PA and production zone PB that to take into account other mainly non-hydrogeological factors such as distance from the existing production boreholes, and practical aspects of planning future infrastructure, as well as the distance between the boreholes.

Both prospective production zones that were subjected to ground geophysical investigation are shown on Table 7.2 below, together with description of their structural setting.

In addition it was also decided in consultation with the Client that an existing production borehole (BH 6830) be re-tested at higher rate. BH 6830 was drilled as aproduction boewholew during the DWA 1990 (BRGM project).

Table 7.2 Summary of Prospective Production Areas

Production Area	General Location	Selection Reason/Comments
Malwelwe	Within Malwelwe area	• the NE and the SW boundaries are dominated by the NW-SE structural trends. • both F9 and F11 mark the boundaries to the NW and SE. • the steep Main Graben southern edge is the boundary to the south. • the uplifted Botlhapatlou Host forms the eastern boundary. • Malwelwe wellfield central area is dominated by the Main Graben

Sorilatlholo	Within Malengwana area	• bound by F4 and Z1 to the north and south • extension to the east is controlled by basalt thickness • extension to the east is governed by the reduction of the aquifer, absence of basalt. • Sorilatlholo wellfield is centred on Malengwana area where basalt thickness is optimum (50-400m).

The same geophysical survey methodology was applied as in the Exploration Phase, i.e. TDEM and magnetic profiling at 10 m stations along surveyed traverses. However, as a result of limitations in penetration depth that became evident during the Exploration Phase, the VES was not used.

Closely spaced traverses and TDEM soundings were carried out, utilising some of the exploration data set to supplement this ‘grid’ approach. Continuity of the observed anomalies across the traverses was assessed, and production drill sites were chosen as appropriate.

The closely spaced approach allowed investigation to be focused on an identified structure and structures could be closely followed. The available geophysical quantities for the Production Phase also facilitate the investigation of more potential production sites so that additional sites could be pegged allowing better choices as drilling progressed.

Very limited geophysical surveying was applied at locations where new production boreholes were to be drilled adjacent to exploration boreholes drilled during the Exploration Phase.

The prospective exploration boreholes that were selected for production drilling are detailed in Table 7.3 below.

Table 7.3 Exploration Boreholes to be Re-developed for Production Purposes

Selected Boreholes for Re-Development	General Location	Description/ Comments
BH 10671	Malwelwe Wellfield	Exploration borehole
BH 10672	Malwelwe Wellfield	Exploration borehole
BH 10673	Malwelwe Wellfield	Exploration borehole
BH 10674	Malwelwe Wellfield	Exploration borehole
BH 10679	Malwelwe Wellfield	Exploration borehole

7.2.1 Site Selection of Potential New Production Sites

Target Area A (Malwelwe Wellfield)

From the studies carried out during the Construction Stage 2A five exploration boreholes (Bh10671, Bh10672, Bh10673, Bh10674, and Bh10679) were selected for re-development as production sites because they are high yielding boreholes with excellent abstraction characteristics (as determined from test pumping analysis).

From the overall results of the exploration activities, in particular the geophysical surveying, it has also been concluded that an additional five or six more production boreholes can be located within Target area A and in the vicinity of the Malwelwe Wellfield as defined by the original BRGM production boreholes. BRGM recommended a distance of 1.5 km as minimal distance between production boreholes and a distance of 1.8 km production borehole separation in the final distribution of boreholes is envisaged.

In order to locate the specific sites for these additional 5-6 production boreholes supplementary geophysical surveys were undertaken during Construction Stage 2B, utilising the optimised techniques applied during the exploration stage.

A total of 7 sites have were selected for supplementary surface geophysical investigations in Malwelwe Wellfield (Figure 5.10). The criteria used to select the sites are illustrated in Table 7.4. Three of the sites for investigations are positioned on exploration geophysical lines L4, L20 and L22. Additional lines L36, L37, L38 and L39 are selected at prime areas within the new wellfield delineated area, Figure 5.10.

Table 7.4 Potential Additional Production Sites in Target Area A (Malwelwe Wellfield)

Line No.	Line Length (km)	Survey Methods	Reasons For Line Selection
L4	1	EM, TDEM	This is at the centre of the Main Graben about 3 km north of BH6825. Anomalous EM results from first survey surveys confirmed the extension of a fault on which a high yielding BH10679 about 1.8km east of this site. Two short (500m) lines are proposed for geophysics.
L20	1	EM, TDEM	The site is centred on L20/1670 within the Main Graben and is very identical toBH10679 2km west. Groundwater potential is excellent on this site.
L22	3	EM, TDEM, Magnetics	Site L22/1400 has exceptionally good anomalies from EM/Mag and they need to be resolved further by closely spaced lines so that a similar borehole to BH6830 can be developed. It is on the Demonstration Ranch.
L36	3	EM, TDEM, Magnetics	Within the Main Graben at the intersection of two regional faults **F10** and A-A'.
L37	3	EM, TDEM, Magnetics	This site has identical conditions where BH10674 was drilled and proved to be high yielding. It is on the contact between Main Graben and Ranch Horst.
L38	3	EM, TDEM, Magnetics	Site is within the Main Graben on a local fault. Low potential site.
L39	3	EM, TDEM, Magnetics	On the edge of the Main Graben and Ranch Horst where a regional fault passes through. BH10672 is along this same fault and it is hoped that same hydrogeological conditions prevail.

Table 7.5 Summary of Selected Production Drilling Sites- Malawelwe

No.	Line No.	Site Code	Exploration/ Production Bh No	Coordinates (Cape Datum)	
				Easting	Northing
1	12-1	L12-1/250	Bh10671	323656	7345931
2	16-1	L16-1/250	Bh10673	331615	7350901
3	18-1	L18-1/230	Bh10674	325897	7350849
4	19-2	L19-2/250	Bh10679	323127	7349325
5	21-1	L21-1/270	Bh10672	325782	7354685
6	20-1	L20-1/240	Bh 10750	325218	7349267
7	4-2	L4-2/250	Bh 10752	321290	7348843
8	12	L12/1810	Bh 10747	323634	7345797

No.	Line No.	Site Code	Exploration/ Production Bh No	Coordinates (Cape Datum)	
9	14-1	L14-1/650	Bh 10754	327931	7347735
10	22-1	L22-1/710	Not drilled	323964	7356027
11	36	L36/1690	Not drilled	326106	7346747
12	38	L38/1570	Bh 10755	321212	7351028
13	39	L39/1610	---	327311	7353450

Target Area B (Sorilatholo Wellfield)

The proposed 'Sorilatholo Wellfield' is a relatively large area in Target Area B which extends from Tshatshane cattle-post in the west to the Bh10686 (Fig 5.11). This proposed wellfield zone is about 45 km across and 20 km wide. Although areas further east can be developed, the seriously limiting factors are the thick basalt and thus the associated high costs of drilling and pumping from the deep boreholes.

Within Target Area B successful exploration boreholes Bh10681, Bh10682, Bh10685, Bh 10686 and Bh10687 are regarded as 5 potential production borehole sites within the proposed Sorilathoro Wellfield. An additional seven sites were proposed for further ground geophysics with the intention of drilling 5 more additional production boreholes.

The 7 additional potential production sites selected for supplementary geophysical surveys are shown in Table 7.6 below. The selection of additional sites was primarily to increase the number of production boreholes within the delineated 'Sorilatholo Wellfield' area to 10.

Table 7.6 Potential Additional Production Sites in Target Area B (Sorilatholo Wellfield)

Line No.	Line Length (km)	Survey Methods	Reasons For Line Selection
L40	3	EM, TDEM, Magnetics	On a regional fault dividing two blocks hydrogeological (**Class 2_B** and **Class 1_B**).
L41	3	EM, TDEM, Magnetics	Similar to L40. Depth to Basalt-Ntane contact is ~150 m - 200 m.
L42	3	EM, TDEM, Magnetics	The site is characterized by high density of regional and local fault patterns. Depth to Basalt-Ntane contact is ~250 m.
L43	3	EM, TDEM, Magnetics	Along the **Z2** fault zone which separates two blocks with contrasting basalt thicknesses. Depth to Basalt-Ntane contact is ~250 m – 300 m.
L44	3	EM, TDEM, Magnetics	Within block with thin basalt flow and deep fractures of basalts expected. Depth to Basalt-Ntane contact is ~150 m – 200 m. Ntane sandstone is expected to be thin (>50m)
L45	3	EM, TDEM, Magnetics	Intended to tape groundwater resource from intense fractures associated with regional and local faults. Depth to Basalt-Ntane contact is ~150 m - 250m.
L46	3	EM, TDEM, Magnetics	Depth to Basalt-Ntane contact is ~100 m - 200 m while the Ntane sandstone is probably thin (>50m).

All the data was interpreted in comparison to both the exploration geophysics and the drilling results. Table 7.7 below gives summary details of selected production drill sites.

Table 7.7 Summary of Selected Production Drilling Sites

No.	Line No.	Site Code	Exploration/ Production Bh No	Coordinates (Cape Datum)	
				Easting	Northing
1	40	L40/2250	Not drilled	280842	7366021
2	41	L41/1990	Bh 10745	285584	7367781
3	42	L42/1250	Bh 10740	297493	7375249
4	43	L43/2390	Bh 10743	294118	7373350
5	44	L44/1550	Bh 10741	297556	7372490
6	45	L45/2170	Bh 10742	303987	7372839
7	46	L46/1500	Not drilled	302736	7379995

7.3 Production Borehole Design and Drilling

The drilling of 15 production boreholes in Malwelwe and Sorilatlholo was expected to take 4 months when two high capacity drilling machines were deployed, at an average work rate of 8-10 days per borehole. This fairly lengthy construction time per borehole was assumed because the boreholes were designed with 15 inch (381mm) drilling to depths of the order of 250-375 metres with fully cased and screened 10 inch completion, and substantial development time for the argillaceous Ecca sandstone was anticipated.

The boreholes were drilled with a combination of DTH and tricone with the use of stiff foam. A starting diameter of 22 inches (445 mm) was to allow the casing-off of the Kalahari Group with 15 inch (558.8mm) casing. The Kwetla argillaceous unit was drilled at 18 inches and cased off with a 15 inch (381mm) casing. The 18 inches drilling was terminated at the bottom of the mudstones where the 15 inches casing was properly grouted to effectively seal off the overlying mudstones and any possible saline water. The final drilling diameter through the Ecca aquifers was 15 inches. The boreholes were completed at 10 inches (245mm) with epoxy-coated casings and bridge slotted screens set to the full depth (maximum 375m) of the hole. Formation stabiliser or gravel pack was considered necessary to stabilize the sandstones of the Boritse and Kweneng Formations. Experience gained during the Exploration Phase indicates that this design was appropriate and was similar to that used by DWA in other projects.

The typical production borehole design is shown in Figure 7.1 and the Ntane production borehole drilling results are summarized in Table 7.8. For production boreholes in Ecca the construction details are in Table 7.9 Borehole BH 10754 is slightly different in that wire-wound 8 (203mm) inches screens were used.

Unfortunately, considerable delays were experienced during the production drilling contracting work. These were mainly due to the following:

- Equipment mobilization was delayed
- Teething problems were experienced with the use of the Elephent rig that was to pre-set the 15 inches casing and move to the next hole
- At Bh10746 and Bh10754 ini9tial boreholes were lost andreplacement holes had to be drilled.

- Borehole development issues were experienced in Bh 10751

The work programme was thus unavoidably extended by 3 months in order to complete the required number of production boreholes.

7.3.1 Borehole Geophysical Logging

No additional logging was introduced during the Production Phase because it was felt that formation chips visual logging was sufficient for the construction of the production boreholes. The exploration boreholes logging results correlated very well with the geologist logs because the lithologies are distinct and easy to see the necessary aquifer boundaries

Table 7.8 Summary of Ntane Boreholes Drilling Results

BH No	UTM Coordinates (Cape Datum)		Depth (m)	W/strike (mbgl)	Final Yield (m^3/hr)	RWL (mbgl)	TDS @ 1st WS (mg/l)	pH	Drilling Details (Interval (m)/ Diameter (mm))	Casing Details (Interval (m)/ Diameter (mm))	Final Hole Diameter (mm)	Aquifer
	Easting	Northing										
10740	297493	7375249	222	123	7	57.3	512	8.82	0 - 42m / 304.8mm 42 - 222m / 254mm	0 - 10.21m / 304.8mm 0 - 42.7m / 254mm	254	Ntane
10741	297556	7372490	282	dry	dry	dry	dry	dry	0 - 42m / 304.8mm 42 - 282m / 254mm	0 - 8.1m / 304.8mm	254	dry
10742	303987	7372839	315	191, 216	25	93.7	287	8.67	0 - 42m / 304.8mm 42 - 315m / 254mm	0 - 10.09m / 304.8mm 0 - 42m / 254mm	254	Ntane
10743	294118	7373350	281	168	119	49.15	500	6.9	0 - 42m / 304.8mm 42 - 281m / 254mm	0 - 7.891m / 304.8mm 0 - 42.73m / 254mm	254	Ntane
10744	302736	7379995	256	174	119	63.4	446	8.76	0 - 60m / 304.8mm 60 - 256m / 254mm	0 -9.64m / 304.8mm 0 - 61m / 254mm	254	Ntane
10745	285584	7367781	300	232	33	52	480	6.58	0 - 47m / 304.8mm 47 - 300m / 254mm	0 - 6.06m / 304.8mm 0 - 47m / 254mm	254	Ntane

Table 7.8 Summary of Ecca Boreholes Drilling Results

BH No	UTM Coordinates (Cape Datum)		Depth (m)	W/strike (mbgl)	Final Yield (m^3/hr)	RWL (mbgl)	TDS @ 1st WS (mg/l)	pH	Drilling Details (Interval (m)/ Diameter (mm))	Casing Details (Interval (m)/ Diameter (mm))	Screen Details (Interval (m)/ Diameter (mm))	Final Hole Diameter (mm)	Aquifer
	Easting	Northing											
10746	323127	7349325	280	147	112	65.43	437	7.95	0 - 139m / 584.2mm 139 - 283m / 381mm	0 - 138.67m / 381mm 0 - 156m / 254 mm 161 - 176m / 254mm 181 - 201m /mm 211 - 221m / 254mm 226 - 245 m / 254mm 265 - 280m / 254mm	156 - 161m /254mm 176 - 181m / 254mm 201 - 211m / 254 mm 221 - 226m / 254mm 245 - 265m / 254 mm	254	Ecca
10747	323627	7345632	176			67.84	410	7.43	0 - 101m / 584.2mm 101 - 176m / 381mm	0 - 101.19 m / 381mm		381	Ecca
10748	331580	7350840	177	95	7.7	53.96	310	7.75	0 - 72 m / 584.2mm 72 - 177m / 381mm	0 - 72m / 381mm 0 - 70m / 254mm 80 - 95m / 254mm 120 - 125m / 254mm 150 - 175m / 254mm	95 - 120m / 254mm 125 - 150m / 254mm	254	Ecca
10749	325763	7354404	291	112	22.3	56.1	412	7.04	0 -101.m / 584.2mm 101 - 291m / 381 mm	0 - 101.12 m / 381 mm 0 - 111m / 254mm 121 - 131m /254mm 141 - 161m / 254mm 176 - 186m / 254mm 196 - 211m / 254mm 231 - 246m / 254mm 271 - 291m / 254mm	111 - 121m / 254mm 131 - 141m / 254mm 161 - 176m / 254mm 186 - 196m/ 254mm 211 - 231m / 254mm 246 - 271m / 254mm	254	Ecca
10750	325180	7348961	281						0 - 91m / 584.2mm 91 - 281m / 381mm	0 – 101.12m / 381mm		381	Ecca
10751	332580	7350840	281	88, 209	80.35	63.44	423	5.48	0 - 89m / 584.2mm 89 - 281m / 381mm	0 - 88.73m / 381mm 0 - 91m / 254mm 106 - 111m /254mm 126 - 166m / 254mm 171 - 176m / 254mm 186 - 201m / 254mm 216 - 221m /254mm 236 - 246m / 254mm 261 - 281m / 254mm	91 - 106m / 254mm 111 - 126m / 254mm 166 - 171m / 254mm 176 - 186m / 254mm 201 - 216m / 254mm 221 - 236m / 254mm 246 - 261m / 254mm	254	Ecca

10752	321293	7348837	300	143	15.94	63	360	5.05	0 - 142m / 584.2mm 142 - 300m / 381mm	0 - 142.41m / 381mm 0 - 150m /254mm 175 - 215m / 254mm 220 - 225m /254mm 245 - 255m / 254mm 285 - 300m / 254mm	150 - 175m / 254mm 215 - 220m / 254mm 225 - 245m /254mm 255 - 285m /254mm	254	Ecca
10753	327354	7353651	264						0 - 57m / 584.2mm 57 - 264m / 381mm	0 - 56.52m /381mm		381	Ecca
10754	327027	7348371	310	152, 223	117.7	73.36	448		0 - 151m / 381mm 151 - 310m / 304.8mm	0 - 7.13 m / 381mm 0 - 151m / 203.2mm 171 - 219m / 203.2mm 259 - 265m / 203.2mm 300 - 310m / 203.2mm	151 - 171m / 203.2mm 219 - 259m / 203.2mm 265 - 300m / 203.2mm	203.2	Ecca
10784	321211	7351035	300	146	7.56	72	452	7.2	0 - 144m / 584.2mm 144 - 300m / 381mm	0 - 142m / 254mm 167 - 202m / 254mm 207 - 212m / 254mm 217 -232m / 254mm 247 - 257m /254mm 282 - 300m / 254mm	142 - 167m /254mm 202 - 207m /254mm 212 - 217m /254mm 232 - 247m / 254mm 257 - 282m / 254mm	254	Ecca

7.4 Production Borehole Testing

Test pumping activities were undertaken by the Contractor, assisted by a sub-contractor. All production boreholes were tested and the same approach adopted during the Exploration Phase was followed.

