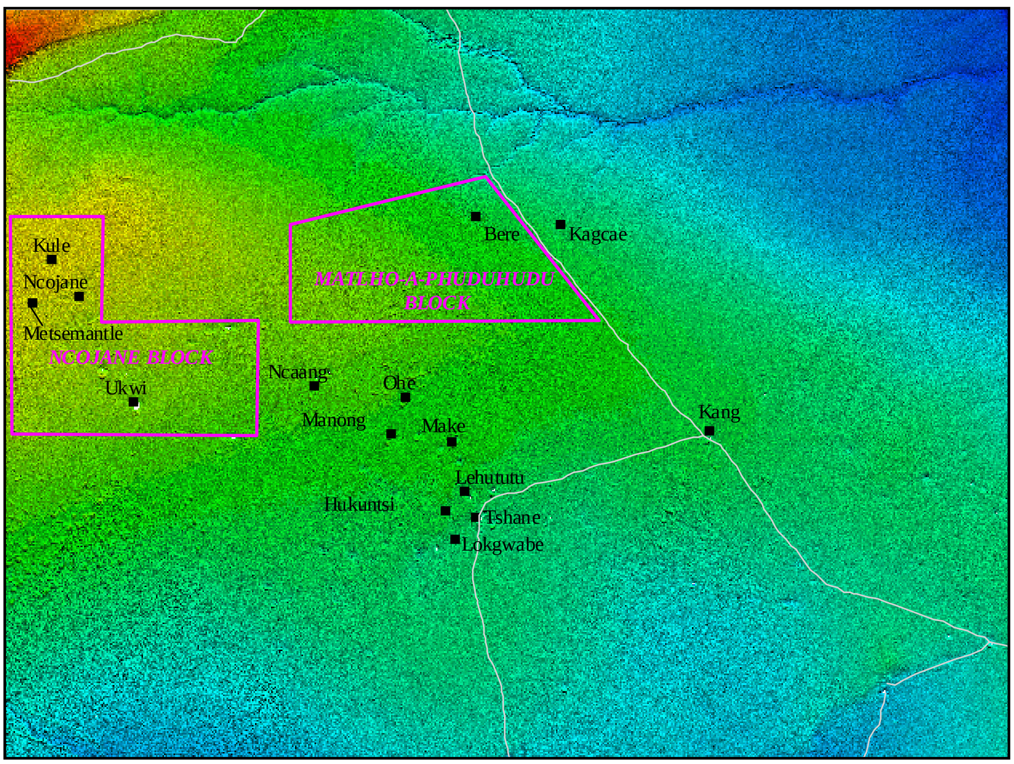
REPUBLIC OF BOTSWANA

Department of Water Affairs
Ministry of Minerals, Energy and Water Resources

Matsheng Groundwater Development Project

(TB- 10/3/93/2001-2002)



FINAL REPORT
VOLUME 1
MAIN REPORT

MARCH 2008

WRC

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PREFACE

This Final Report (**Volume 1, Main Report**), contains an overview of all activities completed under the project and summarises the analysis undertaken. The report also contains the recommended abstraction rates for the newly developed wellfield to ensure sustainable and reliable water supply for the Matsheng Villages and the secondary demand centres up to and beyond the year 2023 project planning horizon.

The complete reporting of this Project has been compiled in 6 volumes and an Executive Summary as listed below:

Volume No.	**Report Name**
	Executive Summary
Volume 1	**Main Report**
Volume 2	Hydrogeological Report
Volume 3A	Airborne and Ground Geophysics Report
Volume 3B	Transient Electromagnetic Sounding Data, Interpretation and Plots (Part 1 and 2)
Volume 3C	Downhole Geophysical Logging Report
Volume 4	Hydrochemistry and Environmental Isotopes Report
Volume 5	Groundwater Modelling
Volume 6	Preliminary Wellfield Design and Cost Estimates

SUMMARY

This Final Report (**Volume 1, Main Report**), contains an overview of all activities completed under the project and summarises the data analysis undertaken. The report includes an analysis of ASTER imagery interpretation, aeromagnetic data analysis, interpretation of ground geophysical survey and downhole geophysical logging data, drilling and pumping test data interpretation, groundwater quality data, isotopes and groundwater level monitoring. It also contains recommended abstraction rates for the newly developed wellfield to ensure sustainable and reliable water supply for the Matsheng Villages and the secondary demand centres up to and beyond the year 2023 project planning horizon.

A comprehensive analysis of the aquifer systems of the project area indicates that the Otshe aquifer in the Ncojane block has the best potential for development of long term water supply wellfields for the project area demand centres while the Ntane aquifer in the Matlho-a-Phuduhudu Block does not have the potential for large scale wellfield abstraction and was recommended for development of village scale water supply boreholes. The newly developed wellfield, Ncojane Wellfield was assessed to have a sustainable capacity of **9600** m^3/d. In terms of groundwater quality, the new production boreholes have groundwater which falls within the Class II specifications of the BOS 32:2000 drinking water standards. Recharge assessment through numerical modelling, isotope studies and groundwater level monitoring indicates that periodic recharge occurs to the Ecca (Otshe) aquifer, while there are very little indications for groundwater recharge to the Ntane aquifer within the boundaries of the current project.

ACKNOWLEDGEMENTS

Water Resources Consultants (WRC) would like to thank the project supervisors: Mr N. Mangisi and his predecessor Mr C. Chilume and other staff members of the Department of Water Affairs (DWA) who were generous in providing information and guidance at all stages of the Project. Their constructive views and advice were most appreciated.

WRC also wishes to express sincere thanks to Dr. A. R. Tombale, Permanent secretary; Mr. V. Bagopi and Mr B. Paya, the Director of Water Affairs; and Mr. I. Mannathoko, Head Groundwater Division, Department of Water Affairs for providing us with an opportunity to work on this challenging Project.

WRC is particularly thankful to the Ncojane community as a whole and to the government officials based in Ncojane, CharlesHill and Ghanzi. WRC also thank CharlesHill, Hukuntsi and Ghanzi Land board, who provided guidance on number of occasions ranging from arranging meetings, obtaining data and information, clearing of the sites for drilling and other associated matters.

WRC Project Team deserves special thanks and appreciation for performing their duties with dedication, diligence and to high professional standards. The Personnel involved in the project included:

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WRC takes this opportunity to thank members of the Project Steering Committee particularly: Mr J. Ntsatsi, Mr N. Mbuli, Mr K. Setimela, Mr T. Setloboko representing the Department of Water Affairs; Mr Keakantse,from Ghanzi/CharlesHill Land Board, Dr. G. Tshoso, Mr C. Chilume, and Mr M. Keeletsang from Department of Geological Survey, Mr J. Monggae from GeoScience Consulting Services and Mr M. Madi from Hukuntsi Water Unit..

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We also take this opportunity to pay tribute to the late Mr. Flenner Linn, one of our team members, who passed away after a road accident in Zambia. May God rest his soul in peace.

Last but not least we would like to express our appreciation to the Ncojane Police, Marakanelo C. J. S. School Staff, and Ncojane Post Office Staff for giving us access to their communication devices whenever required.

Water Resources Consultants is most grateful to everyone who assisted throughout the course of the Project.