- calibration,
- step test and
- constant rate test (CRT) sequence,
- recovery monitored to within 95% after CRT.

A total of 16 boreholes (1 existing production boreholes and 15 project Production boreholes) have been test pumped. Only one existing borehole Bh6830 was test pumped. Test results are tabulated in Tables 7.9 and 7.10

Constant rate tests (CRT) varied in duration between 3 and 5 days depending on the pumping response. In cases where stabilization of the water level was attributed to under pumping, tests were usually restricted to shorter periods of 2 or 3 days. Reasons for under-pumping included:

- Gross under estimation of borehole capacity during the air-lifting process was most common in high yielding boreholes (BH 10746, 10751, 10754). Yield estimation during drilling is mainly a function of several factors that include compressor performance, formation properties (transmissivity and porosity) and groundwater head.

Table 7.9 Project – Ntane Test Results For Production Boreholes

BH No	Water Strike (m)	RWL (m)	Pump setting (m)	Available Drawdown (m)	CRT Rate (m³/hr)	Drawdown (m)	Duration (hours)	Transmissivity (m²/d)			
								CRT Cooper-Jacob	Recovery Cooper-Jacob	CRT Test Curve	Adopted T value
10740	123	70.8	180	109.25	8	59.45	78	5.3	1.9	4.4	3.5
10741	Dry										
10742	191, 216	92.4	218	125.6	15	63.98	120	11.32	4.58	9.3	8
10743	168	62.8	150	87.2	80	47.78	75	52.4	59.3	44.25	52
10744	174	92.4	140	47.6	100	45.91	86	55.22	191	25.5	110
10745	232	72.5	200	127.5	20	57.49	95	14.76	6.67	15	12

Table 7.10 Project – Ecca Test Results for Production Boreholes

BH No	Water Strike (m)	RWL (m)	Screened Interval (m)	Pump setting (m)	Available Drawdown (m)	CRT Rate (m³/hr)	Drawdown (m)	Duration (hours)	Transmissivity (m²/d)		
									CRT Cooper-Jacob	CRT Test Curve	Adopted T value
10746	147	65.2	156-160 176-181 201-211 221-226 245-265	150	84.82	70	57.04	96	40.6	109	**70**
10747		68		151	82.05	10	63.45	27	4.45	2.25	**3.5**
10748	95	67.2	95-120 125-150	160	92.8	25	48.36	91	9.92	7.9	**9**
10749	112	56.4	111-121 131-141 161-176 186-196 211-231 246-271	148	91.6	35	44.81	120	10.2	38	**25**
10750		70.6		270.5	199.9	5	139.73	36	0.493		**0.5**
10751	88, 209	63.5	91-106 111-126 166-171 176-186 201-216 221-236 246-261	90	26.53	70	17.47	96		320	**300**
10752	143	61.3	150-175 215-220 225-245 255-285	181	119.7	25	110.67	48	4.73	21.75	**13**

10753		59		215	156.05	10	68.1	26	1.71	1.8	**1.7**
10754	152, 223	72.3	151-171 219-259 265-300	120	47.7	106	24.05	120	141	372	**250**
10784	146	70.4	142-167 202-207 212-217 232-247 257-282	200	129.65	12	63	60	3.9	2.1	**3**

7.4.1 Ecca Boreholes - Test Pumping Results

Step Tests

A summary of the production boreholes step test results is provided in Table 7.11. Step test graphs are included in Appendix C. No significant temporal trends during pumping with respect to conductivity or TDS were noticed. Age variation in borehole efficiencies is evident in Table 7.11 Bh10749, 10748 and Bh10751 show low efficiencies of less than 50%. The low values for Bh10751 are a result of poor pumping rates. Fall in borehole efficiency over the duration of the step test was largest in Bh10784 at around 52%. The smallest fall was in Bh10752. However the drawdown interval over which the efficiency fall occurs is important in estimating the efficiency of a borehole.

Table 7.11 Production Boreholes - Step Test Results

BH No.	Step	Discharge (m³/hr)	Drawdown (m)	Conductivity (µS/cm)	Efficiency (%)	CRT Rate (m³/h)
10746	1	10	3.86		79.4	70
	2	20	7.39		65.9	
	3	30	14.85		56.3	
	4	40	24.27		49.1	
	5	50	28.80		43.6	
	6	60	41.03		39.2	
10747	1	3	8.92	934	73.8	10
	2	6	17.87	929	58.5	
	3	9	33.25	917	48.5	
	4	12	63.93	909	41.4	
	5	15	79.15		36.1	
10748	1	8	8.46	748	37.4	25
	2	12	14.36	757	28.5	
	3	16	23.2	760	23.0	
	4	20	35.49	771	19.3	
	5	24	49.06	751	16.6	
10749	1	10	7.15	854	42.3	35
	2	15	10.58	851	32.8	
	3	20	20.06	862	26.8	
	4	25	27.73	825	22.7	
	5	30	32.79	876	19.6	
	6	35	44.24	877	17.3	
	7	40	86.72	879	15.5	
	8	50			12.8	
10750	1	2	4.70	810	89.9	5
	2	4	11.21	692	81.5	
	3	8	23.34	761	68.8	
	4	12	41.38		59.5	
	5	16	66.30		52.4	
	6	20	98.65		46.8	
10751	1	30.15	2.86		18.1	70
	2	35.06	4.89		16.0	
	3	40.09	5.74		14.3	
	4	45.09	8.63		12.9	
	5	55.34	10.37		10.8	
	6	65.07	13.73		9.3	
	7	75.09	19.47		8.2	

10752	1	5	13.28	850	84.2	25
	2	10	40.10	780	72.7	
	3	15	61.70	780	64.0	
	4	20	91.83	805	57.1	
	5	30	114.39	760	47.0	
10753	1	3	6.83	845	49.4	10
	2	6	14.22	875	32.8	
	3	9	24.63	878	24.6	
	4	12	63.93	836	19.6	
	5	16	130.2	842	15.5	
	6	20	152.00		12.8	
10754	1	40.22	3.05		54.9	106
	2	60.68	6.222		44.7	
	3	70.20	11.10		41.1	
	4	80.35	14.15		37.9	
	5	96.35	16.11		33.7	
10784	1	4	19.62	870	61.7	12
	2	8	50.56	768	44.7	
	3	12	91.55	917	35.0	
	4	16	127.12	920	28.8	

Constant Discharge Rate Tests

Project production boreholes including existing Bh6830 were pumped for constant rate and the pumping duration ranged from 60 hrs for low yielding boreholes to 120 hrs for high yielding boreholes depending on the aquifer's response to the abstraction. Field data collected during CRT is tabulated in Table 7.12

Table 7.12 Production Boreholes - Constant Rate Pumping Field Test Details

BH No	Water Strike (m)	RWL (m)	Pump setting (m)	Available Drawdown (m)	CRT Rate (m³/hr)	Drawdown (m)	Duration (hours)
10746	147	65.2	150	84.82	70	57.04	96
10747		68	151	82.05	10	63.45	27
10748	120	67.2	160	92.8	25	48.36	91
10749	112	56.4	148	91.6	35	44.81	120
10750		70.6	270.5	199.9	5	139.73	36
10751	88, 209	63.5	90	26.53	70	17.47	96
10752	143	61.3	181	119.7	25	110.67	48
10753		59	215	156.05	10	68.1	26
10754	152, 223	72.3	120	47.7	106	24.05	120
10784	146	70.4	200	129.65	12	63	60

The drawdown data for each of the CRTs are included in Appendix C. Included on these graphs are the Jacob straight line analyses in determining transmissivities. Similar graphs for the recovery data are also included. The transmissivity values are tabulated in Table 7.13 below. In addition, the CRT data has been analysed using the DWA Test Curve programme. The Test Curve plots are also included in Appendix C.

Table 7.13 Production Boreholes - Transmissivity Analyses

BH No	**RWL (m)**	**Pump setting (m)**	**Available Drawdown (m)**	**CRT Rate (m^3/hr)**	**Drawdown (m)**	**Duration (hours)**	**Transmissivity (m^2/d)**		
							CRT Cooper-Jacob	**CRT Test Curve**	**Adopted T value**
10746	65.2	150	84.82	70	57.04	96	40.6	109	**70**
10747	68.0	151	82.05	10	63.45	27	4.45	2.25	**3.5**
10748	67.2	160	92.8	25	48.36	91	9.92	7.9	**9**
10749	56.4	148	91.6	35	44.81	120	10.2	38	**25**
10750	70.6	270.5	199.9	5	139.73	36	0.493		**0.5**
10751	63.5	90	26.53	70	17.47	96		320	**300**
10752	61.3	181	119.7	25	110.67	48	4.73	21.75	**13**
10753	59.0	215	156.05	10	68.10	26	1.71	1.8	**1.7**
10754	72.3	120	47.7	106	24.05	120	141	372	**250**
10784	70.4	200	129.65	12	63.00	60	3.9	2.1	**3**
6830	52.50	103	69.73	120	4.10	71		710	**700**

Transmissivity values from the Project production boreholes in the Malwelwe area generally range between 2m^2/day and 320 m^2/day. These values are similar to values determined for exploration boreholes as well as the BRGM (DWA 1991) boreholes in the area. The corresponding transmissivity values determined by BRGM some 20 years ago are presented in Project Review Report (DWA 2010) and show similar trends.

This data interpretation confirms a high transmissivity area within the central portion of Target Area A centred around Bh6827 - Bh6825 - Bh10746 - Bh10751, with transmissivity on the upper end of the range around 300-400 m2/day. High values seem to occur where the Ecca aquifer is thickest, as at Bh10746 and Bh10751. The area around Bh6829, located on the steep edge of the Main Graben, seems to be a low transmissivity area, probably due to a reduced thickness of the aquifer. A similar trend is also observed at Bh10747 some 3.7km west with an intercepted basement at 172m depth. This low transmissivity trend related to reduced Ecca aquifer thickness is also evident at Bh6828 to the south and the recently drilled project borehole Bh10677 with an airlift yield of only 2.3m^3/hr.

Specific capacities at different times during the CRT were also analysed and the data is tabulated in Table 7.13.

Borehole Efficiency Analysis

The assessment of test pumping data (steps and CRT), has revealed that 7 of the production boreholes in Malwelwe Bh10746, 10748, 10749, 10751, 10752, 10754 and 10784 have the potential to be utilised for production purposes. In addition Bh10671, an exploration borehole is to be utilized as a production borehole in place of production borehole Bh10747 which is low yielding.

However, analysis of individual borehole step test performance of these boreholes has revealed both efficient and considerably less efficient boreholes, almost certainly as a result of borehole construction (screens). Table 7.14 below gives a breakdown of efficiency over the discharge rate that was used. Bh 10751 had to be developed for long hours to improve its low efficiencies.

Table 7.14 Production Borehole Efficiency Comparison

Borehole No.	Steps Pumping Range (m^3/hr)	Efficiency % Max - min	CRT Rate (m^3/hr)	Comments
10746	10-60	79- 39	70	
10747	3- 15	74- 36	10	Drilled as a low yield Bh
10478	8- 24	37- 16	25	
10749	10- 50	42- 13	35	
10750	2- 20	90- 47	5	Drilled as a dry Bh
10751	30- 75	18- 8	70	
10752	5- 30	84- 47	25	
10753	3- 20	49- 13	10	Drilled as a dry Bh
10754	40- 96	54- 33	106	
10784	4- 16	62- 29	12	
6830			120	
10671	5 – 25	87 - 59	20	Exploration Bh

The most efficient borehole Bh10750 is a low yielding borehole that could be pumped only at 5m^3/hr after yield assessment during step testing. High efficiency values were possible at very low (2-8m^3/hr) discharge rates when linear well losses are dominant. In high yielding borehole non-linear losses tend to be dominant as the flow is centralized by the pump. The size of the borehole also plays critical role and Bh10754 which is 8inches diameter could have been affected considerable at high pumping rates of 100m^3/hr.

Specific Capacity Evaluation

Despite known drawbacks in the use of specific capacity in the estimation of yield potential of a borehole, an evaluation was made on all Ecca boreholes. The potential pitfalls of using specific capacity to project possible productivity include:

- pumping time,
- pumping rate and
- well construction
- hydraulic boundary effects

The specific capacity S_c is the ratio of discharging (Q) to steady drawdown (S_w).

$$S_c = Q/S_w$$

For a given discharge a well is often assumed to have a constant specific capacity. Any significant decline in the specific capacity of a well can be attributed either to a reduction in transmissivity due to a lowering of the groundwater level in an aquifer or to an increase in well loss associated with clogging or deterioration of the well screen or productive zones.

For individual borehole comparison purposes capacities at 24hr, 48hr and 72hrs were calculated and theses are tabulated in Table 7.15 . It is evident that the high yielding (>50m^3/hr) boreholes have high specific capacities with a range of 2-9m^2/hr. Most boreholes have indicated fairly constant specific capacities across the three time periods except for the low yielding boreholes.

The influence of hydraulic boundaries is evident in almost all the test pumping data in the Project Area. Both positive and negative boundaries are present. BH10746 shows recovery tendencies when pumped at 50m^3/hr and again at 70m^3/hr. The structural set up in the area (Inception Report, March 2009) displays significant hydraulic barriers and boundaries and these come into play during pumping. Negative boundaries tend to reduce specific capacities and this effect will be further highlighted when calculating abstraction rates for production borehole.

Table 7.15 Ecca Constant Rate Test Results and Specific Capacity Values

BH No.	Pumping Rate (m³/hr)	Pumping Duration (hrs)	Final Drawdown (m)	Final Specific Capacity (m²/hr)	Specific Capacity 24 Hrs (m²/hr)	Specific Capacity 48 Hrs (m²/hr)	Specific Capacity 72 Hrs (m²/hr)	Adopted Specific Capacity (m²/hr)
10746	70	100	57.23	1.22	1.32	1.31	1.24	1.22
10747	10	27	63.45	0.16	0.16			
10478	25	96	48.27	0.52	0.57	0.56	0.53	0.53
10749	35	120	44.81	0.78	0.89	0.85	0.84	0.78
10750	5	36	139.73	0.04	0.05			
10751	70	96	17.47	4.01	4.32	4.24	4.11	4.01
10752	25	48	110.67	0.23	0.23	0.23		0.23
10753	10	27	68.1	0.15	0.15			0.15
10754	106	120	24.05	4.41	5.03	4.92	4.74	4.41
10784	12	60	107.57	0.11	0.13	0.12		0.11
6830	120	71	4.1	29.27	32.61	31.09	29.27	28.27

[1] Jacob straight line method of analysis

7.4.2 Ntane/ Lebung Boreholes - Test Pumping Results

Step Tests

A summary of the Ntane/Lebung production borehole step test results are provided in Table 7.16. Step test graphs are included in the Project Data Book (Technical Report Number -7). The two boreholes (BH 10743 and 10744) show high efficiencies.

Boreholes BH10740, 10742 and 10745 show negative slopes and these were interpreted to indicate borehole development during pumping.

Table 7.16 Ntane/ Lebung Boreholes - Step Test Results

BH No.	Step No.	Discharge (m³/hr)	Drawdown (m)	Efficiency (%)	CRT Rate (m³/h)
10740	1	3.04	26.85	Negative slope	8
	2	6.02	34.3		
	3	9.03	53.72		
	4	14.96	89.48		
10742	1	5.02	18.53	Negative slope	15
	2	10.5	32.58		
	3	15.07	48.92		
	4	20.05	71.80		

10743	1	20	8.16	83.0	80
	2	40	19.32	70.9	
	3	60	31.42	61.9	
	4	80	45.18	55.0	
	5	90	50 .00	52.0	
10744	1	10	3.86	79.4	100
	2	20	7.39	65.9	
	3	30	14.85	56.3	
	4	40	24.27	49.1	
	5	50	28.80	43.6	
	6	60	41.03	39.2	
10745	1	10	29.54	Negative slope	20
	2	20	44.62		
	3	30	65.00		
	4	40	92.71		

Constant Discharge Rate Tests

Field data collected during CRT is tabulated in Table 7.17 below and it highlights the high heads in all the boreholes.

Table 7.17 Ntane/ Lebung Boreholes - Constant Rate Test Data

BH No	Water Strike (m)	RWL (m)	Pump setting (m)	Available Drawdown (m)	CRT Rate (m³/hr)	Drawdown (m)	Duration (hrs)
10740	123	70.8	180	109.25	8	59.45	78
10741	dry						
10742	191, 216	92.4	218	125.6	15	63.98	120
10743	168	62.8	150	87.2	80	47.78	75
10744	174	92.4	140	47.6	100	45.91	86
10745	232	72.5	200	127.5	20	57.49	95

The drawdown data for each of the CRTs are included in the Project Data Book (Technical Report Number -7). Included on these graphs are the both Testcurv and Jacob straight line analyses in determining transmissivities. Similar graphs for the recovery data are also included. The transmissivity values are tabulated in Table 7.18 below. In addition, the CRT data has been analysed using the DWA Test Curve programme. The Test Curve plots are also included in the Project Data Book.

Table 7.18 Ntane/ Lebung - Constant Rate Test Results and Transmissivity Values

BH No	RWL (m)	Pump setting (m)	Available Drawdown (m)	CRT Rate (m³/hr)	Drawdown (m)	Duration (hrs)	Transmissivity (m²/day)			
							CRT Cooper -Jacob	Recovery Cooper-Jacob	CRT Test Curve	Adopted T values
10740	70.8	180	109.25	8	59.45	78	5.3	1.9	4.4	4
10741	dry									

10742	92.4	218	125.6	15	63.98	120	11.3	4.58	9.3	8.5
10743	62.8	150	87.2	80	47.78	75	52.4	59.3	44.25	50
10744	92.4	140	47.6	100	45.91	86	55.2	191?	25.5	40
10745	72.5	200	127.5	20	57.49	95	14.8	6.67	15	12

[1] Jacob straight line method of analysis

Transmissivity values from the Ntane/Lebung boreholes generally range between 2 m^2/day and 25 m^2/day within the Sorilatholo Wellfield. Similar range of values were also derived during the exploration phase and at that time the values were definitely not a true reflection of the properties of the Ntane/Lebung aquifer due to test pumping problems encountered.

Specific Capacity Evaluation

Specific capacities at different times during the CRT were also analysed for the Ntane/Lebung aquifer production boreholes and the data is tabulated in Table 7.19 below. The values are generally lower than those determined during the Exploration Phase. This is attributed to the drilling of less successful site that did not strike any water in the basalt indicating less fracturing at these sites.

Table 7.19 Ntane/Lebung Production Boreholes Specific Capacities

BH No.	Pumping Rate (m³/hr)	Pumping Duration (hrs)	Final Drawdown (m)	Final Specific Capacity	Specific Capacity 24 Hrs (m²/hr)	Specific Capacity 48 Hrs (m²/hr)	Specific Capacity 72 Hrs (m²/hr)	Adopted Sp. Capacity (m²/hr)
10740	8	77	59.45	0.13	0.15	0.14	0.13	0.13
10742	15	120	63.98	0.23	0.26	0.25	0.24	0.24
10743	80	75	47.78	1.67	1.82	1.75	1.68	1.68
10744	100	94	45.91	2.18	2.58	2.45	2.25	2.25
10745	20	96	57.52	0.35	0.36	0.36	0.35	0.35

7.5 Final Production Borehole Details

At the end of the Production Phase a total of 16 new production boreholes had been drilled and tested as per tables above (also includes an existing production borehole BH 6830). Production boreholes BH10741, 10747, 10750, and BH 10753 were essentially low yielding for production purposes.

Five production boreholes were established in the Sorilatlholo Wellfield and seven were added to the Malwelwe Wellfield which has BH6824, 6825, 6826, 6827, 6828 and BH6830 productive boreholes and BH6829 as a low yielding borehole. These were established some 20 years ago by BRGM (DWA, 1991).

The construction of the Exploration borehole in Sorilatholo allow the use of these boreholes for abstraction purposes and these have been added to the production set totalling 11 production boreholes. Tables 7.20 gives details and location of all the production boreholes in both wellfields.

Table 7.20 Malwelwe and Sorilatlholo Wellfields Production Boreholes Listing

Malwelwe Wellfield Boreholes			
BH No	**UTM Coordinates (Cape Datum)**		**Aquifer Type**
10746	323127	7349325	Ecca
10747	323627	7345632	Ecca
10748	331580	7350840	Ecca
10749	325763	7354404	Ecca
10750	325180	7348961	Ecca
10751	332580	7350840	Ecca
10752	321293	7348837	Ecca
10753	327354	7353651	Ecca
10754	327027	7348371	Ecca
10784	321211	7351035	Ecca
6824	318997	7345934	Ecca
6825	321370	7346340	Ecca
6826	317896	7345895	Ecca
6827	314841	7345521	Ecca
6828	331851	7341522	Ecca
6829	327360	7345991	Ecca
6830	322964	7358486	Ecca

Sorilatlholo Wellfield Boreholes			
BH No	**UTM Coordinates (Cape Datum)**		**Aquifer Type**
10740	297493	7375249	Ntane
10741	297556	7372490	Ntane
10742	303987	7372839	Ntane
10743	294118	7373350	Ntane
10744	302736	7379995	Ntane
10745	285584	7367781	Ntane
10681	289750	7369191	Ntane
10682	295503	7378174	Ntane
10683	284324	7390209	Ntane
10684	280869	7374594	Ntane
10685	279366	7369911	Ntane
10686	314234	7382261	Ntane
10687	306490	7373066	Ntane
10688	314426	7369115	Ntane

Construction details of these production boreholes are tabulated in various tables in the report. Test pumping data analysis resulted in the production rates calculation as tabulated in Tables 7.21 and 7.22 below. Both the DWA RVWS Manual and the specific capacity approach were used for comparison and the adopted values were then determined.

Table 7.21 Calculated Abstraction Rates for new Production Boreholes in the Malwelwe Wellfield

BH No.	Calculated Pump Setting Depth (m)	Calculated drawwdown (m)	Adopted Specific capacity (m^2/hr)	Specific Capacity Calculated Abstraction Rate (m^3/hr)	DWA WDM Calculated Abstraction Rate (m^3/hr)	Proposed Abstraction Rate (m^3/day)
10746	150	85	1.22	**51.8**	**49**	**70**
10748	150	83	0.53	**22**	**14**	**20**
10749	150	94	0.78	**36.7**	**25**	**35**
10751	90	27	4.01	**54**	**46**	**100**
10752	180	118	0.23	**13.6**	**22**	**30**
10754	150	78	4.41	**172**	**67**	**100**
10784	180	110	0.11	**6**	**6**	**12**

10671	150	82	0.75	**31**	**17**	**20**
6824	98	33	7.336	**121**	**70**	**80**
6825	100	33	7.46	**123**	**76**	**100**
6826	140	82	4.181	**171**	**38**	**40**
6827	105	40	7.937	**158**	**80**	**90**
6828	125	47	1.015	**24**	**23**	**25**
6829	115	38	0.25	**5**	**4**	**0**
6830	140	15	28.27	**212**	**80**	**120**

Table 7.22 Calculated Abstraction Rates for new Production Boreholes in the Sorilatlholo Wellfield

BH No.	Rest Water Level (m)	Recommended Pump Setting Depth (m)	Available Drawdown (m)	Adopted Specific capacity (m^2/hr)	Specific Capacity Calculated Abstaction Rate (m^3/hr)	DWA WDM Calculated Abstraction Rate (m^3/hr)	Proposed Abstraction Rate (m^3/day)
10740	70.75	180	109.3	0.13	7.1	5.93	**7**
10741	dry						
10742	92.4	180	87.6	0.24	10.5	11.32	**11**
10743	62.8	150	87.2	1.68	73.2	52.4	**60**
10744	92.4	150	57.6	2.25	64.8	55.22	**60**
10745	72.5	180	107.5	0.35	18.8	14.76	**17**
10681	42.92	180	137.1	0.256	17.5	10.45	**15**
10682	65.96	180	114.0	0.482	27.5	20.81	**25**
10683	Low yield						
10684	Low yield						
10685	76.9	180	103.1	0.54	27.8	23.28	**25**
10686	79.9	180	100.1	0.15	7.5	5.44	**6**
10687	96.28	180	83.7	0.479	20.1	15.45	**18**
10688	79.3	180	100.7	0.333	16.8	13.33	**15**

8. RESOURCES QUANTIFICATION

The numerical modelling of the groundwater flow within Project Area was aimed at quantifying the renewable groundwater resources and to define possible extractable volumes. Furthermore it was imperative to assess long term effects as well as investigate possible interference between the various wellfields of Gaotlhbogwe, Malwelwe and Jwaneng Northern Wellfield.

For these reasons the modelling approach was applied at regional level to allow all inclusive groundwater balance assessment.

The conceptual model presented in Chapter 4 was used in the development and coding of the numerical model as presented below. Technical Report No. 4, Groundwater Resources Modelling presents comprehensive details of the modelling undertaken during the project.

8.1 Numerical Model Design

The MODFLOW code (McDonald M.G., Harbaugh A.W., 1988) is the most universal software in numerical groundwater modeling. Processing Modflow (PMWIN 7.0.11) (Chiang, W., H., Kinzelbach W., 2003) was selected, principally because it is already known and has been extensively used on other DWA projects in Botswana and it has an excellent link with parameter optimization program PEST. Such a link allows for time efficient automatic calibration of the model, which is always the most time consuming procedure in the overall numerical modeling process. The topology, layer management (from the GIS geological model) and Processing Modflow input and output data transfer was handled using ArcGIS and Surfer 8.0, (Golden software Inc. 2002)

8.2 Concepts and General Assumptions

The following general assumptions were made in the formulation of the modelling process:

- A Finite Difference MODFLOW model solution based on a rectangular model grid
- 1-LAYER 2 dimensional model
- Only horizontal fluxes, with Kx and Ky are simulated due to a ONE-LAYER model.
- Transmissivity and storage coefficient varies due to confined and unconfined conditions. During transient model calibration transmissivity and storage coefficient is automatically convertible between confined and unconfined conditions, depending on the calculated head in relation to the top of the aquifer (MODFLOW Option 3, McDonald M.G., Harbaugh A.W., 1988).

8.3 Aquifer Geometry and Grid Design

The MODFLOW code allows for the use of a regular, rectilinear, block-centred grid type model. A square grid of 1km^2 consistent with UTM coordinates has been selected, (see Fig. 8.1). The grid size was minimised over the Jwaneng, Gaotlhobogwe and Malwelwe Wellfields to increase model accuracy during simulation of abstraction.

The model area extent was based on interpretation of the geology and groundwater piezometry. To the south and east, the model boundary is defined by the edge of the Karoo basin defined by Proterozoic basement high which is a groundwater divide. To west, the model extends beyond 50km beyond Jwaneng Wellfield and the western boundary is hydrogeological, defining groundwater discharge out of the aquifer. The boundary was delineated 50km from the edge of the wellfield to limit impacts of drawdown from the wellfield on the boundary.

The northern boundary of the model is defined by the Zoetfontein Fault.

8.4 Initial Parameters

8.4.1 Piezometric Head

Groundwater head distribution for the Ecca aquifer was generated from 96 boreholes with water level data gathered in 2005 from Jwaneng, Gaotlhobogwe and Malwelwe Wellfields. Groundwater levels show a flow from the southeast to the northwest indicating the regional groundwater flow system. Drawdown footprints are shown around Gaotlhobogwe and Jwaneng Wellfields due to pumping. The regional groundwater levels which were used to generate initial heads for the steady state model are shown in Figure 8.2.

8.4.2 Transmissivity

Transmissivity distribution within the model area was based on test pumping data carried out during different projects for the three wellfields. The data is presented below. Distribution of aquifer transmissivity is spatially related to structures as indicated by transmissivity values obtained from Malwelwe, Gaotlhobogwe and Jwaneng Wellfields, where thickness of the Ecca aquifer is controlled by faulting. Transmissivity values obtained from the wellfield studies is shown in Table 8.1

Table 8.1 Transmissivity Values from the wellfields

Location	Minimum Transmissivity (m2/d)	Maximum Transmissivity (m2/d)	Source
Jwaneng Wellfield	500	5000	GCS, 2001 in WSB Report, 2009
Gaotlhobogwe Wellfield	4	982 (mean 200)	WSB 2009
	9	330 (mean 68)	WCS 1998
Malwelwe	73	526	WSC 2011

The data shows that there is high spatial variation in transmissivity in Gaotlhobogwe Wellfield, indicating disposition and variation in thickness of the Ecca aquifer. The thicker Ecca aquifer in Malwelwe Wellfield, and particularly in Jwaneng, results in high transmissivity within the two wellfields.

8.4.3 Storage (confined/unconfined)

Results of test pumping data from the three wellfields show values of storage coefficient that range from confined to unconfined aquifer conditions. Values of 1x10-4 to 2.5x10-4 indicate confined aquifer conditions while values of 0.01 to 0.03 indicate unconfined aquifer conditions, Table 8.2.

Table 8.2 Storage values from the wellfields

Location	Minimum Storage	Maximum Storage	Source
Jwaneng Wellfield	$1x10^{-4}$	0.01	GCS, 2001 in WSB Report, 2009
Gaotlhobogwe Wellfield	$2.54x10^{-4}$	0.03 $8x10^{-3}$ mean	WCS 1998
Malwelwe Wellfield	1x10-4	0.05	WSC 2011

The data indicates similar range of storage coefficient values obtained by different and independent sources.

8.4.4 Boundary Conditions

Three boundary conditions have been defined for the model. Definition of model boundaries was based on hydrogeological, geological and topographical data evaluation.

Inflow boundary

Both groundwater piezometry and topography show a groundwater divide marking a basement high to the south and east of the Karoo basin. Groundwater flow is from the basement highs into the Karoo basin.

This model boundary has been defined as an inflow boundary and is numerically represented as below:

$Q_b = C_b.(h_b - h)$, where

$C_b = K.L$ and
C_b is the hydraulic conductance at the boundary,
h_b is the head at the boundary and
h is the head in the aquifer.

The hydraulic conductance C_b is a function of the hydraulic conductivity K and the length of the boundary, L. With increased drawdown in the aquifer due to pumping, Q_b will decrease as the head at the boundary also decreases.

Outflow boundary

This boundary defines groundwater outflow from the model area. This boundary is defined based on piezometric heads and is shown to the north where the Zoetfontein fault is porous and allows flow across it. Part of this northern outflow boundary is marked by the Gaotlhobogwe valley.

To the west, the boundary simulates groundwater discharge to the west of Jwaneng Wellfield, where a NW flow leaves the model area.

Numerically the outflow boundary is defined by

$$Q_d = C_d.(h - h_d)$$

$C_d = K.L$, Q_d is inflow into the drain,
C_d is the hydraulic conductance of the boundary,
h is the head in the aquifer and
h_d is the drain elevation.

When $h>h_d$, there is flow into the drain and out of the model and when $h<h_d$, flow is cut out and no flow can take place from the drain into the aquifer, thus a conservative type boundary.

These types of boundaries have been design to limit the influx from the boundaries into the model during abstraction.

Elsewhere, groundwater flows parallel to the model boundary, indicating no horizontal flux across the boundary and the model boundary is defined by Q=0 - no flow boundary condition. The model boundaries are represented in Figure 8.3.

8.4.5 Recharge and Groundwater Flux

Recharge

Various projects, including the GRES project (1995) indicated that recharge through the Kalahari aquifer could be minimal to nil, with recharge rates estimated below 5mm/yr. Within the model, low recharge rates have been assigned over the sandveld, with recharge rates of <2mm/yr. High recharge is expected along the Gaotlhobogwe valley, where the overlying mudstones have been deeply incised exposing or nearly exposing the Ecca aquifer, evapotranspiration rates are also high along the valley.

Horizontal Groundwater Flux

Using simple analytical solution to estimate the horizontal inflow into the model from the groundwater divide, an inflow rate of 13,176m^3/d was estimated, Table 8.3 and will be verified from the steady state numerical model water balance.

Table 8.3 Estimation of Inflow Volume from Analytical Aolution

Description	Quantity	Dimension
Length of boundary	180,000 (180km)	m
Average thickness of aquifer at boundary	60	m
Hydraulic gradient at boundary, calculated from piezometry	0.001 (10m/10km)	0.001
Hydraulic conductivity	1.22	m/d
Inflow rate (Q=KIA)	13,176	m^3/d

8.5 The Steady State Numerical Model

The objective of the steady state groundwater flow model was to simulate groundwater flow observed in the Project Area and reproduce the observed groundwater heads at each measuring point though calibration of groundwater recharge and evapotranspiration using measured aquifer hydraulic conductivity and transmissivity as control. Inflow at the southern and eastern boundaries was also controlled from estimates of the analytical solution to limit the degrees of freedom in the estimated model parameters.

8.5.1 Model Calibration

The calibration process was performed through the automated inverse calibration method by running **P**arameter **Est**imation programme **PEST**. By assigning aquifer parameters to PEST and assigning range of possible values for the parameters based on field measurements, PEST searches for a set of aquifer parameters (recharge, evapotranspiration, hydraulic conductivity, conductance at the boundaries) for which the difference between modelled and measured hydraulic heads is reduced to a minimum. This is done through evaluating the objective function $\mathbf{\Phi}$ (sum of squared difference between model calculated and observed head values).

ϕ is numerically expressed as

$$\phi = \sum_{i=1}^{n} (h_c - h_o)^2 ,$$

where h_c is the calculated head and h_o is the observed head, and n is the number of observations.

8.5.2 Model Calibration Results

Hydraulic Heads

Sixty-six (66) head observations were used for the model calibration. The observations were spatially representative of the whole model area. A number of calibrations were run before an objective function of 1129m^2 was achieved and this was regarded as satisfactory, with the maximum calibration error being less than 10m at all boreholes**.** Figure 8.4 shows modelled and observed heads scatter diagram from the steady state calibration.

Transmissivity

Aquifer transmissivity was automatically calculated from the model during optimisation of hydraulic conductivity. The use of hydraulic conductivity to calibrate the model has an advantage over the use of transmissivity in that:

- Transmissivity is allowed to vary as the aquifer saturated thickness changes, this is particularly important for the transient model and occurs in the natural state.

- Aquifer thickness is highly variable particularly within the Gaotlhobogwe Wellfield and the eastern part of the project, use of transmissivity would require delineating numerous transmissivity zones with each variation in aquifer thickness, resulting in a complex model.

- The use of hydraulic conductivity has produced a very simple model zoning with only 3 hydraulic conductivity zones for the whole model area although transmissivity is highly variable.

Optimised hydraulic conductivity and transmissivity values are shown in Table 8.4

Table 8.4 Optimised Transmissivity Values

Zone	Area	Optimised value K	Aquifer thickness (m)	Optimised Transmissivity (m^2/day)	Field measured values (m^2/day)	Source of data
HK1	Jwaneng Wellfield and west of Gaotlhobogwe valley	4	200-300	800-1200	500-1000	WSB 2009 Report
					1000-5000	
HK2	Gaotlhobogwe valley	1	60-200	60-300	9-330	WCS 1998
					4-982	WSB 2009
HK3	Malwelwe	2	60-300	120-600	73-526	WCS 2011

The modelled transmissivity values are within the range of values obtained from studies in the area, with high transmissivity in Jwaneng Wellfield and lowest in Gaotlhobogwe Wellfield due to reduced aquifer thickness. The modelled values are on the conservative side, particularly for Jwaneng Wellfield.