ACRONYMS AND ABBREVIATIONS

ACL	Analytical Compu Log
AIDS	Acquired Immune Deficiency Syndrome
AMSL	Above Mean Sea Level
AMT	Audio Magneto-Telluric
ART	Anti-retroviral Therapy
ASTER	Advance Space-borne Thermal Emission and Reflection Radiometer
BGL	Below Ground Level
BH	Borehole
CMB	Chloride Mass Balance
CSAMT	Controlled Source Audio Magneto-Telluric
DGS	Department of Geological Surveys
DWA	Department of Water Affairs
EC	Electrical Conductivity
FSD	Fracture Spatial Density
GIS	Geographic Information System
GS	Ground Surface
GCS	Geotechnical Consulting Services (Pty) Ltd.
HBC	Home Based Care
HIS	Hue- Intensity- Saturation
HLEM	Horizontal Loop Electromagnetic
Hz	Hertz (Unit of frequency)
JICA	Japan International Cooperation Agency
m	Meter
m atoc	Meter above top of casing
m bgl	Meter below ground level
m3/day	Meter cubic per day
m3/hr	Meter cubic per hour
mg/L	Milligram per litter
msec	Milli-seconds
MT	Magneto-Telluric
MRT	Mean Residence Time
NDVI	Normalised Difference Vegetation Index
NSAMT	Natural Source Audio Magneto-Telluric
PCIAC	Petro-Canada International Assistants Corporation
PMC	Percent Modern Carbon
PVC	Poly-Vinyl Chloride
RGB	Red- Green - Blue
PPK	Post Processing Kinematics
RTP	Reduce to Pole
SRTM	Shuttle Radar Topography Mission
SWIR	Short Wave Infra-Red
TB	Tuberculosis
TDEM/ TEM	Time-Domain Electromagnetic/ Transient Electromagnetic
TDS	Total Dissolved Solids
TIR	Thermal Infra-red
UTM	Universal Transverse Mercator
VES	Vertical Electrical Sounding
VNIR	Visible Near Infra-Red
WCS	Wellfield Consulting Services (Pty) Ltd.
WRC	Water Resources Consultants (Pty) Ltd.
µS/cm	Micro-Siemens per centimeters (Unit of EC)
Ω-m	Ohm-meter (Unit of resistivity)

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1 INTRODUCTION, PROJECT IMPLEMENTATION AND SCOPE OF THIS REPORT

1.1 INTRODUCTION

Water Resources Consultants (Pty) Ltd (WRC) was contracted by the Department of Water Affairs (DWA) to execute the Matsheng Groundwater Development Project. Project activities commenced on 1st of August 2004 with field activities for the production phase completed in October 2007. Draft Final and Final Reporting for the project was carried out over the period November 2007 to March 2008.

The project area consists of two blocks, the Ncojane and the Matlho-a-Phuduhudu Blocks with the Ncojane Block falling in two administrative districts of Kgalagadi and Ghanzi whilst the Matlho-a-Phuduhudu Block falls within the Ghanzi District. Both blocks are located to the south of Ghanzi Township and bound in the east by the Trans-Kalahari highway and to the west by the Namibian Border (**Figure 1.1**).

Primarily, the goal of the Matsheng Groundwater Development Project was to locate and develop sufficient potable groundwater resources for supply to the demand centres of northern Kgalagadi District, specifically the primary demand centres comprising of the Matsheng villages (Hukuntsi, Tshane, Lehututu and Lokgwabe), as well as the "secondary" demand centres located in central and southern Ghanzi District up to the year 2023. Water demand estimates by WRC and the National Water Master Plan Review (2006) indicates that the total 2023 water demand for the primary and secondary demand centres will be 1655 and 1683 m3/day respectively.

To accomplish this goal, groundwater resources of two major aquifer systems of the project area were investigated. The Ntane Sandstone Aquifer present in the Matlho-a-Phuduhudu Block was investigated during the Hunhukwe/Lokalane Groundwater Survey Project (WCS, 2001), and the Ecca Aquifer present across much of the project area was the main focus of the current project. The specific project's objectives as set out in the Terms of Reference were as follows:

a. The collection, collation and analysis of all relevant hydrogeological data in the project area and surrounding areas

b. Selection of target areas based on (a) above for geophysical investigations to site 30 exploration and 10 production boreholes

c. Siting of 30 exploration and 10 production boreholes using appropriate geophysical techniques

d. Drilling and test pumping of 30 exploration and 10 production boreholes

e. To determine aquifer parameters and assess groundwater quality

f. Surveying of all project boreholes to facilitate the generation of a digital elevation model of the area as well as a groundwater-head map

g. To upgrade the existing hydrologic monitoring networks in the project area through the purchase and installation of additional data loggers and rain gauges

h. To assess the spatial and temporal distribution of groundwater recharge in the area

i. Assessment of the developed numerical groundwater model of the groundwater system in the area to further refine the model if need be and re-evaluate the available resources and appraise different pumping configurations to determine the most efficient design for any proposed wellfield

j. Estimate costs of developing a wellfield in the area and delivering water to the demand centres

k. Carry out an Environmental Impact Assessment Study (by an independent consultant) to determine the effect of the project on the environment and propose mitigation measures

l. To report all findings and recommendations in the different reports

This report, ***The Final Report*** is compilation of the findings of the groundwater investigation programme including an evaluation of the hydrogeological systems of the project area, resource assessment, as well as recommendations for groundwater abstraction from the installed wellfield.

1.2 WATER DEMAND AND SUPPLY

1.2.1 OVERVIEW

The term 'Matsheng villages' refers to a grouping of four villages, Hukuntsi, Tshane, Lehututu and Lokgwabe, located in northern Kgalagadi District. Hukuntsi, which is the best developed of the four in terms of infrastructure, is the sub-district headquarters for Northern Kgalagadi Administration Centre and houses several government offices. These villages are located within approximately a 10 km radius from each other and are connected by tarred roads. Prior to the year 2000, when an integrated water supply scheme interconnecting the four villages was commissioned, each of the four Matsheng villages had its own separate water supply scheme that sourced water from boreholes tapping shallow perched aquifers in Kalahari Beds (DWA, 2003). Some of these production boreholes have since been decommissioned due to factors such as increasing salinity, nitrate pollution, reported eccoli contamination, and declining yields. The above factors, together with the realisation that the perched Kalahari Beds aquifers supplying the Matsheng villages are not sustainable, prompted the Department of Water Affairs to seek alternative sources of water in the area, leading to the present project. The primary goal of the project is to develop potable groundwater resources to meet the water demand of the Matsheng Villages together with other demand centres located in Northern Kgalagadi District as well as central and western Ghanzi District through the year 2023.

Because of the broad list of villages provided in the Terms of Reference for this project, the villages were categorised into three demand centres to allow for a logical assessment of the water demand. These demand centres are as follows:

- The four Matsheng Villages - Hukuntsi, Lehututu, Lokgwabe and Tshane. These are regarded as the '***Primary Demand Centres***' and the project is principally focused on meeting their water demand
- Nineteen villages and settlements located in Northern Kgalagadi and Western/Southern Ghanzi Districts around the Ncojane Block. These were termed as '***Secondary Demand Centres***' and in addition to meeting the demand of the primary demand centres the project will also cater for these.
- Eight villages and settlements in central Ghanzi District including Ghanzi Township. These have been referred to as '***Additional Demand Centres***' and will be given lower priority.

The population of the villages and settlements that have been included in this assessment are listed in **Table 1.1** and their location is shown in **Figure 1.2.** The Central Static's Office 2001 population census gives the total population for the Primary Demand Centres including associated localities as 8,202, with Hukuntsi having the highest population of 3,801 (CSO, 2001). For the Secondary Demand Centres the population is 13,641 with Charles Hill having the highest population of 1,819 while for the Additional Demand Centres, the population is 15,973, with Ghanzi Township having the largest population at 10,795. Of these demand centres, Ghanzi Township is a designated planning area with a statutory development plan, while Hukuntsi is not a designated planning area, however village development was published in July 2004 for Hukuntsi.

From the onset, the project was carried out with a goal of meeting the demand for the Matsheng Villages as well as some villages in the secondary demand centres which fall within the exploration blocks.

1.2.2 WATER SUPPLY AND DEMAND

1.2.2.1 OVERVIEW OF WATER SUPPLY

Based on a review of existing information in the project area, the following conclusions can were reached regarding the water supply:

1. According to the records provided by the Water and Wastewater Department in Hukuntsi, the September 2004 supply for the Matsheng Villages is 912 m^3/d.. However data from the Regional Master Plan for the Western Region (July 2004) indicates that the available supply is 510 m^3/day. During the field visits to the project area, an acute shortage of water was observed for all the four Matsheng villages. It is therefore likely that the reported supply rate of 912 m^3/day is overestimated. The exact abstraction rates for Matsheng Villages is not easy to verify due to un-availability of reliable abstraction data since 1998 when DWA closed their offices in Hukuntsi

2. Only a handful of the original production boreholes in the Matsheng villages are operational mainly due to water quality deterioration associated with nitrate and ecoli contamination as well as yield declines. This highlights the need for effective aquifer management including source protection, particularly in areas with such limited potable water resources.