Groundwater Recharge

Three zones were optimised for recharge. The lowest recharge value was 1.7mm/yr over the whole model area except along the Gaotlhobogwe valley where an exceptionally high value of 17mm/yr was calibrated with the set of hydraulic conductivity values assigned. A small zone with a recharge value of 1.5mm/yr was calibrated around Gaotlhobogwe Wellfield. The high recharge rate over Gaotlhobogwe valley can be attributed to flash floods within the valley during high rainfall events as well as thin mudstone over the valley as the valley has been deeply incised, with the Ecca aquifer sub-outcropping allowing infiltration of surface water into the groundwater system. Spatial distribution of recharge is shown in Figure 8.5.

Evapotranspiration

Two zones were delineated, with evapotranspiration rates of 0mm/yr over the entire model area, except the Gaotlhobogwe valley where an evapotranspiration rate of 2mm/yr was calibrated.

The net recharge along the Gaotlhobogwe valley is 15mm/yr, which is the difference between recharge and evapotranspiration. Figure 8.6 shows distribution of groundwater evapotranspiration within the model area.

The Model Water Balance

A model water balance shows the different flux components of groundwater flow into and out of the model. At the end of a steady state simulation, the inflow and outflow of groundwater components should balance or be within acceptable limits, taking into account model numerical dispersion effects.

Total inflows are represented by groundwater recharge and horizontal infow from the groundwater divide. Groundwater recharge accounts for 87% of the total aquifer inflow of 90,429m^3/d/. Given that the total abstraction at steady state is 40,560m3/d, abstraction accounts for 45% of the total aquifer inflow volumes. This implies the outflow from the aquifer at the western and northern boundaries has been reduced by nearly 50%. The western outflow boundary accounts for 16,400m^3/d out of 45,576m^3/d as a result of abstraction from Jwaneng Wellfield, with an abstraction of 32,111m^3/d (See Table 8.5).

Table 8.5 Model Water Balance at end of Steady State

Source	Inflows (m3/d)	Outflows (m3/d)	Balance Inflows (m^3/d)
Southern and eastern flux from water divide	12610	-1867	10743
RECHARGE	77819	0	77819
DRAINS		-45576	-45576
ET		-2285	-2285
Abstraction		-40560	-40560
SUM	**90429**	**-90288**	**141**
DISCREPANCY	**0.16 [%]**		

8.5.3 Comments on the Steady State Model

Calibration of the steady state model has been achieved through calibration of recharge and evapotranspiration against known values of transmissivity obtained from extensive groundwater exploration and investigation studies in the area.

By fixing transmissivity and inflow at the boundary, uncertainties in the model are reduced with degrees of freedom allowed only on the recharge and evapotranspiration to the aquifer system.

The set of transmissivity values used to calibrate the model optimised a recharge value of 15mm/yr along Gaotlhobogwe valley. Recharge rates estimation has been problematic in Botswana with estimated rates highly variable. Rates optimised by WSB, 2009 were less than 1mm/yr. These rates were based on a model calibrated with hydraulic conductivity of 0.24m/d (T of 8.2m^2/d for layer 4, 34m thick) to 13m/d (maximum T of 1,425m^2/d for layer 3, 155m thick) representing layer 3 and 4 of the model for upper and lower Ecca aquifer. (WSB 2009). The transmissivity values are within the range of values and agree with optimised values for the current model, but the current model would not optimise such low recharge with the modelled transmissivity values.

Use of hydraulic conductivity to calibrate the model has resulted in a simple zonation, with only 3 zones optimised for the whole model area. Calibrating the model with hydraulic conductivity allows for the aquifer to vary transmissivity, which is important for transient model to avoid over-estimating resources where transmissivity is otherwise used and remains constant.

An initial analytical solution used to estimate inflow from the basement high to the south and east (Section 8.4.5, Table 8.3) indicated an estimated daily inflow from the groundwater divide of 13,176m^3/d. This inflow rate was sunsequently used in the PEST parameter optimisation package within the PMWIN model programme to calibrate hydraulic conductance at the model inflow boundaries. From this optimisation exercise an inflow rate of 12,610m^3/d was obtained, which is very similar to the value calculated by the initial analytical solution and indicates that the model is reliably calibrated.

Using the analytical solution to estimate inflow at the boundary also reduced the degrees of freedom of unknown terms in the model, thereby increasing confidence level in the model calibration results.

8.6 Transient Modelling

Transient modelling involves simulating long-term groundwater level fluctuations within the aquifer as a response to groundwater abstraction and other external and internal stresses – change in recharge, evapotranspiration and horizontal inflow rates. Inducing stress to the aquifer through abstraction and simulating the response provides accurate estimation of the true aquifer hydraulic parameters when it is subjected to stress, particularly on a long-term.

A transient model does help provide a verification of the accuracy of the steady state model results. Where observed and model calibrated time series data does not match during transient model calibration, a revisit of the steady state model is often carried out and the parameters optimised during steady state calibration altered, thereby enabling refining of the steady state model.

Long term groundwater abstraction and water level monitoring data was gathered from Jwaneng Wellfield, Gaotlhobogwe Wellfield and Malwelwe Wellfield. The water level data consisted of data from non-pumping observation boreholes and pumping observation boreholes (Gaotlhobogwe Wellfield only).

Private boreholes were also identified in the area and where possible, pumping rates have been obtained otherwise most of them are based on estimates from verbal communication with the owner.

The transient model data was from 2005, the beginning of steady state model to 2009 which is the last year with data that was made available.

8.6.1 Transient Abstraction and Water Level Data

Groundwater Abstraction – Jwaneng Wellfield

Groundwater abstraction from Jwaneng Wellfield decreased from 11,7Mm^3/yr in 2005 to 7,13Mm^3/yr in 2009. The years 2008 and 2009 showed the lowest groundwater abstraction from the wellfield in years. The decrease was attributed to the global recession in 2008 and 2009 which forced Jwaneng mine to reduce mining activities hence water demand (Jwaneng Wellfield Monitoring Report, 2009).

No data was yet available for 2010 and 2011 during compiling of the report. Figure 8.7 show groundwater abstraction volumes from the wellfield from 2005 to 2009.

Groundwater Abstraction – Gaotlhobogwe Wellfield

Figure 8.8 shows annual groundwater abstraction from Gaotlhobogwe Wellfield (source WSB 2009). Although abstraction started in 2009, the pumping was low and erratic, with an average yearly abstraction rate of 200,000m^3/yr from 1995 to 1999. Significant pumping started in 2000, with an annual abstraction of approximately 1,500,000m^3/yr. This increased significantly to 2,500,000m^3/yr to 3,000,000m^3/yr between 2001 and 2005, before dropping to 2,000,000m^3/yr to 2,500,000m^3/yr from 2006 to 2009 with an average abstraction rate of 2,200,000m^3/yr over the three years. However data gathered from DWA on individual borehole abstractions showed that in 2005, total abstraction from Gaotlhobogwe Wellfield increased to 3,482,000m^3/yr instead of 3,000,000m^3/yr. As no data was available from 2009, it is estimated that the pumping rate increased after 3 high yielding boreholes BH10549, BH10550 and BH10553 were drilled.

Groundwater Abstraction – Other Nodes

Other abstraction centres in the area are private boreholes with daily pumping rates of 8m^3/d to 75m^3/d. A village of importance to the modelling in the area is Malwelwe, currently being supplied by two boreholes BH6828 and BH6830 pumping at 8m^3/hr and 10m^3/hr respectively. Assuming 15 hours of pumping per day, the estimated daily pumping volumes from the two boreholes is 270m^3/d.

Groundwater Levels – Malwelwe Wellfield

In Malwelwe area and east Gaotlhobogwe Wellfield, the water level decline from 2005 to 2009 is at maximum 1m. This response is due to pumping in Gaotlhobogwe Wellfield and the graphs are shown in Figure 8.9.

Groundwater Levels – Gaotlhobogwe Wellfield

In Gaotlhobogwe Wellfield, groundwater levels have decreased by 12m-30m and in some boreholes up to 50m. In observation boreholes water level decline of 4m has been observed and the huge difference in drawdown between pumping boreholes and observation boreholes shows a low to medium transmissive aquifer, with limited lateral spread of the cone of depression and increased drawdown within the vicinity of the boreholes. Water level graphs in Gaotlhobogwe Wellfield are shown in Figure 8.10.

Groundwater Levels – Jwaneng Wellfield

In Jwaneng Wellfield water levels have gone down by 10m-14m in observation boreholes over 20 years, a drawdown rate of nearly 0.5m/yr. From 2005 to 2009 observation boreholes show a recovery in water levels as a result of decreased abstraction from approximately 11.5Mm^3/yr to 7.5Mm^3/yr. Figure 8.11 shows groundwater level graphs for Jwaneng Wellfield.

8.6.2 Transient Model Calibration Results

Specific storage and specific yield were assigned to the model to enable the model to simulate conversion between confined (specific storage) and unconfined (specific yield) conditions during groundwater abstraction. Optimised values for the storage terms are shown in Table 8.6.

Table 8.6 Storage Parameters used in the Model Calibration

Wellfield	Specific storage 1/m	Average aquifer thickness (m)	Storage coefficient (calculated from average aquifer thickness)	Specific yield	Field measured values
Gaotlhobogwe	1x10^{-6}	100	1x10-4	0.001	2.5x10^{-4} – 0.03
Jwaneng	1x10^{-6}	250	2.5x10^{-4}	0.003	1x10^{-4} – 0.01
Malwelwe	1x10^{-6}	150	1.5x10^{-4}	1x10^{-3}	1x10^{-4} – 0.052

Model Calibration Results – Gaotlhobogwe Wellfield

Transient model calibration heads for Gaotlhobogwe production boreholes are shown in Figure 8.12 with a well-calibrated model for the observed and modelled heads. Lack of observation data limits calibration of data to 2011. The huge difference between modelled and observed heads for BH7931 can be attributed to errors in water level measurements.

Model Calibration Results – Malwelwe Wellfield

Figure 8.13 shows calibration results for Malwelwe boreholes. No major groundwater movement has occurred in Malwelwe. A constant decline in water levels is attributed to abstraction from Gaotlhobogwe Wellfield with a decline rate of at most 0.25m/yr. Fluctuations at BH6375 are a response to groundwater abstraction from BH6828, abstracting close to 8m^3/hr.

Model Calibration Results – Jwaneng Wellfield

Results of transient model modelled and observed head fluctuations are shown in Figure 8.14. The calibration is from monitoring boreholes within and around the wellfield area. The water levels show a recovery in water levels from 2008 as a result of reduction in groundwater abstraction. This recovery trend from observation boreholes is reflected in the modelled heads.

8.6.3 Comments on the Transient Model Calibration

Storage coefficient values determined from test pumping data interpretation have been successfully used in the transient model calibration to simulate measured groundwater abstraction and water level fluctuations as a response to the abstraction. The transient model calibration increases the level of confidence in the numerical groundwater model used to represent the hydrogeological system of the Ecca aquifer within the modelled area.

Optimised hydraulic conductivity, out fluxes and influxes calibrated from the steady state model have been confirmed to from the transient calibration model to accurately represent the set of parameters optimised to generate observed groundwater abstraction and water level fluctuations.

Although the biggest abstraction rate in the area is from Jwaneng Wellfield, groundwater level decline in the wellfield is less than from Gaotlhobogwe Wellfield where only a third of the abstraction volume of Jwaneng Wellfield is taking place, confirming the high transmissivity values of the Ecca aquifer in the Jwaneng Wellfield.

The successful calibration of the transient model, using model parameters generated from field measurements and investigations increase the level of confidence in using the numerical model to make predictions on the impact and aquifer behaviour to long-term groundwater abstraction from established wellfields.

Update of the numerical model with data from 2009-2011 would be useful in calibrating the remaining years of the modelled period. This will not alter the calibration results achieved so far but will increase accuracy of the starting heads in the predictive model used to simulate groundwater abstraction from 2012-2020.

8.6.4 Transient Model Sensitivity Analysis

To assess the degree and uncertainty in the calibrated transient model, a sensitivity analysis was performed in the model. This was done by systematically changing the optimized specific yield (Sy) and observing changes in drawdown at two selected boreholes at Malwelwe (BH6825) and Gaotlhobogwe (BH6875). For this model, 1%, 5%, 50% and 200% of the optimized specific yield was applied and the resulting drawdown was compared. The drawdown–time curves at boreholes BH6825 and BH6875 as a result of changing the specific yield was plotted as shown of Figure 8.15 and Figure 8.16.

The results of sensitivity analysis on specific yield and the results are summarised in Table 8.7 below.

Table 8.7 Transient Sensitivity Analysis Results

		Maximum Transient Drawdown				
Wellfield	**Borehole**	**Sy - Optimised**	**D.down at Sy - 1%**	**D.down Sy - 5%**	**D.down Sy - 50%**	**D.down Sy - 200%**
Malwelwe	BH6825	16.50	22.10	22.09	19.05	13.74
Gaotlhobogwe	BH6875	10.42	12.65	12.80	11.74	8.88

- The results show that a 50 % decrease in the optimized specific yield will increase the drawdown in Malwelwe and Gaotlhobogwe by 2.55m and by 1.32m respectively.

- Increasing the specific yield at both Malwelwe and Gaotlhobogwe by 50 % reduces the drawdown due to more groundwater introduced into the aquifer.

- During the pumping period-1 (2012 – 2016) the water levels at Malwelwe Wellfield (BH 6825) recover by 5m due to the reduction of pumping at Gaotlhobogwe from 24hours to 15 hours per day.
- Pumping period-2 (2017 – 2021) water levels at Malwelwe (BH 6825) decline by less than 5m.

- At Gaotlhobogwe (BH 6875) the drawdown is reduced from about 10m during the transient state to less than 5m during pumping Period -1 (2012 – 2016) due reduced pumping from 24hours/day to 15 hours/day.

8.7 Predictive Modeling

The objectives of the predictive modeling were;

- To simulate groundwater abstraction from Jwaneng Wellfield, Gaotlhobogwe Wellfield, and Malwelwe Wellfield to the year 2020.

- To assess the potential of each individual borehole in meeting the demand growing water demand for Molepolole, Thamaga and the BDF Air Base to the year 2020.

- To verify the recommended abstraction rates interpreted from test pumping data by numerical groundwater modelling.

- To assess the potential of the groundwater resources in meeting the projected water demand.

- Assess the overall regional groundwater flow regime as a result of abstraction to 2020.

Five scenarios were designed to assess various pumping scenarios to meet water demand for Molepolole, Thamaga, BDF Air Base and other local demand centres. The scenarios were also designed to assess interference between Jwaneng Wellfield and Gaotlhobogwe/Malwelwe Wellfields. The scenarios were simulated to the year 2020 planning horizon from 2012 (See Table 8.8).

Table 8.8 Predictive Model Scenarios

Scenario	Description	Pumping Design	Comment
1	Meet water demand growth for Molepolole, Thamaga and BDF Air Base system to 2020.	Pumping from both Malwelwe and Gaotlhobogwe Wellfields optimising recommended abstraction rates. Pumping each borehole at most 15 hours/day to meet a demand of 15,754m^3/d in 2012-2020 and 18,006m^3/d in 2017-2020.	Assess interference between Jwaneng and Gaotlhobogwe/Malwelwe
	Jwaneng abstracts at 11.7Mm^3/yr		
2	Meet water demand growth for Molepolole system and 10% additional water demand. Jwaneng increasing pumping from wellfield by 50%	Assess possibility of all boreholes pumping a maximum of 15 hours a day	Assess interference between the two wellfields due to double Jwaneng mine increases water abstraction to meet demand for CUT 8 project
3	Meet predicted demand growth for Molepolole system	All abstraction to come from Malwelwe Wellfield, with no pumping in Gaotlhobogwe	Stopping abstraction in Gaotlhobogwe Wellfield will allow water levels to recover
	Jwaneng abstracts at 11.7Mm^3/yr		
4	Meet predicted demand growth for Molepolole system	Abstraction to meet demand to come from Gaotlhobogwe Wellfield and Malwelwe to be phased in to meet shortfall	Save immediate costs of developing a new wellfield and develop the wellfield infrastructure in Malwelwe in phases as when required
	Jwaneng abstracts at 11.7Mm^3/yr		
5	Meet predicted demand for Molepolole system to 2020	Both Gaotlhobogwe and Malwelwe Wellfields to meet water demand of 15,794m^3/d from 2012-2016. From 2017, NSC will come into effect supplying 15,252m3/d	NSC predicted to come in 2017
	Jwaneng abstracts at 11.7Mm^3/yr		With NSC supplying 15,252m3/d, a deficit of 5148m3/d will be created from a demand of 18,006m3/d. This can be met from the wellfield or NSC can supply meet the total demand.

8.7.1 Water Demand and Borehole Abstraction Rates

Water Demand

Based on population growth figures, the water demand for Molepolole with its associated villages and Thamaga will rise from 15,000m^3/d in 2011 to 18,000m^3/d by 2020. Table 8.9 shows the water demand figures based on population growth. This water demand will be met from Gaotlhobogwe and Malwelwe Wellfields.

Table 8.9 Water Demand Growth to 2020

Molepolole & Thamaga Water Demand (m^3/day)

2012- 2016	2017- 2021
15,754	18,006

For all the five scenarios, the maximum abstraction rate of 11,700,000m^3/yr (32,111m^3/d) for Jwaneng Wellfield boreholes will be used in all the scenarios, except in scenario 2 where the demand from Jwaneng Wellfield is estimated to increase by 50% (17,580,000m^3/yr i.e. 48166m^3/d) due to water demand from CUT 8 project.

Borehole Abstraction Rates

Table 8.10 shows the recommended abstraction rates for all the production boreholes in Gaotlhobogwe and Malwelwe Wellfields that will be simulated to meet the projected water demand to 2020. Daily pumping volumes for 15 hours, 18 hours and 24 hours have been calculated.