3. In order to alleviate the acute water shortage for the Matsheng villages, a DWA commissioned project to interconnect the four villages was completed in 2005. The source for this project is four boreholes (BH7854, BH7856, BH8570 and BH8571) located in Lokgwabe and Lehututu Villages**.** According to information supplied by the Hukuntsi water unit (2008), the daily abstraction rate from these boreholes is 700 m^3/d (**Table 1.2**). Although the reported abstraction rate is more than the estimated daily water demand for the Matsheng Villages (2004 to 2010), acute water shortages are still common place probably indicating that, the supply infrastructure is inefficient (leakage or wastage) or the supply is overestimated. In view of the fact that the interconnection project is temporary measure designed to cater for the Matsheng Villages supply up to 2009, estimates for new supplies were made assuming that all the supply has to come from new sources after 2009. This is because the current supply is from perched Kalahari Beds aquifers which are not sustainable for long term water supply and are vulnerable to pollution.

4. For the Secondary Demand Centres, existing records and field observations indicate that there is currently no major supply shortfalls in most of these villages. However, the settlements of Ngwatle, Ncaang, and Monong have very serious water shortages with water supply being through bowsers. Additional water resources to cater for the needs of the Secondary Demand Centres were developed during this project.

5. Existing records seem to indicate that there is no water shortage in the villages classified as Additional Demand Centres with the exception of Ghanzi Township. However as per the Regional Master Water Plan for the Western Region (2004), there is shortage of water in these villages. It has to be noted that these villages were not considered as the main demand centres and therefore no detailed review of their current water supply was undertaken. In addition to this the demand for these villages was not catered for when developing the new wellfields.

1.2.2.2 WATER DEMAND

The following assumptions were made when deciding the wellfield capacity

1. The water supply for the Matsheng Villages has to be met from the new wellfields from 2009 as the village interconnection scheme completed in 2005 was an emergency programme designed to alleviate acute water shortage experienced by these villages.

2. Water demand for the Secondary Demand Centres has to be met from the new wellfields as and when the need arises.

3. The water supply for Villages classified as Additional Demand Centres has to be met from different sources other the new wellfield boreholes

Based on the projected populations and the per capita water consumption assessed during the project, water demand projections for the project area's demand centres is given in **Tables 1.3** to **1.5**. The main observations are as follows:

1. The 2004 water demand for the Matsheng Villages (Primary Demand Centres) is 576 m^3/d and is estimated to increase to 863 m^3/d by the year 2023. This figure (863 m^3/d, for 2023) is very comparable with the National Water Master Plan Review (NWMPR, 2006) figure of 888 m^3/d (**Table 1.6**).

2. For the secondary demand centres, the 2004 and 2023 water demands were obtained as 600 m^3/d and 792 m^3/d respectively by WRC. The relatively low increase in the water demand for the secondary demand centres is attributed to low increases in the population of these centres, which among other factors can be attributed to the impacts of HIV/AIDS (CSO, 2001). Again the year 2023 water demand estimate by WRC is very close to the figure of 795 m^3/d contained in the NWMPR.

3. For the "Additional Demand" centres, the water demand is estimated as 879 m^3/d for 2004 whilst for the year 2023 the demand is estimated as 1319 m^3/d. The National Water Master Plan Review gives an estimated demand of 3019 m^3/d for these centres which is ~2.4 times the WRC estimate. It has to be noted that the demand for the "Additional Demand Centres" was not considered during the project execution following discussions with Client.

The total combined water demand for the Primary and Secondary Demand Centres for 2023 based on WRC estimates is 1655 m^3/d (~0.604 million cubic metres/yr).

Table 1.1 Population of the Demand Centres

District	Village	No. of Associated Localities	Population					
			1971	1981	1991	2001	Associated Localities	Total Population (2001)
Primary Demand Centres (4): Matsheng Villages								
Kgalagadi N.	Hukuntsi	7	1160	2009	2562	3807	324	4131
Kgalagadi N.	Lehututu	1	448	713	1304	1719	59	1778
Kgalagadi N.	Lokgwabe	5	300	866	1037	1304	131	1435
Kgalagadi N.	Tshane	0	604	637	706	858	0	858
Total								**8202**
Secondary Demand Centres (19) :Northern Kgalagadi and Western /Southern Ghanzi District								
Ghanzi	Charles Hill	4			996	1819	192	2051
Ghanzi	Ncojane	25	921	945	1448	1185	591	2030
Ghanzi	Tsootsha (Kalkfontein)	11	1155	978		1397	249	1646
Ghanzi	Karakobis	18	658	573	562	785	328	1113
Ghanzi	Mamuno				65	40	-	
Ghanzi	Makunda	19			200	331	990	1321
Ghanzi	New Xanagas	13			149	540	242	782
Ghanzi	Bere	12				385	313	698
Ghanzi	Kacgae	3				282	184	466
Ghanzi	Kule	16	540	637	656	741	283	1024
Ghanzi	Metsimantle					160		160
Kgalagadi	Monong				232	172		172
Kgalagadi N.	Ncaang					175		175
Kgalagadi N.	Hunhukwe				356	431	148	579
Kgalagadi N.	Ngwatle				92	206	0	206
Kgalagadi N.	Make				182	366	0	366
Kgalagadi N.	Ukwi				313	453	1	454
Ghanzi	Metsimantsho	-	-	-	144	152	152	304
Ghanzi	Ranyane	-	-	-	39	94		94
Total								**13,641**
Additional Demand Centres (8) : Central Ghanzi								
Ghanzi	Ghanzi Township	15	1198	3281	5550	9934	861	10795
Ghanzi	Chobokwane	21	-	-	192	484	477	961
Ghanzi	Qabo	0	-	-	-	401	0	401
Ghanzi	East Hanahai	1			373	405	20	425
Ghanzi	West Hanahai	7				560	182	742
Ghanzi	New Xade	6			528	930	164	1094
Ghanzi	Groote Laagte	2			278	483	129	612
Ghanzi	Dekar	0			627	943	0	943
Total								**15,973**
Grand Total								**37,816**

Sources: CSO 1971,1981,1991,2001 Population and Housing Census

Notes:

1. Mamuno is an associated locality of Charles Hill
2. Metsimantle and Ranyane are associated localities of Ncojane
3. Kalkfontein is also known as Tsootsha
4. Metsimantsho farm is a locality with no affiliation
5. Spellings for the Village Names are based on CSO 2001 Population and Housing Census

Table 1.2 Summary of Water Supply Boreholes, Matsheng (2008)

Loc	BH No	TDS (mg/L)	Static Water Level (m)	Pump Intake (m)	Recom Hrs of Operation	Recom Yield (m^3/hr)	Daily Yield at Recom Hrs of Operation	Matsheng Demand (2023)	Potential Shortfall (2023)
Lokgwabe	8570	284	19.50	29	10	10	100		
	8571	348	14.31	25	10	33	330		
Lehututu	7854	371	18.23	36	10	12	120		
	7856	399	18.10	37	10	15	150		
Total							**700**	**863**	**-163**

Table 1.3 Projected Water Demand for the Primary Demand Centres (Matsheng Villages)

Village	Year 2004		Year 2006		Year 2010		Year 2020		Year 2023	
	Projected Population	Water Demand (m^3/d)	Projected Population	Water Demand (m^3/d)	Projected Population	Water Demand (m^3/d)	Projected Population	Water Demand (m^3/d)	Projected Population	Water Demand (m^3/d)
Hukuntsi	4093	282	4295	296	4729	326	6331	437	6733	465
Lehututu	1858	128	1957	135	2171	150	2235	154	2195	151
Lokgwabe	1440	99	1440	99	1558	108	1809	125	1863	129
Tshane	976	67	976	67	1082	75	1519	105	1716	118
Total	**8367**	**576**	**8668**	**597**	**9540**	**659**	**11894**	**821**	**12507**	**863**

Table 1.4 Projected Water Demand for the Secondary Demand Centres (19 Villages)

Village	Year 2004		Year 2006		Year 2010		Year 2020		Year 2023	
	Projected Population	Water Demand (m^3/d)	Projected Population	Water Demand (m^3/d)	Projected Population	Water Demand (m^3/d)	Projected Population	Water Demand (m^3/d)	Projected Population	Water Demand (m^3/d)
Charles Hill	2142	120	2326	130	2682	150	3067	171	3551	198
Ncojane	1437	80	1436	80	1434	80	1432	80	1429	80
Kalkfontein	1459	81	1496	83	1562	87	1678	94	1701	95
Karakubis	847	47	885	49	954	53	1081	60	1107	62
Mamuno	79	4	90	5	106	6	137	8	137	8
Makunda	371	21	397	22	445	25	537	30	557	31
Bere	413	23	430	24	462	26	519	29	530	30
Kacgae	301	17	313	17	335	19	374	21	382	21
Kule	762	43	774	43	796	44	832	46	840	47
Metsimantle	161	9	166	9	175	10	193	11	203	11
Monong	161	9	155	9	145	8	130	7	127	7
Ncaang	189	11	197	11	213	12	242	14	247	14
Hunhukwe	450	25	461	26	482	27	517	29	524	29
Ngwatle	247	14	275	15	331	18	449	25	447	25
Make	429	24	471	26	552	31	718	40	756	42
Ukwi	492	27	517	29	562	31	646	36	663	37
New Xaanagas	561	31	573	32	595	33	633	35	641	36
Metsimantsho	159	9	164	9	173	10	202	11	211	12
Ranyane	98	5	101	6	107	6	125	7	130	7
Total	**10758**	**600**	**11227**	**625**	**12111**	**676**	**13512**	**754**	**14183**	**792**

Table 1.5 Projected Water Demand for the Additional Demand Centres

Village	Year 2004		Year 2006		Year 2010		Year 2020		Year 2023	
	Projected Population	Water Demand (m^3/d)	Projected Population	Water Demand (m^3/d)	Projected Population	Water Demand (m^3/d)	Projected Population	Water Demand (m^3/d)	Projected Population	Water Demand (m^3/d)
Gantsi	11335	632	12244	683	13981	780	15840	884	18154	1013
East Hanahai	413	23	417	23	425	24	438	24	441	25
West Hanahai	638	36	689	38	786	44	977	55	1019	57
Chobokwane	513	29	530	30	562	31	618	34	629	35
Qabo	420	23	432	24	453	25	490	27	498	28
New Xade	839	47	790	44	713	40	603	34	584	33
Groote Laagte	547	31	589	33	668	37	822	46	856	48
Dekar	1034	58	1091	61	1197	67	1377	77	1437	80
Total	**15739**	**879**	**16782**	**936**	**18785**	**1048**	**21165**	**1181**	**23618**	**1319**

Table 1.6 Comparison of WRC and NWMPR (2006) Water Demand Estimates

Primary Demand Centres (Matsheng Villages)

Year	Water Demand (m^3/d) WRC	Water Demand (m^3/d) NWMPR
2006	597	648
2010	659	676
2020	821	835
2023	**863**	**888**

Secondary Demand Centres

Year	Water Demand (m^3/d) WRC	Water Demand (m^3/d) NWMPR
2006	644	531
2010	676	592
2020	754	757
2023	**792**	**795**

Additional Demand Centres

Year	Water Demand (m^3/d) WRC	Water Demand (m^3/d) NWMPR
2006	936	1910
2010	1048	2137
2020	1181	2867
2023	**1319**	**3073**

1.3 SCOPE OF THIS REPORT

This Final Report (**Volume 1, Main Report**), contains an overview of all activities completed under the project and summarises the analysis undertaken. The report also contains recommended abstraction rates for the newly developed wellfield to ensure sustainable and reliable water supply for the Matsheng Villages and the secondary demand centres up to and beyond the year 2023 project planning horizon.

The final reporting for this project has been compiled in 6 volumes as listed below:

Executive Summary

Volume 1 Main report
Volume 2 Hydrogeological Report
Volume 3A Airborne and Ground Geophysics Report
Volume 3B Transient Electromagnetic Sounding Data, Interpretation and Plots (Part 1 and 2)
Volume 3C Downhole Geophysical Logging Report
Volume 4 Hydrochemistry and Environmental Isotopes Report
Volume 5 Groundwater Modelling Report
Volume 6 Preliminary Wellfield Design and Cost Estimates

Figure 1.1 Project Area Location Map

Figure 1.2 Location of the Demand Centres

2 PROJECT AREA BACKGROUND

2.1 PHYSICAL SETTING

2.1.1 LOCATION

As indicated in **Chapter 1**, the project area consists of two blocks, the Ncojane and the Matlho-a-Phuduhudu Blocks and is located in the western part of Botswana (**Figure 1.1**). It falls within two administrative districts of Kgalagadi and Ghanzi districts. The Matlho-a-Phuduhudu Block falls within the Ghanzi District while the Ncojane Block straddles both the Kgalagadi and Ghanzi Districts. Both blocks are located south of Ghanzi Township, west of the Trans-Kalahari Highway, and east of the Namibian boarder. The Trans-Kalahari Highway is the main access road into the project area. Bere, Hunhukwe, Lokalane, Ncaang and Monong villages/settlements are located within and in the vicinity of the Matlho-a-Phuduhudu Block, while Kule, Ncojane, Metsimantle, Metsimantsho, Ukwi and Ngwatle villages/settlements are located within the Ncojane Block. The Matsheng villages, comprising of Hukuntsi, Tshane, Lehututu and Lokgwabe and associated localities, are located approximately 120 to 150 km south of the Matlho-a-Phuduhudu Block and 150 to 200 km southeast of the Ncojane Block (**Figure 1.2**).

2.1.2 PHYSIOGRAPHY AND GEOMORPHOLOGY

Gently undulating topography in which fossil vegetated dunes, pans and dry river valleys occur are the principal geomorphologic features of the project area. A topographic map of the project area, generated using 5 m interval DTM data obtained from the Department of Surveys and Mapping (2004), is given in **Figure 2.1**. In general, the area slopes from west to east with a surface divide oriented NW-SE running through the area. To the north of this divide, the general slope is toward the northeast whilst to the south the overall slope is to the southwest (**Figure 2.1**) .The highest elevation in the project area of about 1285 m above mean sea level (amsl) occurs near Kule village in the northern part of the Ncojane Block while the lowest elevation of about 1030 m is present south east of Tshane Village. The numerous pans and depressions are also clearly visible in the contour map, particularly in the southern parts of both the Ncojane and Matlho-a-Phuduhudu blocks. Some of the pans follow a linear pattern aligned northwest to southeast along major structural lineament directions obtained from satellite imagery interpretation.

2.1.3 CLIMATE

In terms of climate, the study area is arid to semi-arid (WCS, 2001; Bhalotra, 1987). Rainfall data from four locations (Kang, Tshane, Ncojane and Ghanzi) in and around the project area indicate that rainfall mainly occurs during the warm to hot summer months of September to April (**Figure 2.2)**. The highest annual rainfall recorded in the area was 858 mm in 1974 in Ghanzi while the lowest annual rainfall on record is 99 mm recorded in Ncojane in 1995. Most of the rain fall occurs between the months of November to March, the peak rainy months being January and February. Mean annual rainfall amounts range from 250 mm in Ncojane in the west to 456 mm in Ghanzi in the northeast. Tshane has a mean annual rainfall of 350 mm (**Figure 2.3)**. The mean maximum temperature ranges from 29^o to 34^oC in the summer months and between 23^o to 27^oC in the winter months. The mean minimum temperature ranges from 11^o to 20^oC in the summer months and between 5^o to 8^oC in the winter months. Night time temperatures below freezing are common during the winter months in the Kalahari Desert. The average relative humidity recorded at Ghanzi ranges between 28 and 45% and that at Tshane it ranges between 24 and 35% (DWA, 2003). The average potential evapotranspiration calculated from data obtained from the ADAS station in Matlho-a-Phuduhudu is 1700 mm/annum (Chilume, 2001). Overall, the area is characterised by low rainfall and high potential evapotranspiration resulting in soil moisture deficits hence very low potential for annual groundwater recharge under normal rainfall conditions.