Table 8.10 Abstraction rates for Gaotlhobogwe and Malwelwe Wellfield Production Boreholes

Wellfield	Borehole Number	Q (m^3/hr)	Daily Pumping rates (m^3/day)		
			15 hours	18 hours	24 hours
Gaotlhobogwe	10551	15	225	270	360
	7864	12	180	216	288
	10553	57	855	1026	1368
	8132	60	900	1080	1440
	9574	12	180	216	288
	10550	62	930	1116	1488
	9572	18	270	324	432
	9571	18	270	324	432
	7966	42	630	756	1008
	10549	24	360	432	576
	6875	98	1470	1764	2352
	9379	100	1500	1800	2400
	10343	20	300	360	480
	10344	15	225	270	360
Malwelwe	10746	70	1050	1260	1680
	10671	20	300	360	480
	10748	20	300	360	480
	10749	35	525	630	840
	10751	70	1050	1260	1680
	10752	30	450	540	720
	10754	100	1500	1800	2400
	10784	12	180	216	288
	6824	80	1200	1440	1920
	6825	100	1500	1800	2400
	6826	40	600	720	960
	6827	90	1350	1620	2160
	6828	25	375	450	600
	6830	100	1500	1800	2400

8.7.2 Predictive Modeling Results

The predictive modelling was divided into 2 stress periods.

- Stress period 1 – from 2012 to 2016 with 5 time steps representing each year

- Stress period 2 –from 2017-2020 with 4 time steps representing each year

Drawdown was calculated from 2012 to 2020 for each production borehole in Malwelwe and Gaotlhobogwe Wellfields. For Jwaneng Wellfield, the maximum drawdown within the wellfield has been given as the resultant drawdown for each scenario. Details of abstraction rates for different scenarios are in the Groundwater Resources Modeling – Technical Report No:-4.

Scenario-1 Results

In this scenario abstraction to meet demand comes from both Malwelwe and Gaotlhobogwe Wellfield. Due to low abstraction rates in Gaotlhobogwe boreholes, 57% of the boreholes are shut off and the remaining 6 pumping boreholes have abstraction rates reduced, with each borehole pumping a maximum of 15 hours. Abstraction rates from production boreholes used to simulate abstraction to meet water demand for Scenario 1. In this scenario, abstraction has been recommended from high yielding boreholes, with low yielding boreholes introduced gradually to offset water demand in the successive stress period.

Water levels will recover in some boreholes in Gaotlhobogwe Wellfield as a result of reduction in abstraction rates due to introduction of Malwelwe Wellfield. New boreholes in Gaotlhobogwe Wellfield- BH10549, BH10550 and BH10551 which were pumping 1300m^3/d to 1700m^3/d to 2011 have daily abstraction rates reduced to 400m^3/d resulting in water level recovery. Gaotlhobogwe Wellfield recovers by 22m. In Malwelwe, maximum drawdown is 14m, with maximum drawdown of 5m in Jwaneng Wellfield. A summary of Scenario-1 predictive modeling results is as shown in Table 8.11.

Table 8.11 Drawdown Results for Scenario 1

Wellfield	Maximum Drawdown (m)	Comments
	2012-2020	
Gaotlhobogwe	1	Recovery of water levels in due to introduction of Malwelwe 57% of the boreholes switched off and in others abstraction rates reduced.
		Water levels in Gaotlhobogwe Wellfield recover by 16m
		Drawdown footprint shows minimal interference between the wellfields.
Malwelwe	16	Drawdown in Malwelwe between 8-16m
Jwaneng	5	Drawdown rate in Jwaneng maintained at approximately 0.5m/yr

Scenario-2 Results

Scenario 2 simulates abstraction from both Malwelwe and Gaotlhobogwe Wellfields to meet demand, with an increase of 50% in abstraction from Jwaneng Wellfield and a 10% increase in the water demand for Molepolole and Thamaga.

Water levels will recover in some boreholes in Gaotlhobogwe Wellfield as a result of reduction in abstraction rates due to introduction of Malwelwe Wellfield. In this scenario water level recovery in Gaotlhobogwe is 5m less than in scenario 1 as a result of increase abstraction by 10%. In Malwelwe Wellfield, maximum drawdown in Scenario 2 is 17m and 18m in Jwaneng Wellfield, see Table 8.12.

Table 8.12 Drawdown results for Scenario 2

Wellfield	Maximum Drawdown (m)	Comment
	2012-2020	
Gaotlhobogwe	-11	Recovery of water levels due to introduction of Malwelwe.
Malwelwe	17	Incremental drawdown of 1m than in scenario1 due to 10% increase in abstraction.
Jwaneng	18	Increasing abstraction by 50% in Jwaneng will result in increase the drawdown from 5m in scenario 1 to 18m in scenario 2.
		No impact on Gaotlhobogwe Wellfield

Scenario-3 Results

In Scenario 3, all the demand to 2020 will be met from Malwelwe Wellfield and resting Gaotlhobogwe Wellfield to allow for recovery. Due to increased abstraction from Malwelwe boreholes, all boreholes pump a minimum of 20 hours from 2012-2016 and 22-24 hours from 2017 to 2020.

Due to non abstraction in Gaotlhobogwe Wellfield, water levels will recover by an average of 35m by 2020. Due to increase abstraction from Malwelwe Wellfield, drawdown will increase to 23m, with the minimum drawdown being 11m, the highest drawdown in Gaotlhobogwe Wellfield from all the scenarios. Maximum drawdown on Jwaneng will be 5m see Table 8.13.

Table 8.13 Drawdown results for Scenario 3

Wellfield	Maximum Drawdown (m)	Comment
	2012-2020	
Gaotlhobogwe	-35	Recovery of water levels due to introduction of Malwelwe.
Malwelwe	23	Highest drawdown of all the scenarios
Jwaneng	5	Similar with scenario 1,4 and 5

Scenario-4 Results

In Scenario 4, all the demand to 2020 will be met from Gaotlhobogwe Wellfield with deficit in each successive year augmented from Malwelwe Wellfield. All boreholes in Gaotlhobogwe Wellfield pump for 24 hours.

Maximum drawdown in Gaotlhobogwe Wellfield will be 26m in 9 years, a rate of 2.8m/yr. Contribution from Malwelwe Wellfield will be between 3000m^3/d to 4800m^3/d, with Gaotlhobogwe supplying between 14000m^3/d to 15000m^3/d. Table 8.14 shows drawdown results from scenario 4.

Table 8.14 Drawdown results for Scenario 4

Wellfield	Maximum Drawdown	Comment
	2012-2020	
Gaotlhobogwe	26	Recovery of water levels due to introduction of Malwelwe.
Malwelwe	7	General drawdown 4m and maximum 7m at pumping boreholes
Jwaneng	5	Jwaneng Wellfield will not be affected by pumping in Gaotlhobogwe or Malwelwe

Scenario-5 Results

In Scenario 5, the NSC is envisaged to be ready to supply Molepolole and Thamaga from 2016. The estimated supply from NSC is 15,252m^3/d. Water demand of 15,754m^3/d for 2012-2016 will be met from both Malwelwe and Gaotlhobogwe Wellfields. From 2017 to 2020, demand will be met from the NSC supplying 15,252m^3/d to meet a demand of 18,006m^3/d and this will create a deficit of 2,754m^3/d to be met from the wellfields. Alternatively all the supply will come from the NSC and the wellfields will provide back up for the NSC.

Water levels in Gaotlhobogwe will recover fully by 2020, with no drawdown impact in Malwelwe Wellfield. Recovery in Gaotlhobogwe will by 20-47m in 2020 with an average recovery of 35m. Drawdown in Jwaneng Wellfield will be 5m see Table 8.15.

Table 8.15 Drawdown results for Scenario 5

Wellfield	Maximum Drawdown	Comment
	2012-2020	
Gaotlhobogwe	-35 (-20 - -47)	Full recovery in Jwaneng and Malwelwe Wellfields
Malwelwe	0	
Jwaneng	5	Drawdown in Jwaneng will be 5m

8.7.3 Evaluation of maximum available drawdown and total drawdown from modelled Scenarios.

To evaluate the sustainability of each borehole in each scenario to meet the required water demand, the available drawdown for each borehole has been calculated to enable comparison of available drawdown with modelled drawdown. For Malwelwe Wellfield where pumping has not taken place, the full available drawdown has not been yet utilised. In Gaotlhobogwe Wellfield, pumping has been taking place from 1995 and part of the available drawdown has already been utilised. The available drawdown for Gaotlhobogwe is then based on the remaining available based on current water levels at the end 2011. Available drawdown (ADD) is calculated as:

ADD = WS-RWL +0.5*SAT, where *ADD* is available drawdown, *WS* is depth to water strike in mbgl and *RWL* is static/rest water level in mbgl.
The water strike is at the contact of the top of the Ecca aquifer and the confining mudstone layer. This definition means water levels can only be lowered from the confining head level above the top of the aquifer to the middle (half thickness) of the saturated aquifer thickness and avoids complete dewatering of the aquifer.

Table 8.16 and Table 8.17 show available drawdown for Malwelwe and Gaotlhobogwe Wellfields. The tables show that since Malwelwe Wellfield has not yet been utilised, available drawdown ranges from 78m to 160m. In Gaotlhobogwe Wellfield, most of the drawdown has been utilised and available drawdown ranges from 49m to 98m, with only one borehole BH8132 with an available drawdown of >100m (127m).

Table 8.16 Available drawdown for Malwelwe boreholes

BH No	SWL (mbgl)	Water strike (mbgl)	Confining Head (mamsl)	Top of Aquifer (mbgl)	Bottom of Aquifer (mbgl)	Aquifer thickness (m)	Available Drawdown (m)
6824	58.42	103	44.58	103	246	143	**116**
6825	60.51	109	48.49	109	245	136	**117**
6826	56.97	209	152.03	209	242	33	**169**
6827	56.27	132	75.73	132	235	103	**127**
6828	72.60	134	61.40	134	195	61	**92**
6829	71.12	130	58.88	130	205	75	**96**
6830	49.87	70	20.13	70	185	115	**78**
10746	65.43	147	81.57	147	283	136	**150**
10747	67.84	102	34.16	102	170	68	**68**
10748	53.96	120	66.04	120	166	46	**89**
10749	56.10	112	55.9	112	283	171	**141**
10751	63.44	88	24.56	88	273	185	**117**
10752	63.00	143	80.00	143	296	153	**157**
10754	73.36	152	78.64	152	310	158	**158**
10784	72.00	146	74.00	146	291	145	**147**

Table 8.17 Available drawdown for Gaotlhobogwe boreholes

BH No	SWL (2011) (mbgl)	Water strik (mbgl)	Confining Head (mamsl)	Top of Aquifer (mbgl)	Bottom of Aquifer (mbgl)	Aquifer thickness (m)	Available Drawdown (m)
6875	26	48	22	48	102	54	49
7864	54	55	1	55	172	117	59.5
7966	60	76	16	76	148	72	52
8132	80	96	16	96	319	223	127.5
9379	30	48	18	48	100	52	44
9571	91	116	25	116	193	77	63.5
9572	73	90	17	90	178	88	61
9574	106	88	-18	88	208	120	42
10551	72	83	11	83	210	127	74.5

10550	64	101	37	101	224	123	98.5
10549	62	88	26	88	223	135	93.5
10553	36	54	18	54	215	161	98.5
10643	28	54	26	54	200	146	99
10644	69	86	17	86	130	44	39

8.7.4 Comments on the Predictive Model

The predictive model has been undertaken based on transient model calibration results which optimised storage coefficient values for the predictive model to enable making predictions on drawdown impacts from Gaotlhobogwe and Malwelwe Wellfields abstraction to meet water demand.

Five scenarios were designed to evaluate impact of groundwater abstraction from:

- Combined Gaotlhobogwe and Malwelwe Wellfields
- Malwelwe Wellfield only
- Gaotlhobogwe supplying 84% of the water demand and deficit coming from Malwelwe
- Introducing NSC from 2017
- Increasing abstraction in Jwaneng Wellfield by 50%

All the scenarios revealed that effective management of Gaotlhobogwe Wellfield will require reducing the pumping hours for all the production boreholes to at most 15 hours per day. This can only be achieved through a combination of groundwater abstraction from Malwelwe and Gaotlhobogwe Wellfields.

The model reveals that Gaotlhobogwe Wellfield cannot be pumped for 24 hours a day, the best practice will be to pump each borehole a maximum of 15 hours as this allows the aquifer to start recovering from present water levels.

The model shows Malwelwe Wellfield has good potential groundwater resources. Scenario 3 which simulated abstraction from Malwelwe Wellfield only showed at the current recommended borehole abstraction rates, the wellfield will not meet all the demand to 2020 pumping each borehole for 24 hours.

However only 25% of the available drawdown would have been utilised, indicating the abstraction rates can be increased to utilise available drawdown, thereby meeting the predicted water demand.

This will however require groundwater monitoring before recommended abstraction rates can be increased.

The total available production boreholes between the two wellfields are 26 and this allows variation of pumping system and provides back-up for downtime in other boreholes.

The recommended abstraction scenario is Scenario 1 which utilises both wellfields, as this allows Gaotlhobogwe Wellfield to recover and Malwelwe Wellfield does not abstract at 24 hours a day.

8.7.5 Modelling Conclusions and Recommendations

The present findings regarding the Ecca groundwater resources are based on the amount and quality of data currently available. Future projects in the area will assist in gaining a better understanding of the resource and in subsequent upgrading of the present hydrogeological and numerical models. Nonetheless, the present findings are regarded as accurate and as realistic as the data set will allow, and will serve as a reliable reference for future work.

General conclusions that can be drawn from the numerical modelling exercise are itemised below.

- The groundwater resources of the Ecca are better in a structurally disturbed Karoo sedimentary basin where structures have a great influence on groundwater quality distribution (both vertically and spatially), piezometry and groundwater flow regime.

- Future investigations that could contribute to the numerical model should verify nature, mechanism and quantity of groundwater recharge and evapotranspiration along the Gaotlhobogwe valley.

- Calibration of the steady state model has been achieved through calibration of recharge and evapotranspiration against known values of transmissivity obtained from extensive groundwater exploration and investigation studies carried out in the area.

- By fixing transmissivity and inflow at the boundaries, uncertainties in the model are reduced with degrees of freedom allowed only on the recharge and evapotranspiration to the aquifer system.

- The set of transmissivity values used to calibrate the model optimised the recharge value of 15mm/yr along Gaotlhobogwe valley. Recharge rates estimation has been problematic in Botswana with estimated rates highly variable. Rates optimised by WSB, 2009 were less than 1mm/yr. These rates were based on a model calibrated with hydraulic conductivity of 0.24m/d (T of 8.2m^2/d for layer 4, 34m thick) to 13m/d (maximum T of 1,425m^2/d for layer 3, 155m thick) representing layer 3 and 4 of the model for upper and lower Ecca aquifer. (WS B2009). The transmissivity values are within the range of values and agree with optimised values for the current model, but the current model would not optimise such low recharge with the modelled transmissivity values.

- Use of hydraulic conductivity to calibrate the model has resulted in a simple zonation, with only 3 zones optimised for the whole model area. Calibrating the model with hydraulic conductivity allows for the aquifer to vary transmissivity, which is important for transient model to avoid over-estimating resources where transmissivity is otherwise used and remains constant.

- Analytical solution used to estimate inflow from the basement high to the south and east gave a daily inflow rate of 13,210m^3/d. This inflow rate was used to calibrate hydraulic conductance at the inflow boundary and an inflow rate of 12,610m^3/d was obtained.

- Using the analytical solution to estimate inflow at the boundary also reduced the degrees of freedom of unknown terms in the model, thereby increasing confidence level in the model calibration results.

- The transient state model was used to simulate long-term water level and abstraction data gathered from the wellfields and other boreholes identified in the Project Area.

- Storage coefficient values determined from test pumping data interpretation have been successfully used in the transient model calibration to simulate measured groundwater abstraction and water level fluctuations as a response to the abstraction.

- The transient model calibration increases the level of confidence in the numerical groundwater model used to represent the hydrogeological system of the Ecca aquifer within the modelled area.

- Optimised hydraulic conductivity, out fluxes and influxes calibrated from the steady state model have been confirmed to from the transient calibration model to accurately represent the set of parameters optimised to generate observed groundwater abstraction and water level fluctuations.

- Although the biggest abstraction rate in the area is from Jwaneng Wellfield, groundwater level decline is less than water level decline in Gaotlhobogwe Wellfield where only a third of the abstraction volume of Jwaneng Wellfield is taking place. This confirms the high transmissivity values of the Ecca aquifer in the Jwaneng Wellfield.

- The successful calibration of the transient model, using model parameters generated from field measurements and investigations increase the level of confidence in using the numerical model to make predictions on the impact and aquifer behaviour to long-term groundwater abstraction from established wellfields.

- Update of the numerical model with data from 2009-2011 would be useful in calibrating the remaining years of the modelled period. This will not alter the calibration results achieved so far but will increase accuracy of the starting heads in the predictive model used to simulate groundwater abstraction from 2012-2020.

The predictive modelling has been undertaken based on transient model calibration results which optimised storage coefficient values for the predictive model to allow predictions on drawdown impacts from Gaotlhobogwe and Malwelwe Wellfields abstraction to meet water demand.

Five scenarios were designed to evaluate impact of groundwater abstraction from:

- Combined Gaotlhobogwe and Malwelwe Wellfields
- Malwelwe Wellfield only
- Gaotlhobogwe supping 84% of the water demand and deficit coming from Malwelwe
- Introducing NSC from 2017
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All the scenarios revealed that effective management of Gaotlhobogwe Wellfield will require reducing the pumping hours for all the production boreholes to at most 15 hours per day. This can only be achieved through a combination of groundwater abstraction from Malwelwe and Gaotlhobogwe Wellfields.

- The model reveals that Gaotlhobogwe Wellfield cannot be pumped for 24 hours a day, the best practice will be to pump each borehole a maximum of 15 hours as this allows the aquifer to start recovering from present water levels.

- The model shows Malwelwe Wellfield has good potential groundwater resources. Scenario 3 which simulated abstraction from Malwelwe Wellfield only showed at the current recommended borehole abstraction rates, the wellfield will not meet all the demand to 2020 pumping each borehole for 24 hours.

- However only 25% of the available drawdown would have been utilised, indicating the abstraction rates can be increased to utilise available drawdown, thereby meeting the predicted water demand.

- This will however require groundwater monitoring before recommended abstraction rates can be increased.

- The total number of available production boreholes between the two wellfields is 26 and this allows variation of pumping clusters and provides back-up for downtime in other boreholes.

- The recommended abstraction scenario is Scenario 1 which utilises both wellfields, as this allows Gaotlhobogwe Wellfield to recover and Malwelwe Wellfield is not pumped at 24 hours a day.

9. GROUNDWATER RESOURCES DEVELOPMENT STRATEGY

9.1 Proposed Abstraction Areas and Potential Demand

The Malwelwe potable groundwater resources have been re-evaluated in the central zone of the Project Area and nine (9) new production boreholes have been drilled. It was envisaged that these would be an ‘add on’ to the 6 production boreholes developed some 20 years by BRGM and suitable wellfield infrastructure to utilise all these site is to be developed.

The total number of production boreholes in the Malwelwe Wellfield is 15 production boreholes.

To the north of the Zoetfontein Fault on the Lebung/ Ntane a separate new wellfield has been defined and partially initiated though not fully investigated. The Lebung/ Ntane aquifer is centred on Sorilatlholo and 11 boreholes are available for water supply. Six of these boreholes were drilled as exploration boreholes and the rest (5) were drilled as production boreholes with a 10 inches completion diameter.

Malwelwe and Sorilatlholo Wellfields are some 60km apart and when the current exploration and development programme started the development approach was focused on Malwelwe. The engineering considerations in determining the preliminary design proposals and budget cost estimates as specified in the ToR was thus also only focussed on Malwelwe.

Of significant importance in this engineering aspect of the project has been the estimation of future water demand at each of the three major population centres of Molepolole, Thamaga and the BDF air base to be served by the new system.

In addition, other local demands in villages and farmer’s cattle posts have been accommodated in the resources evaluation process. It has been assumed that the proposed Sorilatlholo Wellfield will be used (at least initially) to supply the medium to small villages in the immediate area.

Thus in assessing the resource capabilities only the estimated demands and abstraction requirements for the Gatlhobogwe, Malwelwe and Jwaneng Northern Wellfields have been evaluated using a newly developed numerical model. The results of this component of the project are presented in detail in Technical Report No. 4. Groundwater Resources Modelling Report.

Major findings in relation to incorporating the additional production boreholes into the sub-regional supply system are:

- That from onset all existing production boreholes in Gaotlhobogwe and Suping Wellfield are reduced to pump only for a 15 hr/day at the recommended abstraction rate.
- These reduced pumping hours (15hrs/day) are recommended to allow for aquifer recovery and this is achievable if the new Malwelwe production boreholes are in place.
- The timing of introducing new production boreholes into the supply system should be governed by monitoring the demands at the supply centres.
- 2 years has been envisaged as the time that will elapse before the production boreholes drilled under the current project come into operation.

9.2 Design Criteria

The following overall criteria have been considered in the preliminary system design:

- flexibility of operation and ease of maintenance
- robustness and reliability of plant
- standardisation of plant and equipment
- cost effectiveness

The Malwelwe system configuration consists of the following:

- ➢ A total of 12 production boreholes (both existing and newly drilled), set out as distributed in Map 2.
- ➢ Each borehole will be equipped with a submersible pump set at a depth consistent with pump operation.
- ➢ New collector mains totalling 46.95km from the boreholes to a raw water collector tank near Malwelwe village before boosting it to Serinane.

Full details of the preliminary design and costing exercise summarised below are contained in Technical Report No. 6, Engineering and Costs Estimates Report.

9.2.1 Borehole Equipment and Pumping Rates

- It is envisaged that supply from operating production boreholes will be required for a maximum of 15 pumping hours per day.

- Only manual operation has been considered, although it is suggested that with the scale of wellfield expansion and accessibility constraints an automated control and operation system may now be much more viable.

- Boreholes will be equipped whenever possible with standard borehole pumps.

- Each borehole will pump at rates consistent with the drawdown characteristics of each hole into collector mains sized to be economical for the various pumping installations.

- Collector mains will discharge into larger transmission mains and the larger transmission mains will discharge directly into raw water collector tanks near Malwelwe village .

9.2.2 Storage Reservoirs

- Sufficient storage reservoir capacity has been provided to ensure that shortfalls in supply are avoided and peak demands are met, and to enable pumps to perform uniformly under balanced flow conditions.

- Provision of adequate operational storage will allow pumps to operate continuously without frequent on-off cycles. The system will be able to maintain adequate suction head on the pumps and meeting the water supply required, thereby saving wear and tear on control equipment normally associated with intermittent starting, and thus minimising maintenance costs.

- Reservoir sites will be determined depending on site geology, accessibility, availability of electrical services, the cost of land, gravity flow and hydraulic considerations, and applicability for reservoir overflows and other discharges.

- For ease of operation and taking the Malwelwe distance to Serinane, collector reservoirs inside the wellfield area are proposed.

- Storage reservoirs are of water-retaining reinforced concrete construction, circular in plan, with a reinforced concrete roof, complete with the necessary access manholes and ventilators in order to effect ease of inspection and maintenance.

- The capacity of the reservoirs should be kept to the absolute minimum in order to reduce retention times consistent with turn-over of fresh water. Should additional capacity be required for future expansion, further reservoirs could be constructed on a modular basis.

9.2.3 Transmission Pipelines

The following items have been considered in the development of transmission pipeline design criteria:

- Alignment and route selection have been done in such a manner as to avoid conflicts. Other surface and subsurface facilities in the Malwelwe village are to be accommodated during construction.
- Availability of bedding and backfill material along pipeline routes,
- Pipeline materials,
- Pipe pressure classes,
- Pipe fittings and specials including air release valves, inline valves and washouts,
- Road, utility and wetland crossings,
- Metering facilities, and
- Hydraulic design.

Hydraulic design of the pipelines has accounted for hydraulic issues such as pipe sizing to keep velocities and pressures within designated ranges, transient pressures, friction losses and economic considerations.

9.2.4 Water Quality

- No on-site treatment of the groundwater supply is envisaged to be necessary.
- Materials for pumps and pipeline construction should be selected to minimise the wear and tear normally associated with slightly corrosive waters (see Technical Report No. 5, Hydrochemistry and Recharge).

9.2.5 Power Supply

- Existing BPC power line will need to be extended or and may need to be upgraded to supply the proposed new wellfield.
- Within the wellfield, tertiary power in the form of overhead lines on wooden poles should follow the routes of the access roads to supply the individual borehole pumps.

- A telemetry operating system could then be considered for the wellfield thereby saving the wear and tear on control equipment normally associated with intermittent starting, and thus minimising maintenance costs.

9.2.6 Reticulation

- Materials of reticulation construction should be able to withstand the slightly corrosive nature of the water being pumped, and any possible corrosive Kalahari superficial sand conditions.
- The reticulation pipe-work linking boreholes to the storage reservoir should, as far as is practical, be set out so that during normal operation a minimum number of boreholes will discharge into anyone length of pipe-work at a time. On this basis, pipe diameters can be optimized and standardized to create uniform flow conditions. Pressures in the system can then also be balanced, and by a careful choice of pipe material, friction losses, and thereby pumping costs, can also be minimized. The common practise in DWA is that standardiszed uPVC is used and only the sizes can be varied.

9.3 Preliminary Design Specifications

9.3.1 Pumping Plant

It is assumed that, within minor limits, the depth of the pump setting in each borehole will be approximately the same. Discharge characteristics should, therefore, be very similar, and should allow the standardization of borehole pumping equipment.

Preliminary design has been based on the general specifications for a multistage, centrifugal, electric submersible pump capable of discharging a maximum average flow of 125 m^3/hour maximum against a total static and dynamic head of 160 metres. Pump and motor should be of stainless steel construction for long life application.

9.3.2 Pump Duties

Preliminary design has been based on the recommended discharge rate from each borehole in Malwelwe Wellfield over a 15 hour pumping day. The theoretical maximum delivery capacity of the expanded wellfield systems is thus 11,880m^3/day.

However, it has been decided to reserve BH 10748 (20m^3/hr) and BH 10784 (12m^3/hr) for supply to Malwelwe, Ngware and Botlhapatlo villages. This leaves a total of **11,400m^3/day** for supply to Molepolole, Thamaga and the BDF Camp.

This delivery rate have been beset as the maximum operational limit of the wellfield in order to minimize the risk of excessive abstraction, which may result in unacceptably high drawdown and possible long-term deterioration in aquifer performance.

For the purposes of preliminary design, the proposed pump settings, abstraction, new collector mains and raw storage reservoir capacity have been determined on this premise. Table 9.1 below details both pump setting and the recommended abstraction rates of both the new and the old production boreholes.

Table 9.1 Recommended Development Details for Malwelwe Wellfield Boreholes

BH No.	X coord	Y coord	Depth (m)	Rest Water Level (m)	Recommended Pump Setting Depth (m)	Available drawdown (m)	Recommended Abstraction Rate (m^3/hr)	Pumping period (hrs)	Recommended Daily Abstraction (m^3/day)	Water Delivery Point
10746	323127	7349325	280	65.2	150	85	**70**	15	1050	To Molepolole/Thamaga via Serinane Pumping Station
10748	331580	7350840	177	67.0	150	83	**20**	15	300	To Ngware and Botlhapatlou Villages
10749	325763	7354404	291	56.4	150	94	**35**	15	525	To Molepolole/Thamaga via Serinane Pumping Station
10751	332580	7350840	281	61.5	90	27	**100**	15	1500	To Molepolole/Thamaga via Serinane Pumping Station
10752	321293	7348837	300	61.3	180	118	**30**	15	450	To Molepolole/Thamaga via Serinane Pumping Station
10754	327027	7348371	310	72.3	150	78	**100**	15	1500	To Molepolole/Thamaga via Serinane Pumping Station
10784	321211	7351035	300	70.4	180	110	**12**	15	180	To Malwelwe and Marotswane Villages
10671	323627	7345632	174	58.0	150	82	**20**	15	300	To Molepolole/Thamaga via Serinane Pumping Station
6824	318997	7345934	246	59.8	98	33	**80**	15	1200	To Molepolole/Thamaga via Serinane Pumping Station
6825	321370	7346340	235	61.8	100	33	**100**	15	1500	To Molepolole/Thamaga via Serinane Pumping Station
6826	317896	7345895	242	60.74	140	82	**40**	15	600	To Molepolole/Thamaga via Serinane Pumping Station
6827	314841	7345521	235	57.0	105	40	**90**	15	1350	To Molepolole/Thamaga via Serinane Pumping Station
6828	331851	7341522	210	75.44	125	47	**25**	15	375	To Molepolole/Thamaga via Serinane Pumping Station
6830	322964	7358486	193	50.0	140	15	**120**	15	1800	To Molepolole/Thamaga via Serinane Pumping Station
Total Recommended Daily Supply to Serinane Pumping Station (m^3/day)									**12,150**	

9.3.3 Access Roads

- Tertiary access roads linked to existing rural roads should be provided to each individual production borehole
- The routes of the tertiary access roads to individual boreholes should be set out on the same pattern as the collector mains and should run adjacent to them.

9.3.4 Proposed Collector and Transmission Network

Networks for the various supply centres are shown in diagrammatic form in Figure 9.1 and Figure 9.2 and are described in summary below:

Supply to Serinane

- The supply to Serinane Pumping Station will be from the Malwelwe Wellfield where 12 production boreholes have been developed with a combined yield of some 12,150m^3/day. This is adequate to augment Gaotlhobogwe Wellfield to satisfy the 2020 demand for Molepolole/Thamaga and the BDF Air Base which is estimated to be approximately 20,400m^3/day. The balance of supply (8250 m^3/day) is to be pumped from the existing Gaotlhobogwe, Suping and Ramapatlhe Wellfields.
- A series of collector pipelines in the Malwelwe Wellfield has been proposed to collect water from each borehole. The collector pipelines are then interconnected to transfer water from the wellfield to a raw water collector tank to be located on the southern outskirts of Malwelwe Village.
- From the raw water collector tank, the water will pass through a treatment plant which is being proposed to reduce the high levels of Iron and Total Hardness.
- From the treatment plant, the water will be pumped to a treated water tank before being pumped to Gaotlhobogwe Wellfield pump station from where it will be pumped to Molepolole with a branch feeding the BDF Camp.
- The transmission main from Malwelwe Wellfield to Gaotlhobogwe Wellfield has been designed with an oversized capacity of approximately 30% to accommodate future inputs from the wellfield as stipulated in the Terms of Reference.
- In order to reduce high friction losses in the transmission pipeline, velocities have been limited to 1.0m/s. This would result in a pipe diameter of 600mm. Ductile Iron is being proposed as the material of choice for the transmission pipeline.
- The existing transmission pipeline from Gaotlhobogwe Wellfield to Molepolole is a 500mm diameter Ductile Iron pipeline. Clearly, this pipeline is not adequate to transmit the combined flow from the two wellfields.
- The above scenario requires that the existing transmission pipeline needs to be upgraded to a larger diameter pipeline in order to enable it to carry design flows up to the design horizon of 2020.
- However, from a practical point of view, it would be better to construct a parallel pipeline to the existing pipeline. The additional pipeline would also require to be 600mm diameter to cater for the additional flow from Malwelwe Wellfield. The pipeline to BDF Camp will be maintained at the current size.
- From Molepolole, a portion of the water will be transferred to Thamaga.

Supply to Malwelwe

- Supply to Malwelwe will be from a new borehole BH10784 drilled close to the current pipeline from BH6830.
- BH 10784 has a production capacity of 12m^3/hr and at pumping period of 10hr/day or less it will meet the Malwelwe and Marotswane villages water requirement with a combined estimated demand of 45m^3/day
- Consequently, only one borehole will be available for supply. The old borehole BH4506 on the road to Letlhakeng will be a back up borehole to the local supply.

Supply to Ngware and Botlhapatlou

- Supply to Ngware and Botlhapatlou will be from BH10748
- BH10748 has a production capacity of 20m^3/hr and should meet the combined estimated demand of 70 m^3/day.
- Unfortunately there is no back up borehole available.

9.4 Engineering Budget Estimates

Estimates of capital costs tabulated below have been based on the preliminary design options proposed. **However, it must be stressed that at this stage of development these costs are estimates only and are meant solely to indicate the likely magnitude of finance involved for Client's guidance. These budget estimates must be further refined during subsequent more detailed design stages of the wellfield development as more accurate design specifications become available.**

Table 9.2 Capital Cost Estimates for the Proposed Malwelwe Wellfield Development

No.	DESCRIPTION	AMOUNT (PULA)
1	**Borehole Collector Network** *(Including excavations including rock excavation, bedding and backfilling, pipe laying and testing, manholes, valve chambers, valves and fittings, river and road crossings).*	**28,849,579**
2	**Transmission Mains** *(Including excavations including rock excavation, bedding and backfilling, pipe laying and testing, manholes, valve chambers, valves and fittings, river and road crossings).*	**160,000,000**
3	**Borehole Equipping and Development** *(Including borehole houses, borehole pumps, pipework and control systems).*	**4,000,000**
4	**Storage Reservoirs** *(Including excavations, structural concrete, and installation of and pipework,) for Raw Water Collector Tank and Treated Water Tank.*	**6,000,000**
5	**Treatment Plants** *(Including excavations, superstructure, structural concrete, building works, installation of pumping equipment and pipework).*	**6,000,000**
6	**Pump Stations** *(Including excavations, superstructure, structural concrete, building works, installation of pumping equipment and pipework).*	**6,000,000**
7	**Land Acquisitions/Compensations**	**500,000**
8	**Relocation of Existing Services**	**500,000**

9	**Operator's Housing**	**130,000**
8	**BPC Power Supply**	**2,000,000**
	SUB-TOTAL	**213,979,579**
9	**Contractor's Preliminary and General Items** *(Including Contractor's and Engineer's establishment, site supervision, insurance, material testing etc.) – 10% of Capital Costs*	**21,397,958**
10	**Engineer's Supervision Costs**	**4,850,000**
	SUB- TOTAL	**240,227,537**
	Add 7.5% Contingencies	**18,017,065**
	SUB- TOTAL	**258,244,602**
	Add 12% VAT	**30,989,352**
TOTAL		**289,233,954**

9.5 Groundwater Resources Protection

9.5.1 Groundwater Vulnerability

Groundwater vulnerability and the definition of groundwater protection zones involves evaluation of the degree of exposure of groundwater resources to pollution. The vulnerability depends on, but not limited to the following major factors;

- type of soil and rock overlying the aquifer
- depth to water level
- depth to aquifer
- recharge rates and distribution
- degree of fracturing.

The groundwater vulnerability map produced from evaluation of these factors, together with evaluation of the pollution risk determined from such activities as agricultural, industrial, urban and waste disposal is important in demarcating protection zones where adverse effects to groundwater quality are curtailed.

Table 9.3 lists the above vulnerability factors and gives a qualitative vulnerability potential for each wellfield based on the prevailing hydrogeological and geological conditions of each parameter as established during the Project study.