2.1.4 SURFACE WATER

There are no permanent surface water bodies in the project area because of its semi-arid to arid climatic conditions, high evaporation rates and the high infiltration rate capacity of its sandy soils. However after heavy rainfall events, surface water accumulates in the numerous pans found throughout the project area for relatively long periods of time, and thus pans constitute important source of drinking water for both wildlife and livestock in the area for certain months of the year during the rainy season.

2.2 GEOLOGICAL AND HYDROGEOLOGICAL FRAMEWORK

2.2.1 GEOLOGICAL FRAMEWORK

The project area lies within the Southwest Botswana Karoo Basin, which constitutes one of the seven Karoo basins recognised in Botswana (Smith, 1984; WCS, 2001). This basin is bound in the east by the north-south trending Kalahari Line (approximately west of 22^{O} E), which is an ancient fault system intruded by basic igneous rocks (Smith 1984). In the north, the basin is bound by the northeast-southwest trending Tsau Fault and emergent Proterozoic units of the Ghanzi Group. The Southwest Botswana Karoo basin extents southwards and westwards into South Africa and Namibia respectively. Most of the bedrock geology within the project is obscured by unconsolidated Kalahari Beds sediments of variable thickness and lithologies. Geological descriptions for the area are based mainly on interpretation of geophysical data sets (e.g. aeromagnetic surveys) and lithological information from stratigraphic and water boreholes drilled by various organisations including the Department of Geological Surveys (DGS), Department of Water Affairs (DWA) and private mining companies under various projects.

The Proterozoic Okwa Basement Complex is the oldest bedrock unit in the project area, while the Karoo Supergroup constitutes the most important geologic unit in terms of groundwater resources potential in the project area. The bedrock geology of the project area is illustrated in **Figure 2.4** which also indicates locations for boreholes referred to in the following sections. The regional stratigraphy is summarised in **Table 2.1**. A description of the geology of the project area based on review of existing information and data from the current project is given in the following sections.

Table 2.1 Regional Stratigraphy *(after Carney, et al, 1994)*

Age	Supergroup	Group/Formation	Description
Cretaceous to Recent	Kalahari Beds		Unconsolidated sand, clay, and duricrusts
Cretaceous	Dolerite intrusions and dykes		Dolerite Dykes and sills
Carboniferous to Cretaceous	Karoo	Stormberg Lava	Basalt
		Lebung	Sandstone , minor conglomerates and mudstone
		Ecca	Interlayered sandstone, siltstone, mudstone with carbonaceous mudstones and thin coals seams
		Dwyka	Tillite, mudstone and siltstone
Late Proterozoic		Nama	Conglomerate, sandstones and siltstones
Mid - Late Proterozoic	Damara	Ghanzi	Quartzites, arkoses and shales
		Kgwebe Fm.	Volcano-sedimentary units
		Okwa	Felsites and clastic sedimentary units
Early Proterozoic	Okwa Basement Complex		Granite, gneiss and felsite

2.2.2 PRE-KAROO GEOLOGY

The pre Karoo geology in the project area comprises of rocks of the Okwa basement complex and Ghanzi Group rocks, both of which sub-crop to the north of the project area (**Figure 2.4**). A very brief description of the pre-Karoo geology is given in this report since these units have limited groundwater development potential and did not constitute an exploration target in the present project.

Detailed geological descriptions of the basement formations in the project area can be found in the Hunhukwe/Lokalane Report (WCS, 2001).

2.2.2.1 OKWA BASEMENT COMPLEX

The Okwa Basement Complex is comprised of grey, fine-grained, homogeneous, highly foliated porphyritic felsites and sericitic quartzite, and occurs to the north of the Matlho-a-Phuduhudu Block. Although most of the Okwa units are covered by significant thickness of Kalahari Beds, exposures of these rocks have been reported along the Okwa Valley to the east and west of the east Trans Kalahari highway (WCS, 2001).

2.2.2.2 OKWA GROUP

A small inlier of pre-Karoo sedimentary units of the Okwa Group outcrop along the Okwa Valley in the north of the project area. The Okwa Group was divided into four units A to D by Carney et al, 1994, with Unit A consisting of plagioclase-phyric felsites, Unit B laminated siltstones and red sandstones, Unit C arkosic sandstone overlain by mudstone, and Unit D well-sorted fine to medium sandstones.

2.2.2.3 GHANZI GROUP

The Ghanzi Group, a meta-sedimentary sequence consisting of arkoses, siltstone, shales and minor limestone occurs as a folded northeast-southwest trending ridge north of the project area. It is divided into three formations: the Ngwako Pan, Dekar and Mamuno Formations (Litherland, 1982), from the oldest to the youngest.

The Ngwako Pan Formation consists of purple to reddish-brown medium-grained meta-arkoses interlayered with purple siltstones and argillites.

Overlying the Ngwako Pan Formation are weakly metamorphosed greyish-green fine grained massive arkoses, siltstones and shales which form the Dekar Formation. The siltstones are micaceous and finely laminated with weak cleavage while the shales are dark green, finely laminated and fissile along lamination planes (WCS, 2001).

The Mamuno Formation comprises of purple, highly indurated, fine-grained, massive meta-arkoses and siltstones with intercalations of brown limestones and mudstones towards the top (WCS, 2001).

2.2.3 KAROO SUPERGROUP

The Karoo Supergroup represents an extensive volcano-sedimentary sequence present across much of southern Africa, deposited throughout much of the Paleozoic (Carboniferous to Cretaceous). The lithostratigraphic column of the Karoo Supergroup in the project area together with typical lithologies is given in **Table 2.2** while **Table 2.3** gives boundaries of different lithologic units interpreted from drilling as well as borehole geophysical logging data of project and existing boreholes in the project area**.** A description of the different groups and formations of the Karoo Supergroup is given in the following sections.

2.2.4 DWYKA GROUP

The basal unit of the Karoo Supergroup, the Dwyka Group consists primarily of tillite, with quartzite/granite clasts in a sandstone matrix, purple mudstones (rythmites/varvites) and purple siltstones. In the project area, the Dwyka Group sub-outcrops against the Tsau Fault to the north of the Matlho-a-Phuduhudu Block, unconformably overlying the Ghanzi Group. It also overlies the Okwa Basement in the north-eastern portion of the Matlho-a-Phuduhudu Block. Deep stratigraphic boreholes, BH8645 in the Ncojane Ranches and BH8647 near the Matlho-a-Phuduhudu Demonstration Game Ranch (**Figure 2.4**), encountered a total Dwyka thickness of 188 meters and 104 meters at depths of 414 and 310 meters respectively. In the Ncojane Block, the stratigraphic Masetlheng Pan-1 borehole intercepted 335 meters of Dwyka sediments at a depth of 827 m. These deep boreholes indicate that the thickness of the Dwyka Group increases to the south. None of the groundwater exploration boreholes drilled during the Matsheng Groundwater Development (WRC 2008) and Hunhukwe/Lokalane project (WCS, 2001) encountered the Dwyka Group.

Table 2.2 Karoo Stratigraphy of the Project Area *(Modified from Smith, 1984; JICA, 2002)*

Group	Eastern Namibia	Botswana		Lithology	Age
		West of 22° E Longitude (SW Karoo Basin)	East of 22° E Longitude (Central Kalahari Karoo Basin)		
Stormberg Lava	Kalkrand Basalt?	Stormberg Lava	Stormberg Lava		Triassic to Lower Cretaceous
Lebung	absent	Nakalatlou	Ntane Sandstone	Reddish to pink fine to medium grained sandstone	Permian to Triassic
		Dondong	Mosolotsane	Basal conglomeratic sandstone, greenish-yellow sandstone interbedded with red-brown siltstones, red-brown mudstone	
	Upper Reitmond		absent		
Beaufort	Lower Reitmond	Kule	Kwetla	Basal fine grained sandstone (thin), dark grey mudstone/siltstone/shale purple grey reddish fine to medium sandstone (thin), grey, none carbonaceous purple-brown mudstone (main)	
Ecca	Auob	Otshe	Boritse	Coarsening upwards grey-brown to orange sandstone, micaceous at base and carbonaceous mudstone/siltstone and coal towards top	
				Thin fine grained dark grey sandstone, interbedded dark-grey siltstones/silty mudstone (Main)	
				Fine to medium grained sandstone (occasionally micaceous), overlain by occasionally micaceous dark grey/black mudstone with bands of dull coal	
				Interbedded light grey micaceous siltstone and dark grey mudstone with bright coal bands near top	
			Kweneng	Sequence of fine to medium grained sandstone interbedded with dark grey siltstone/mudstone, silty mudstone and occasionally pyrite reach at top	
				Coarsening upwards sequence of micaceous yellow, grey and brown sandstones, with micaceous siltstone, coarse grained pale grey arkosic sandstone near top	
	Mukorob	Upper Kobe	Bori	Dark grey silty mudstone with thin sandstone, grey micaceous siltstone with very thin coal bands at top	
	Nossob	Lower Kobe (Ncojane Sandstone)		From bottom dark grey siltstone, grey fining upwards sandstone, dark grey siltstone/carbonaceous mudstone	
Dwyka	Dwyka Group	Malogong Formation	Dukwi Formation	Predominantly Tillite with quartzite/granite clasts in sandstone matrix.	Carboniferous to Permian
		Khuis Formation		Purple mudstone rythmites/varvites with dropstones	
		Middlepits Formation		Purple siltstone and very fine sandstone	