Table 9.3 Groundwater Vulnerability within the Wellfields and Project Area

Factor	Prevailing conditions	Vulnerability		Comment
		Malwelwe Wellfield	Sorilatlholo Wellfield	
Nature of soil	The soil consists of loose Kalahari sand inter-layered with calcretised sand, calcrete and silcrete	High – sand Very low -cretes	High – and Very low -cretes	Although sand is permeable, layers of calcrete and silcrete within the sediments provide impermeable base below the sands. This is evidenced by the presence of a perched Kalahari aquifer in fossil river valleys with a calcrete base. Vulnerability is very low to the N but high on Karoo basin edges.
Soil Depth	Thickness of Kalahari varies from 2-20m within the area	Moderate -50m Very Low -50m	Moderate -<50m Very Low - >50m	
Overlying Strata	Both the overlying basalt and Kwetla Formation provides impermeable conditions with variable thicknrsses both on the Ntane and Ecca aquifers	Very low-nil but high in places where Kwetla FORMATION is absent	Low in thick basalt area but high where basat is absent and thin /fractured	Impermeable argillaceous units in Malwelwe Wellfield but S and SE edges are unprotected and direct recharge is evident. The same applies to Ntane but flow is to the N away from the targeted aquifer area.
Depth to Water Level	The depth to water level in the Malwelwe Wellfield is 56 - 75m, with depths of 42 - 97 m in Sorilatlholo Wellfield	Very low	Low-very low	Very low vulnerability
Depth to Aquifer	Depth to aquifer in the Malwelwe area is 88-152m. In Sorilatlholo Wellfield is 123-230m	Low-very low	Low-very low	Very low vulnerability
Recharge	Within the Project Area, direct recharge has been considered to be possible	Medium to low	Medium to low	Medium vulnerability in Malwelwe but Low in Sorilatlholo

Table 9.3 shows that all the factors listed above have little influence in increasing the groundwater vulnerability in the Project Area. Most of the factors except recharge show a low to very low outcome in terms of groundwater vulnerability since the nature of the overlying strata is generally impermeable and where the strata is permeable, the depth of the strata above the aquifer is quite thick (>80m).

In general, the groundwater vulnerability to pollution within the wellfields and the Project Area as a whole is regarded to be minimal given the prevailing geological and hydrogeological conditions.

9.5.2 Protection Zones

In terms of activities and developments within the designated Wellfield Areas it is proposed that the following general rules should be applied:

- Any additional private borehole drilling should be carefully controlled with respect to construction and allowed abstraction which must be approved by the Water Apportionment Board in accordance to the Water Act.

- Surface developments within the Wellfield Areas should be limited to developments that have low pollution potential. These should exclude agricultural developments using any chemicals, industrial developments involving chemical, bacteriological or organic waste or products, or infrastructure developments that may give rise to significant amounts of potential pollutants that are not correctly handled or disposed of.

- All development within the Wellfield Areas should be subject to the execution and approval (by DEA and Council) of an individual Environmental Impact Assessment in accordance with the EIA Act 2005 prior to any permission being given for the development.

- Existing grazing and cattle watering practices (assuming approved borehole construction and watering facilities are in place) within the Wellfield Area should be permitted to continue within the limits of the livestock carrying capacity of the land. Any additional cattle rearing activities only should be allowed within the limits of the carrying capacity and the provisions of the Borehole Act which limits the proximity of boreholes, and any intensive livestock rearing facilities should be subject to an approved EIA prior to implementation.

The above rules with respect to developments within the Wellfield Areas are for general guidance only. Specific guidance should be sought from the Environmental Impact Assessment Report on the Botlhapatlou Groundwater Exploration and Development Project prepared by Aqualogic Pty Ltd.

9.5.3 Wellhead Protection Zones

The study on wellhead protection zones (DWA, 1993) came up with 3 distinct zones of wellhead protection, viz,

Zone 1 – Inner Source Protection Zone (100 day travel time or 100m)
Zone 2 – Fracture Flow Protection Zone (1km radius from borehole)
Zone 3 – Outer Source Protection Zone (100 year travel time)

Zone 1

The innermost protection area is the Operational Courtyard, which comprises a small area of land around the borehole where any activities other than borehole maintenance and monitoring are prohibited. This inner zone is based on the distance equivalent to a specified horizontal flow-time for the prevention of pathogenic contamination of groundwater sources. The guidelines recommended a 100 day travel time, by which it is believed most pathogens would have been eliminated by natural process before reaching the borehole.

Within the Botlhapatlou Project Area, Zone 1 is the most applicable. Pollution risk is only envisaged at the borehole itself since poor borehole construction or damage to the sanitary seals can result in borehole pollution due to direct infiltration of pollutants through the annular space between the borehole and the formation or directly via the inner borehole space if casing material is broken.

The 100 day travel time has been simulated by running particle tracking for a 100 day backward tracking from the production boreholes and evaluating the travel distance generated from the path lines.

The last stress period of the predictive model, 2021 (Stress Period 13 – Scenario 1) has been used for the 100 day backward tracking as it shows the steepest groundwater gradients as well as the highest abstraction rates, thus the maximum travelling distance of particles of all the stress periods.

Figure 9.3 shows results of the 100-day travel time. The data shows that the maximum distance that can be demarcated from the wellfield for a 100 day travel time is < 100m from the wellfield. The time-mark along the particle path generated by the PMPATH Module when backward tracking stays in one position indicating that the particle travel distance falls within the dimensions of the model grid cell of 100m x 100m.

Zone 2

Zone 2 is regarded as the fracture flow zone where fractures are present and are hydraulically connected to the aquifer. Pathogens and contaminants can travel faster to the borehole especially under induced hydraulic gradients due to pumping than where the fractures are absent. This zone has been recommended as a radius of 1km to the borehole.

Due to the nature of the hydrogeological and geological environment, Zone 2 has been found to be unsuitable to simulate for the Botlhapatlou Project Area as there is not enough data on the local geometry of fractures and direct recharge to accurately perform particle tracking within the 1km radius from production boreholes.

Zone 3

This zone has been defined as the Outer Source Protection Zone. In this zone, certain activities can be allowed albeit under control. This zone is demarcated by a 100 year travel time.

The 100 year travel time was simulated using backward tracking for stress period 13 during Scenario 1 (2021). The maximum travel distance demarcated for the 100 year travel time is about 10km in the Malwelwe Wellfield and 5km in the Gaotlhobogwe Wellfield (see Figure 9.4).

9.5.4 Wellfield Protection Zone Delineation

The wellfield protection zone delineation has been delineated on the basis of the 100 year particle travel distances calculated using the Groundwater Model. The 100 year travel time shows travel distances of at most 10km around Malwelwe Wellfield and 5km around Gaotlhobogwe. The protection zone for each wellfield was drawn by constructing a 5km and 10km buffer around Gaotlhobogwe and Malwelwe respectively (see Figure 9.4)

9.6 Resources Monitoring and Management

The existing as well as the new wellfield systems as proposed will be vital to the long term existence of the population and sustainability of the principal users in the region for the foreseeable future. The groundwater resources on which these systems depend have been proven to be adequate for long term supply. The current project has also determined that the behaviour of these potable resources under increased and sustained abstraction will be influenced by geological structures which will in turn impact on groundwater water level overall decline.

It is imperative that the groundwater resources on which both the major villages supply and the Jwaneng Mine depend are properly managed. To facilitate this management process it is essential that the resources are continuously monitored to generate adequate data on which to base management decisions, and from which the numerical model can be upgraded, recalibrated and adapted into a full continuous dynamic management tool.

An effective groundwater monitoring system must provide at least the following data on a regular and continuous basis;

- Groundwater level, water quality and pumping information (volume and period) at every production borehole.
- Groundwater level and water quality information of zones outside the immediate wellfield environment, either as background 'control' data or for specific hydrogeological evaluation purposes.
- Hydrometeorological information at several sites in and adjacent to the wellfield to continue to assess recharge potential.

9.6.1 Distribution of Monitoring Points

Pronounced water level decline has been observed at monitored boreholes in Malwelwe, it can be assumed that this is natural in the area and thus the need for groundwater level and groundwater quality monitoring at the start of abstraction for production boreholes can not be over-emphasised.

Groundwater monitoring in its broadest sense should also continue so as to gather long-term data which will be used for transient model calibration. This data will also improve the understanding of the groundwater flow regime within the Project Area.

9.6.2 Manual Water Level Monitoring

A total of seventeen non production boreholes (Table 9.4) were monitored during the course of the project. Most of these boreholes are located within project Target Area A. Most of these boreholes were previously monitored by the Department of Geological Surveys (DGS) and a few were added during the course of the Project. Project monitoring was carried out from June 2009 to November 2011.

Table 9.4 Manual Water Level Monitoring

BH NO.	UTM Coordinates (Cape Datum)		Start Date	Comments
	Northing	Easting		
6735	331827.76	7336205.01	6/8/2009	declining water level
6736	327334.63	7345931.67	6/9/2009	declining water level
6738	324805.12	7361677.57	6/10/2009	declining water level
6739	336564.89	7346095.28	6/11/2009	declining water level
6742	331317.97	7363508.71	6/12/2009	declining water level

6741	318959.64	7345849.92	6/13/2009	declining water level, last reading affectedby abstraction
6764	317857.43	7345820.55	6/14/2009	declining water level
6766	314741.87	7348248.19	6/15/2009	declining water level
6767	314800.63	7345449.09	6/16/2009	declining water level
6823	324694.10	7361263.99	6/17/2009	declining water level
6824	318959.60	7345853.02	6/18/2009	declining water level, last reading affectedby abstraction
6825	321299.74	7346346.91	6/19/2009	declining water level
6826	317860.28	7345820.59	6/20/2009	declining water level
6827	314803.52	7345446.02	6/21/2009	declining water level
6829	327334.67	7345928.68	6/22/2009	declining water level
8866	310749.78	7351008.28	6/23/2009	declining water level
4695	322825.00	71318461.00	7/9/2009	declining water level, last reading affectedby abstraction

BH 4695 has been monitored continuously every month since June 2009 and is located closer to Gaotlhobogwe Wellfield outside Target Area A. The borehole shows increase in water levels recorded during the period of monitoring (June 2009 - November 2011). The borehole indicates recovery of 0.42m during this period from 74.28m to 73.86m (Figure 9.5).

Borehole BH 6767 and 6827 show a declining trend in water levels. These boreholes started with a steady decline at the beginning of monitoring period followed by rapid decline of water levels towards the middle of monitoring period. The rapid decline of water levels is attributed to test pumping that was conducted on some existing production boreholes. The boreholes then recovered and their water levels started to decline after recovery towards the end of monitoring period.

Boreholes around Malwelwe Village

The four manually dipped boreholes, BH 6824, BH 6825, BH 6764 located around Malwelwe village in the centre of Target Area indicate a fluctuating but declining trend in water levels. An average decline of 0.18m per annum was recorded for these boreholes as in Figure 9.6. Rest water levels for these Ecca boreholes ranges from 59m to 60m.

Eastern Boreholes

These boreholes are located towards the eastern side of Target Area A. Borehole BH 6829 recorded highest water levels decline from 72.92m to 73.22m during the course of project period monitoring. Other boreholes BH 6736, BH 6760 and BH 6735 remained static to slight decline in water levels during the same period. Rest water levels for these boreholes range from 68m to 75m depth.

Northern Boreholes

These boreholes are located on the northern side of Target Area A. BH 6823 and 6738 are located behind the Government Ranch and BH 6742 is located just outside Target Area A. These boreholes show fluctuating decline trend in water levels (Figure 9.7). BH 6823 had 0.34m decline of water level from the highest water level of 52.5m to the lowest water level of 52.84m during the course of project monitoring period.

9.6.3 Digital Water Level Monitoring

Table 3.14 summarises the boreholes that were monitored during the Project and the current status of the digital monitoring programme. Water level-time series graphs from the digital monitoring are shown in the Technical Report Number – 7 (Project Data Book).

Table 9.5 Digital Water Level Monitoring Summary

BH	UTM E	UTM N	Logger Type	Start Date	Comments
9344	268545	7382193	Floater	Sep-09	Static to slight fluctuating water level decline was observed during the first year of monitoring then it remained static.
7548	318763	7325972	Floater	Sep-09	Static water level was observed.
6216	331350	7377370	Floater	Sep-09	There was fluctuation in water level but the trend shows that there was rise in water.
6734	321916	7357098	Floater	Sep-09	Data shows static water levels throughout the monitoring period.
6737	338693	7364285	Floater	Sep-09	Water level fluctuations between Dec 09 and Jan 10 but show static water levels on a long-term.
6762	324796	7361705	Floater	Sep-09	Data shows static water levels throughout the monitoring period.
8026	309702	7332807	Floater	Sep-09	Water level fluctuates, but generally the water level is rising.
8863	309053	7362248	Floater	Sep-09	Water level fluctuations show static water levels on a long-term..
10394	275535	7328455	Floater	Sep-09	Static to slight water level decline was observed over the period of monitoring.
10750	325180	7348961	Floater	Dec 11	New installation in the middle of new Malwelwe Wellfield

9.6.4 Digital Rainfall Monitoring

Table 9.6 shows the location and a summary of the three rainfall monitoring stations established within the Project Area. Project stations were established at Khudumelpye, Serinane and Salajwe villages and their areal distributions are shown in Figure 9.8. The station at Salawe has been decommissioned due to equipment vandalism dispite that the rain-gauge was stationed at the local clinic where fencing security was available.

Table 9.6 Digital Rainfall Monitoring Summary

Rainfall Station	Date Installed	Comments
Khudumelapye Clinic	04-Sep-09	Monitoring on going
Salajwe Clinic	04-Sep-09	Vandalized and decomissioned
Seriname Water Plant	04-Sep-09	Communication Problems

Rainfall data from the different stations show that rainfall within the Project Area is spatially variable, with maximum rainfall amount among the stations ranging from 20 mm/d to as high as 74 mm/d recorded at Khudumelapye Rainfall Station. The rainfall pattern appear to show that frequent rainfall in dry season (June –Sepember) is common.

Instrumentation

A number of DGS digital loggers for monitor the groundwater resources need to be replaced by some new types. It is suggested that alternative types of instrumentation should be considered, taking cognisance of the following comments;

- The Floater loggers are very susceptible to malfunction as a result of tangling and snagging of cables, as well as corrosion of moving parts possibly due to the harsh environment. It is thus not recommended that these units be utilised for long term monitoring.

- Given the problems experienced during the Project, it may be more worthwhile to consider Insitu-Troll loggers rather than floaters.

- The Insitu-Troll logger was used by Resources Services during the Tsabong Project (DWA, 2001) with 100% success rate. An inquiry into the performance of the logger being used for the Matsheng Project has revealed a high success rate so far. These loggers are durable and have direct surface download communication via a vented communication cable made of robust thick stainless steel housed in a thick durable casing, making it water resistant and not easy to break or get entangled. Direct surface communication precludes the requirement to extract the logger for downloading, and a vented cable does away with the requirement for a separate compensating Barometric logger.

It is also essential that the existing rain gauge network be maintained and that each of the production boreholes be equipped with a totalising flowmeter such that abstraction from each borehole is reliably recorded.

Data Collection and Analysis

The following monitoring schedule is proposed for the Wellfields and surrounding area.

- Manual monitoring of the boreholes indicated in Table 7.5 be undertaken at monthly intervals utilising the normal electric contact gauge measurement unit.

- Data from the digital logging units should be downloaded at 3 monthly intervals.

- Digital rain gauges should be downloaded every 3 months as well and batteries should be changed/replaced.

- Flowmeter readings at each production borehole should be recorded at a maximum 1 month interval, or more frequently if possible.

Current monitoring sites are shown in Table 9.7 below. These sites should form the basis of the future sub-regional monitoring network.

Table 9.7 Malwelwe Wellfield Monitoring Sites

BH NO.	UTM Coordinates (Cape Datum)		Start Date	Logger Type
	Northing	Easting		
MANUAL MONITORING				
6735	331827.76	7336205.01	June-09	Dipper
6736	327334.63	7345931.67	June-09	Dipper
6738	324805.12	7361677.57	June-09	Dipper
6739	336564.89	7346095.28	June-09	Dipper
6742	331317.97	7363508.71	June-09	Dipper
6741	318959.64	7345849.92	June-09	Dipper
6764	317857.43	7345820.55	June-09	Dipper
6766	314741.87	7348248.19	June-09	Dipper
6767	314800.63	7345449.09	June-09	Dipper
6823	324694.10	7361263.99	June-09	Dipper
6824	318959.60	7345853.02	June-09	Dipper
6825	321299.74	7346346.91	June-09	Dipper
6826	317860.28	7345820.59	June-09	Dipper
6827	314803.52	7345446.02	June-09	Dipper
6829	327334.67	7345928.68	June-09	Dipper
8866	310749.78	7351008.28	June-09	Dipper
4695	322825.00	7318461.00	July-09	Dipper
DIGITAL MONITORING				
9344	7382193	268545	Sep-09	Floater
7548	7325972	318763	Sep-09	Floater
6216	7377370	331350	Sep-09	Floater
6734	7357098	321916	Sep-09	Floater
6737	7364285	338693	Sep-09	Floater
6762	7361705	324796	Sep-09	Floater
8026	7332807	309702	Sep-09	Floater
8863	7362248	309053	Sep-09	Floater
10394	7328455	275535	Sep-09	Floater
10750	7348961	325180	Dec-11	Floater

At every 3 monthly monitoring data collection the information should be suitably processed and non-digital data digitised into compatible format for examination and evaluation.

Evaluation should take the form of producing graphical plots of various parameters and examining them for any changes or deviation from a known trend. For instance, any serious downward trend in drawdown within the wellfield areas should be identified and flagged for remedial action, which may include altering the pumping regime in order to minimise such changes or which may require further technical advice from DWA, Gaborone. Pump clogging with the build up of slime deposits of iron bacteria should be investigated.

Data Archiving and Numerical Model Updating

It is imperative that all data collected should be stored and archived for future reference and evaluation. This will require the establishment of a simple database, plus a set of files for the non-digital information. It is assumed that this task will be the responsibility of the wellfields operating authority (ie the WUC Molepolole Unit under the advice of DWA).

For resource management it is envisaged that the monitoring data held by the wellfield operator will be periodically submitted to and examined by DWA, Gaborone as part of their Monitoring Unit activities. The data should be compiled and commented upon on an annual basis as part of the Water Apportionment Board (WAB) requirements and Report are to be archived by WAB for future use and model up-date.

It is envisaged that this model updating could also usefully be undertaken on an annual basis to supplement the WAB requirements.

Overall Groundwater Management Criteria

In terms of management of the groundwater resources of the region there are a number of important overriding aspects that need to be kept in mind with regards to long term utilisation of the resources, namely;

- The aquifer is prone to iron/sulphate reducing bacteria that form colonies and grow as clumps on the inside of the well screens as well as the immediate area in the aquifer and is responsible for blockage and reduction of yield in boreholes.

- Periodic borehole cleaning, so far, has proved to be the most effective approach.

- The spatial extent of the potable resources is entirely structurally controlled, and their hydraulic effects are not fully understood.

- The potable resource volume is more than adequate to sustain the projected regional water demand until the design horizon (2020), and thus the greatest risk to this supply is possible over exploitation.

The critical groundwater resource management issue is thus to operate the wellfields in such a manner so as to minimise over-pumping risk. This can be achieved by;

- Operating the production boreholes only at the recommended abstraction rates ie no over pumping.

- Making provision for a number of standby boreholes such that these can be brought on line in the event of other production borehole malfunction or a sudden increase in demand without placing excessive abstraction stress on the remaining operational boreholes. The 2020 spare capacity could be utilised in that manner.

- Operating more boreholes at lower abstraction rates rather than fewer boreholes at high abstraction rates, so distributing the ‘abstraction load’ across the resource area.

- Constantly monitoring the behaviour of the regional and individual borehole water levels and water quality (biofouling) so that any yield or quality deterioration can be recognised early and remedial action can be taken.

- Adhering to the wellfield protection zone criteria and preventing any possibility of anthropogenic pollution of the potable resources. The Malwelwe Wellfield is more prone to this effect than the other wellfields.

10. RECOMMENDATIONS

In Relation to Resource Evaluation

- Available structural, geological and hydrogeological data has been used to establish the initial steady state numerical model of the Project Area,

- Some exploration boreholes should be drilled within the Lebung/ Ntane area north of the Zoetfontein Fault in order to fully investigate and penetrate the deep Ecca aquifer underneath the Ntane and establish its hydraulic properties. Due to likely high head, the upper Ntane aquifer will have to be cased off in order to drill and protect the upper aquifer from the significantly deep Ecca aquifer.

- The hydraulic head relationship between the Ecca aquifer should be established by installing aquifer-specific piezometers within the area or by testing one aquifer and observing the other.

- The vertical variation in salinity within and between the major aquifer horizons should also be more clearly determined by means of a detailed hydrochemical sampling and quality logging exercise.

- Permeability of the intervening layers between the upper and lower Karoo aquifers should be evaluated in order to establish flow rates and permeability within them. The present model would then require modification as this phenomenon could be simulated with the model.

In Relation to Resource Development and Management

- The supply for Molepolole, Thamaga and Thebepatshwa Air Base will be from the Gaotlhobogwe, Malwelwe, Suping and Ramapatle wellfields which have a total yield in excess of the total estimated abstraction demand of 20,400m^3/day.

- Supply to Ngware and Botlhapatlou villages will be from one new borehole BH10748. The borehole yield is 20m^3/hr for a pumping period of 15hrs/day which is adequate to meet the demands of both villages up to the 2020 design horizon.

- Each production borehole should be pumped for the DWA recommended 15 hours/day period to allow for aquifer recovery and all existing production boreholes should be reduced to pump for 15 hrs/day at the recommended abstraction rate.

- Production boreholes should only be operated at the recommended abstraction rates ie no over pumping, and there should be provision for a number of standby boreholes such that these can be brought on line in the event of other production borehole malfunction or a sudden increase in demand (ie minimising excessive abstraction stress on the remaining operational boreholes).Immediate establishment of the Malwelwe Wellfield will facilitate this approach.

- If possible more production boreholes should be operated at lower abstraction rates rather than fewer boreholes at high abstraction rates, so distributing the ‘abstraction load’ across the resource area.

- The need to establish a robust groundwater level and abstraction monitoring programme and database at boreholes within and external to the designated wellfield areas cannot be over-emphasised if the transient numerical model is to be further refined.

- Reliable data can only be gathered by the installation of data loggers in production and monitoring boreholes in the wellfield areas, together with totalising flow meters to record abstraction at each production borehole.

- The following monitoring schedule is proposed for all wellfields and surrounding areas.

    - Monthly – manual dipping of recommended boreholes external to the wellfields utilising the normal electric contact gauge measurement unit.

    - Three monthly – downloading of digital loggers and rain gauges and all rain gauges batteries should be replaced

    - Flow-meter readings at each production borehole should be recorded at a maximum 1 month interval, or more frequently if possible.

- Wellfield area protection is imperative and it is designed to limit certain human activities within these areas in order to minimise groundwater pollution risk. In particular, any drilling of new private boreholes within the wellfield areas should be prohibited, or at least fully controlled and supervised by DWA, to ensure standard construction procedures are followed in order to minimize the risk of direct connection between the surface and the aquifer.

11. CONCLUSIONS

The present findings regarding the groundwater resources contained in the Ecca and Lebung/ Ntane aquifers are based on the review of existing information as well as the large amount of data generated during the current project. However, future projects in the area will assist in gaining a better understanding of the resource, in particular the Lebung/ Ntane groundwater resources north of the Zoetfontein Fault system, and in the upgrading of the present hydrogeological and numerical model to include these resources.

General conclusions relating to the various aspects of the groundwater investigation exercise and the subsequent resources evaluation are summarised as bullet points below.

Geological and Hydrogeological Environment

- The Botlhapatlou Groundwater Project Area is located on the margin of the central Karoo Basin of Botswana and is predominantly underlain by Middle and Upper Karoo strata of the Ecca and Lebung Groups. The area is covered by ubiquitous Kalahari sand and crete deposits that range between 2 and 25 metres in thickness.

- Groundwater is encountered in all sedimentary Karoo strata, but the principal aquifers of the Project Area are the sandstone units of the Ecca and Lebung Supergroups.

- The base of the Karoo has been positively identified where the Dwyka Formation has been encountered and fully penetrated. Elsewhere it is not completely certain that the doleritic/gabbroic rocks intercepted below the Kweneng and the Bori Formation marks the base of the Karoo. This uncertainty is promoted by the occurrence of a deep seated dolerite sill found at or near the base of the Kweneng Formation but overlying the Bori Formation. However, of significance is that these doleritic/gabbroic rocks certainly mark the base of the Karoo aquifer, if not the Karoo Supergroup itself.

- There are 2 major structures which have significant control on groundwater flow and quality within the Project Area; namely Z1/Z2, F5 and F6 (see Map 1). Throughout their length Z1 and Z2 structures have been found to be inconsistent, exhibiting different hydraulic characteristics in different zones and varying from being non-porous (barriers) to porous (broken), as evidenced by the groundwater flow pattern, (Map 4). F5 and F6 form part on the NW/SE trending structures that disrupt the Z1 and Z2 inducing leakage across the structures.

- The spatial variation in groundwater chemistry is structurally controlled whereas the vertical variation of groundwater quality is greatly influenced by lithology and intra-formational layering, principally the presence of coal horizons which result in partial isolation of the various layers within the aquifer.

- The current understanding of the geological and structural pattern of the Project Area has established the framework on which the current conceptual and numerical model of the Botlhapatlou Project Area has been built.

Exploration and Evaluation Techniques

- The project was undertaken in 3 phases, namely Inception, Exploration and Production and Reporting Phases. The geophysical surveys and exploratory drilling and aquifer testing of the Exploration Phase provided the greatest amount of hydrogeological information on which the final groundwater resources evaluation and development was based.

- The applied geophysical methods and techniques were successful to differing degrees in contributing to a more complete understanding of the hydrogeological environment of the Project Area. As expected, the high resolution aeromagnetic data reflected the essential structural setting of the sub-region, which is clearly related to the overall hydrogeological environment.

- The interpreted structures from aeromagnetic data were confirmed on the ground by ground magnetics, time domain electromagnetics (TDEM400 and TDEM200), and horizontal loop multi-frequency electromagnetics respectively.

- From results obtained it is apparent that time domain electromagnetics TDEM200 is the most effective resistivity measuring tool applicable to the sub-region.

- The air percussion drilling techniques employed proved appropriate for the geological environment, but some difficulties were encountered with respect to the significantly high water inflows and high hydrostatic heads. This was especially the case during the production drilling when larger borehole diameters (10” cased and screened completion) were required.

- Borehole geophysical logging provided useful information in relation to formation thicknesses and the overall geological profile for borehole. There was good correlation between the chips logging and the downhole logs.

- Groundwater monitoring was undertaken by manual as well as digital methods at well spread out boreholes throughout the project period. Problems were experienced with digital logger malfunction as well as vandalism so data sets are not continuous.

Groundwater Quality and Vulnerability

- Hydrochemical evaluation indicates that fresh water occurs in all rock types and stratigraphic units.

- There is an inflow/recharge of fresh groundwater from the Karoo basin edge in the south that maintains the groundwater flow system within the Project Area.

- A substantial body of low TDS (<1000 mg/l) groundwater exists in the Ecca aquifer in the Malwelwe Wellfield, apparently fed from south, and the Botlhapatlou ‘High’ is a pronounced groundwater divide.

- Slight vertical mineralization variation within Ecca Boritse aquifer is governed by presence of coal /mudstone/siltstone interlayers, many of which may be laterally impersistent.

- The vulnerability of the groundwater resources in the Botlhapatlou Project Area to anthropogenic pollution is low to very low as a result of the significant depth to the main aquifer and the thickness of the overlying Kalahari deposits and Kwetla mudstone aquiclude.

Groundwater Flow and Replenishment

- The general hydrochemical pattern is that of a throughflow gradually flowing northwards, northwestwards and northeastwards, upon which locally recharged water is superimposed.
- It is likely that recharge occurrs during significant pluvial periods, and then probably only in zones of structural disturbance and thinner unsaturated zone.
- The hydrochemical and 14C evidence suggest possible limited and episodic groundwater recharge in the Project Area where Ca-Mg-HCO_3 and Na-HCO_3 water type has been delineated.
- The hydrochemistry indicates that episodic groundwater recharge may occur in areas with a thin Kwetla and thin Kalahari Group cover, or in the vicinity of more active hydrological systems such as that in the Gaotlhobogwe Valley area.
- Hydrochemical evidence from the low chloride concentration and less dominant sodium concentrations hint at the possibility of some local recharge along prominent geological structures in the area.
- Groundwater monitoring both inside and outside the wellfield areas during the Project has revealed generally static to slightly declining water levels.
- ^{14}C in boreholes decreases with depth throughout the Project Area indicating possible older water at depth in the aquifer.
- The stable isotope (^{18}O and deuterium) pattern in the groundwater is that of water subject to variable degrees of isotope enrichment.
- The deuterium shift method of recharge determination suggests a theoretical mean annual recharge of 8 mm/year in most groundwater for which ^{18}O and deuterium was analysed.

Aquifer Evaluation and Resource Quantification

- The groundwater resource potential of the Ecca aquifer is improved in a structurally disturbed Karoo sedimentary basin where structures have a great influence on groundwater distribution (both vertically and spatially), piezometry and the groundwater flow regime.
- Future investigations that could contribute to the numerical model should verify the nature, mechanism and quantity of groundwater recharge and evapotranspiration along the Gaotlhobogwe ‘fossil’ valley.

- Calibration of the steady state model has been achieved through calibration of recharge and evapotranspiration against known values of transmissivity obtained from extensive groundwater exploration and investigation studies carried out in the area.

- By fixing transmissivity and inflow at the boundaries, uncertainties in the model are reduced with degrees of freedom allowed only on the recharge and evapotranspiration to the aquifer system.

- The set of transmissivity values used to calibrate the model optimised the recharge value of 15mm/yr along Gaotlhobogwe valley. Recharge rates estimation has been problematic in Botswana with estimated rates highly variable. The transmissivity values are within the range of values and agree with optimised values for the current model, but the current model would not optimise low recharge with the modelled transmissivity values.

- Use of hydraulic conductivity to calibrate the model has resulted in a simple hydraulic conductivity zonation, with only 3 zones to optimise the whole model area. Calibrating a model with hydraulic conductivity allows variation of transmissivity, which is important for the transient model thereby avoiding over-estimating of resources.

- The analytical solution used to estimate inflow from the basement high to the south and east gave a daily inflow rate of 13,210m^3/d. This inflow rate was used to calibrate hydraulic conductance at the inflow boundary and an inflow rate of 12,610m^3/d was obtained.

- Using the analytical solution to estimate inflow at the boundary also reduced the degrees of freedom of unknown terms in the model, thereby increasing confidence level in the model calibration results.

- Storage coefficient values determined from test pumping data interpretation have been successfully used in the transient model calibration to simulate measured groundwater abstraction and water level fluctuations as a response to the abstraction.

- The transient model calibration increases the level of confidence in the numerical groundwater model used to represent the hydrogeological system of the Ecca aquifer within the modelled area.

- Optimised hydraulic conductivity, out fluxes and influxes calibrated from the steady state model have been confirmed from the transient calibration model to accurately represent the set of parameters optimised to generate observed groundwater abstraction and water level fluctuations.

- Although the biggest abstraction in the area is from Jwaneng Wellfield, groundwater level decline is less than water level decline in Gaotlhobogwe Wellfield where only a third of the abstraction volume of Jwaneng Wellfield is taking place. This confirms the high transmissivity values of the Ecca aquifer in the Jwaneng Wellfield.

- The successful calibration of the transient model, using model parameters generated from field measurements and investigations increase the level of confidence in using the numerical model to make predictions on the impact and aquifer behaviour to long-term groundwater abstraction from established wellfields.

- Update of the numerical model with data from 2009-2011 would be useful in calibrating the remaining years of the modelled period. This will not alter the calibration results achieved so far but will increase accuracy of the starting heads in the predictive model used to simulate groundwater abstraction from 2012-2020.

- The predictive model has been undertaken based on transient model calibration results which optimised storage coefficient values for the predictive model to allow predictions on drawdown impacts from Gaotlhobogwe and Malwelwe Wellfields abstraction to meet water demand.

- Five scenarios were designed to evaluate impact of groundwater abstraction from:

    - Combined Gaotlhobogwe and Malwelwe Wellfields
    - Malwelwe Wellfield only
    - Gaotlhobogwe supplying 84% of the water demand and deficit coming from Malwelwe
    - Introducing NSC from 2017
    - Increasing abstraction in Jwaneng Wellfield by 50%

- All the scenarios revealed that effective management of Gaotlhobogwe Wellfield will require reducing the pumping hours for all the production boreholes to at most 15 hours per day.

- This can only be achieved through a combination of groundwater abstraction from Malwelwe and Gaotlhobogwe Wellfields.

- The model reveals that Gaotlhobogwe Wellfield cannot be pumped for 24 hours a day, and that the best practice will be to pump each borehole a maximum of 15 hours as this allows the aquifer to start recovering from present water levels.

- The model shows Malwelwe Wellfield has good potential groundwater resources. However, Scenario 3 which simulated abstraction from Malwelwe Wellfield only showed at the current recommended borehole abstraction rates the wellfield will not meet all the demand to 2020, even pumping each borehole for 24 hours.

- Under Scenario 3 only 25% of the available drawdown at Malwelwe Wellfield would have been utilised, indicating the borehole abstraction rates can be increased to utilise available drawdown, thereby meeting the predicted 2020 water demand. This would, however, require groundwater monitoring before recommended abstraction rates can be increased.

- The total number of available production boreholes between the Malwelwe and Gaotlhobogwe Wellfields is 26; this allows variation of pumping clusters and provides back-up for downtime in other boreholes.

- The recommended abstraction scenario is to utilise both wellfields as this allows Gaotlhobogwe Wellfield to recover whilst Malwelwe Wellfield is not pumped at 24 hours a day.

- Although recharge mechanisms in the area are not fully understood current direct recharge to the aquifer from precipitation under the present climatic regime has been regarded as possible, so ensuring a totally conservative approach to the numerical model evaluation.

- The predictive modelling shows that the projected water demand for the population centres in and adjacent to the Project Area until 2020 will easily be met with the production boreholes that have been developed.

Resource Development and Management

- A total of 14 production boreholes (6 existing and 8 new) are proposed to be developed at Malwelwe for supply to Molepolole, Thamaga and Thebepathwa Air base. They will be connected by 46.9km new and existing collector mains from the wellfields to the demand centres and each borehole should be equipped with an electric submersible pump set at a depth consistent with pump operation.

- An outline engineering design and costing for the development of Malwelwe Wellfield has been presented, and indicates a total budget estimate of some Pula 290 million to optimally utilize the groundwater sources that have been identified and delineated.

- With respect to the Malwelwe Wellfield, the entire wellfield area has been designated a Wellfield Protection Zone.

- The current water supply shortage in Molelopole necessitates an immediate full scale wellfield development. However, the need for immediate backup for the current supply pumping boreholes is likely to necessitate the incorporation of an emergency kind of approach for immediate use of these boreholes.

- The Malwelwe Wellfield development is not staged since all boreholes need to be utilized in an abstraction regime that will spread the pumping load and not cause any excessive drawdown at individual sources. This is particularly important since the current supply boreholes at Gaotlhobogwe and Suping are pumping at 24 hrs cycle period.

- With respect to Malwelwe village, borehole BH10784 is to supply the village and an existing BH4506 is be used as a standby source.

- Ngware and Botlhapatlou are to use BH10748 as a supply source and no standby borehole is assigned to this local supply system.

- A post-project digital monitoring network has been designed, with digital monitoring proposed within the wellfield areas and manual monitoring points are within and around the wellfield. A total of 10 digital monitoring points and 17manual monitoring points have been specified, as well as the continuation of the digital rain gauge monitoring.

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