Table 2.3 Interpreted Lithological Boundaries from Drilling and Borehole Logging Data

2.2.5 Ecca Group

The Ecca group in the project area includes the Kobe and Otshe Formations with the former being an equivalent of the Bori Formation and the latter an equivalent of Boritse and Kweneng Formations of the Western Central Kalahari Basin (Smith, 1984).

2.2.5.1 Kobe Formation

The Kobe Formation overlies the Dwyka Group and is divided into Lower Kobe (Ncojane Sandstone) and Upper Kobe. The bottom of the Ncojane Sandstone consists of dark grey siltstone followed by a grey fining upwards sequence of sandstones to dark grey siltstone and carbonaceous mudstones towards the top. The Upper Kobe is mainly comprised of dark grey silty mudstone interlayered with sandstone and is overlain by grey micaceous siltstone with thin coal bands at the top. The Kobe Formation was intercepted in several boreholes in the northern part of the project area (BH7755, BH7760, and BH7768) and in the Ncojane Block (BH10215, BH10216, BH10229 BH10314, BH10217). Coal exploration borehole W3 and stratigraphic boreholes BH8645 and BH8647 penetrated 78, 92 and 76 meters of this formation at depths of 272, 323 and 234 meters, respectively (**Figure 2.4**). Project boreholes, located in the Ncojane block intercepted the Kobe Formation at depths ranging from 212 m to 306 m. However none of these boreholes penetrated its full thickness with BH10217 penetrating 118 m of this formation.

2.2.5.2 Otshe Formation

The transition from Kobe to Otshe Formation is recognised as the first predominantly arenaceous succession overlying the argillaceous and carbonaceous units of the Kobe Formation. The basal units of this formation consist of a coarsening upward sequence of yellow, grey and brown micaceous sandstones alternating with micaceous siltstones. Pale grey coarse grained arkosic sandstone is found near the top of the basal unit of the Otshe Formation.

Overlying this basal unit is a sequence of fine to medium grained sandstones interlayered with dark grey siltstone, mudstone and silty mudstone and is pyritic near the top. This predominantly arenaceous unit is in turn overlain by a relatively thin sequence of interlayered light grey micaceous siltstones and dark grey mudstones with bright coal bands, followed by predominantly fine to medium grained sandstone interlayered with occasionally micaceous dark grey or black mudstone with bands of dull coal. This is overlain by interbedded dark-grey siltstones and silty mudstone with thin fine grained dark grey sandstones near the bottom. The uppermost Otshe Formation comprises a coarsening upwards sequence of grey or brown to orange sandstone, which is micaceous at the base and is capped by carbonaceous mudstone/siltstone and coal towards the top (**Table 2.2**).

The depositional environment of the arenaceous units of the Otshe Formation is predominantly deltaic, while the argillaceous and carbonaceous units are thought to be delta abandonment sequences (Smith 1984).

Coal Exploration borehole W3, located about 10 km east of Ncojane recorded a thickness of 76 m for the Otshe Formation while stratigraphic borehole BH8645 located approximately 20 km east of Ncojane recorded a thickness of 216 m. East of the Kalahari Line (**Figure 2.5**) , the Otshe attains a thickness of between 50 and 80 meters (Smith, 1984). Project boreholes located in the Ncojane Block recorded thicknesses in the range 48 to 146 m. In the south, near the Matsheng Villages, the Otshe Formation attains a thickness of between 150 to 180 meters (WCS, 1996c).

Sandstone units of the Otshe Formation form the most widespread aquifer unit within the project area and constituted the main target aquifer during the exploration phase particularly in the Ncojane Block where the Otshe Formation occurs at relatively shallow depths. Production boreholes were installed into this aquifer for water supply to the primary and secondary demand centres. This aquifer (Aoub Sandstone Formation) is also extensively utilised in eastern Namibia near its western border with Botswana (JICA, 2002).

2.2.5.3 BEAUFORT GROUP (KULE FORMATION)

In the project area, the Beaufort Group is represented by the Kule Formation, which is the equivalent of the Kwetla Formation of the Central Kalahari Basin.

This Formation overlies the Otshe Formation with its base marked by a sharp change in lithology from the underlying carbonaceous/coaly mudstone of the Otshe Formation to fine grained sandstone (Smith 1984). It contains purple, grey and reddish fine to medium grained sandstone, interlayered with dark grey mudstone/siltstone near its base, with the bulk of the formation consisting of grey, purple-brown non carbonaceous mudstone. The top of the formation is marked by the contact between the overlying reddish brown conglomeritic sandstone or reddish mudstone/siltstone with the underlying grey none carbonaceous mudstone. The thickness of the Kule Formation intercepted by boreholes in the project area ranges from 21 to 154 m (average 69 m) in the Ncojane Block at depths ranging from 15 to 153 m. In the Matlho-a-Phuduhudu Block, its thickness ranges from to 10 to 178 m (average 78 m) at depths ranging from 71 to 260 m.

2.2.6 LEBUNG GROUP

The Lebung Group in the project area is represented by the Mosolotsane and Ntane Formations. The Dondong and Nakalatlou Formations of Southwestern Botswana Karoo Basin are equivalent of the Mosolotsane and Ntane Sandstone Formations of Western Central Kalahari Karoo Basin respectively (Smith 1984). The thickness and depth of the different formations of the Lebung Group derived from interpretation of borehole geophysical logging data and drilling lithological details is given in **Table 2.4**. This table also includes the thickness of Kalahari Beds.

2.2.6.1 MOSOLOTSANE (DONDONG) FORMATION

The Mosolotsane (Dondong) Formation unconformably overlies the Kule Formation and is predominantly comprised of reddish brown mudstone, with impersistent basal reddish-brown conglomeritic sandstone or siltstone occurrences, particularly in the northern and western parts of the project area. The depositional environment of this formation is envisaged to be fluviatile terrestrial in a semi-arid climate (Smith, 1984). The basal conglomeritic sandstones have been interpreted as being channel fill deposits, and the mudstones as flood plain sediments and the depositional environment explains the impersistent nature of the sandstone and siltstone units (WCS, 2001).

The depth to the top of the Mosolotsane Formation varies between 20 and 80 meters with a thickness between 27 and 100 meters in the Ncojane Block. It was not intercepted in boreholes drilled in the southern of the Ncojane Block towards Ukwi and Ngwatle (e.g. BH10215, BH10216, BH10217, and BH10214). In the Matlho-a-Phuduhudu block, the depth to the top of this formation increases from west to east where it occurs at about 64 meters (BH9295/BH10220) in the west to 230 meters (BH9297) in the east whilst its thickness ranges from 10 to 85 m (**Table 2.4**).

Table 2.4 Depth and Thickness of the Lebung Group Formations in the Project Area

		Kalahari Beds	LEBUNG GROUP					
			Ntane (Nakalatlou) Formation			Mosolotsane (Dondong) Formation		
Location	BH No	Kalahari Thickness	Ntane Top	Ntane Bottom	Ntane Thickness	Mosolotsane Top	Mosolotsane Bottom	Mosolotsane Thickness
MAP	9134	110	110	170	60	170	215	45
MAP	9236	105	105	180	75	180	210	30
MAP	9237	130	130	210	80	210	230	20
MAP	9238	120	120	170	50	170		
MAP	9239	135	135	230	95	230	260	30
MAP	9240	90	90	205	115	205	215	10
MAP	9241	130	130	178	48	178	220	42
MAP	9243	50	95	150	55	150	180	30
MAP	9244	95	95	125	30	125	190	65
MAP	9245	80	80	100	20	100	125	25
MAP	9291	130	130	165	35	165	190	25
MAP	9292	65	65	70	5	70	110	40
MAP	9293	100	100	140	40	140	160	20
MAP	9294	130	130	148	18	148	175	27
MAP	9297	150	150	230	80	230	260	30
MAP	9298	70	70	129	59	129	150	21
Hunhukwe	8545	70	70	105	35	105	190	85
Ncojane Ranges (MAP)	S8645	42	42	72	30	72	82	10
MAP	9097	78	78	111	33	111	137	26
MAP	9110	51	63	133	70			
MAP	9296	70	70	135	65	135	160	25
MAP	9044	150	150	205	55	205		
MAP	10317	93	93	202	109	202	216	14
MAP	10220	64	Absent	Absent	Absent	64	77	13
Ncojane	10221	42	Absent	Absent	Absent	42	81	39
Ncojane	10222	30	Absent	Absent	Absent	30	127	97
Ncojane	10227	25	Absent	Absent	Absent	25	65	40
Ncojane	10228	25	Absent	Absent	Absent	25	65	40
Ncojane	10211	33	Absent	Absent	Absent	33	81	88
Ncojane	10213	33	Absent	Absent	Absent	33	121	88
Ncojane	10214	37	Absent	Absent	Absent	Absent	Absent	Absent
Ncojane	10215	15	Absent	Absent	Absent	Absent	Absent	Absent
Ncojane	10216	13	Absent	Absent	Absent	Absent	Absent	Absent
Ncojane	10219	14	Absent	Absent	Absent	Absent	Absent	Absent
Ncojane	10229	33	Absent	Absent	Absent	33	117	84
Ncojane	10314	20	Absent	Absent	Absent	20	120	100
Ncojane	10212	27	Absent	Absent	Absent	27	107	80
Ncojane	10315	37	Absent	Absent	Absent	80	153	73
Ncojane	10402	25	Absent	Absent	Absent	25	65	40
Ncojane	10404	33	Absent	Absent	Absent	33	81	48
Ncojane	10405	47	Absent	Absent	Absent	47	86	39
Ncojane	10407	55	Absent	Absent	Absent	55	91	36
Ncojane	10410	60	Absent	Absent	Absent	60	88	28
Ncojane	10411	50	Absent	Absent	Absent	50	77	27

2.2.6.2 Ntane (Nakalatlou) Formation

The Ntane Sandstone, which conformably overlies the Mosolotsane Formation, constitutes the youngest sedimentary unit of the Karoo Supergroup. Its lithologies are primarily friable reddish to pink fine to medium grained sandstone, deposited in an arid aeolian environment. This formation occurs in the Matlho-a-Phuduhudu Block in the eastern part of the project area in what has been termed the 'Ntane Sub-Basin' (WCS, 2001; **Figure 2.4**).

In the north and west it pinches out against older Ecca units and in the south it pinches out against the Mosolotsane Formation. In the absence of Basalts overlying the Ntane sandstone, it is often difficult to distinguish the top of this unit from the basal Kalahari Beds sandstones.

The depth to the top of the Ntane Formation ranges between 42 meters below ground level in the west to 150 meters in the east and its the thickness varies from 5 meters in the west to 115 meters in the east (**Table 2.4**).

2.2.7 Stormberg Lava Group

The uppermost member of the Karoo Supergroup, the Stormberg Lava Group is present in the north-central and north-eastern portions of the Matlho-a-Phuduhudu Block as delineated by the aeromagnetic data interpretation and borehole logs (WCS, 2001). It consists of variably weathered, green or reddish purple, amygdaloidal lava flows and is dark grey in colour when fresh. The Stormberg Lave unconformably overlie the Lebung Group strata in the north, the Okwa Group in the east and Ecca Group in west. The basalt thickness varies from a few meters in the west (north of Ncojane Ranches) to 94 meters (BH9242) in the east.

2.2.8 Post-Karoo Geology

2.2.8.1 Intrusives

A number of dolerite sills/dykes have been intersected in a number of boreholes in the project area as well as interpreted from aeromagnetic data. The dolerites are greenish grey to dark grey in colour, fine to medium grained and massive and in some instances the dolerite is weathered. A dolerite is exposed in Ncojane village.

These dolerite sills were intercepted at various depths throughout the project area ranging from 6 m in Ncojane to over 330 m in the Masetlheng, Ngwatle and the Matlho-a-Phuduhudu areas. In some areas, particularly Ngwatle and Masetlheng multiple sills cutting through the Ecca Group have been encountered and are responsible for the deep depths of the Ecca aquifer. The thickness of the dolerite sills in the Ncojane Block ranges from 3 to 88 m.

In the Matlho-a-Phuduhudu Block, a significant sill has been identified in the south-western portion of the Matlho-a-Phuduhudu area varying in thickness from 24 to 50m.

2.2.8.2 Kalahari Beds

Kalahari Beds form a variable cover over the entire project area. Thomas and Shaw (1991) classified the Kalahari Beds into five major lithological (but not stratigraphic) components: conglomerate and gravel, marl, sandstone, sand, and duricrusts. In the Matlho-a-Phuduhudu Block, the lowermost unit is usually yellow/orange, semi-consolidated, calcretised, 'Kalahari' sandstone which is often difficult to distinguish from the top of the Ntane Sandstone (WCS, 2001). Above this is fine to medium grained sand, with varying calcrete cement and is variably coloured. At the surface, there are silty brown sand and calcrete horizons. In the vicinity of pans, the calcrete horizons are well developed in thickness and extent.

The thickness of the Kalahari cover in the Ncojane Block ranges from 13 m to about 64 m. Although its spatial distribution is variable, there appears to be a general increase from west to east (**Figure 2.5**). In the Matlho-a-Phuduhudu Block, the thicknesses of the Kalahari cover increases from 42 m in the west to 150 m in the east near the centre of the Ntane Sub-basin. This variation in thickness is attributed to the undulating topography of pre-Kalahari topography.

The Kalahari is dry in most cases but it forms perched aquifers close to pans in the Matsheng area with fresh to very saline water quality.

2.2.9 Regional Structural Setting

The project area is located within a regional sedimentary basin, the South West Botswana Karoo Basin which contains mid-Proterozoic and Paleozoic sedimentary rocks. This basin is bounded by the Damara Orogenic Belt, which includes the Ghanzi Ridge, just to the north of the project area. To the west, the basin extends more than 200 kilometres into Namibia where it is bounded by emergent early Proterozoic basement. The southern margin of the basin is less well defined but extends well beyond the project area into northern South Africa and to the east the basin joins the Central Kalahari Sub-basin (Carney et al, 1994; Smith, 1984). In the project area, the Karoo formations dip gently to the east, with Karoo thickness increasing similarly to the east. The pre-Kalahari bedrock surface also slopes generally to the east again with thickness of Kalahari cover increasing to the east.

The dominant regional structural features in the project area are two major cratonic discontinuities, the north-south trending Kalahari Line and the northeast-southwest Makgadikgadi Line. The Kalahari Line is identified in regional aeromagnetic surveys and represents a broad and co-linear series of deep seated faults and coincident mafic intrusions. It is believed to represent the edge of a continental craton of mid-Proterozoic age (WCS, 2001). The Makgadikgadi Line coincides with a zone of increased seismicity which separates regions of strongly contrasting magnetic and gravity signatures (Carney et al, 1994).

The northeast trending Tsau Fault is a major fault in the project area, located along the southern edge of the Ghanzi-Chobe Fold Belt and bounding much of the Karoo formations to the north (**Figure 2.4**). The Tsau Fault, includes a series of thrust faults and forms the stratigraphic boundary between the Karoo to the south and the Ghanzi Group to the north.

Significant lineaments (from Satellite Imagery interpretation) evident in the areas underlain by the Karoo Supergroup may reflect structures, and are oriented NE and ENE sub-parallel to the Tsau Fault. Other lineaments are oriented in a N-S direction and are most probably associated with re-activation of much earlier fractures associated with the Kalahari Line. Some of these structures exert significant control on the depth to the top of the different geological units, groundwater quality and groundwater flow directions in the project area as will be discussed in **Chapter 11**.

A series of NW-SE trending faults/lineaments transect the project area and parallel the direction of the post-Karoo dolerite dyke swarm in north eastern Botswana.

2.2.10 Regional Hydrogeology

The main hydrogeologic units of the project area are aquifer systems developed in Karoo Supergroup sandstones (Ntane and Otshe Formations), with minor aquifers developed in unconsolidated Kalahari Beds, Mosolotsane/Kule Formations and Dwyka Group. A summary of the main features of the different aquifer units of the project area are described below with a more detailed analysis given in **Chapter 11**.

2.2.10.1 Ntane Sandstone Aquifer

The Ntane Sandstone which constitutes the main aquifer unit of the Lebung Group is only well developed in the Matlho-a-Phuduhudu Block, in what was termed the ‘Lebung/Ntane Sub-Basin’ (WCS, 2001). The southern boundary of the Ntane aquifer occurs about 70 km north of the Matsheng villages, where only the lower argillaceous Mosolotsane Formation was intercepted during drilling (DGS, 1996). West of the Matlho-a-Phuduhudu Block, the Ntane Sandstone becomes unsaturated and the formation wedges off against Ecca Group just east of the Ncojane ranches. Groundwater levels of the Ntane Sandstone, where saturated often rise above reported water strikes suggesting that the aquifer is semi-confined in some areas of the Matlho-a-Phuduhudu Block, although for practical purposes it can be considered to be fully unconfined (WCS, 2001). The aquifer has variable yields, ranging from 3 to 54 m^3/hr whilst TDS values of less 500 mg/L were obtained in the central areas of the aquifer. To the south and north, towards the margins of the Lebung/Ntane Sub-Basin, relatively higher TDS values ranging between 900 to 1500 mg/L were obtained.

2.2.10.2 ECCA (OTSHE) SANDSTONE AQUIFERS

Sandstones of the Otshe Formation, which underlie an extensive portion of the project area, constitute the main aquifer unit within the Ecca Group. The Ecca aquifer consists of an alternating sequence of fine to coarse, clean sandstones separated by coals, carbonaceous mudstones, mudstones, shales and siltstones. On average, water strike depths range between 350 and 380 meters (bgl) in the central, eastern and southern parts of the Matlho-a-Phuduhudu Block. In the Ncojane Block and northwestern parts of Matlho-a-Phuduhudu Block, where the Ecca occurs beneath relatively thin Kalahari Beds and Lebung/Beaufort Group rocks, water strikes are generally between 145 to 290 meters below ground level. Borehole yields are variable and range between 20 to over 100 m^3/hr. Groundwater quality is potable in a broad area in the western and northern parts of the study area with TDS values of about 500 mg/l. TDS values tend to increase significantly (>6000 mg/l) to the south and southeast. Existing data together with data collected during the current project also indicates that there is salinity stratification within the Ecca aquifer where both decreases and increases in salinity with depth were observed. Data collected during the current project indicates that the basal sandstones of the Kule and Mosolotsane Formations are often saturated with poor quality groundwater and might pollute the Otshe aquifer if boreholes are not properly constructed.

2.2.10.3 KALAHARI BEDS AQUIFERS

Aquifers are locally developed in the Kalahari Beds in the project area, although water quality (TDS) is extremely variable. The original water supply boreholes for the Matsheng Villages were developed in local Kalahari Beds Aquifers. Some of these production boreholes have since been decommissioned due to several factors including deteriorating water quality (mainly increases of nitrate), eccoli contamination, and declining yields. In adjacent Namibia (JICA 2002), Kalahari Beds aquifers are highly developed and account for greater abstraction (10 MCM/yr) than the underlying Ecca aquifers (5 MCM/yr). However in much of the project area, Kalahari Beds are unsaturated and where they are saturated, the water quality is saline more often than not.

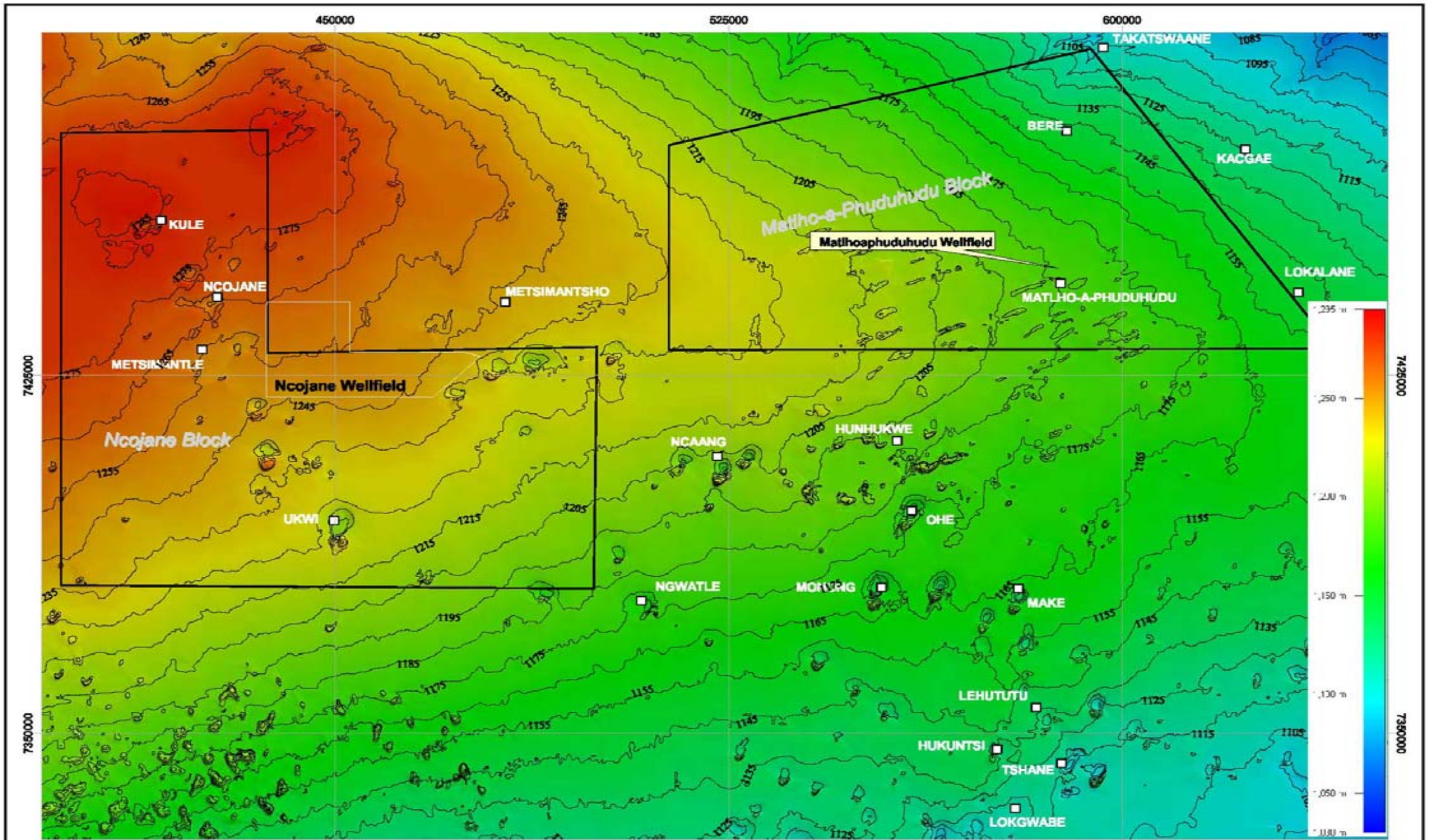

Figure 2.1 Topographic Map of the Study Area

(DEM generated from 5m interval digital contour data obtained from Department of Surveys & Mapping, Govt. of Botswana)

Figure 2.1 Topographic Map of the Study Area

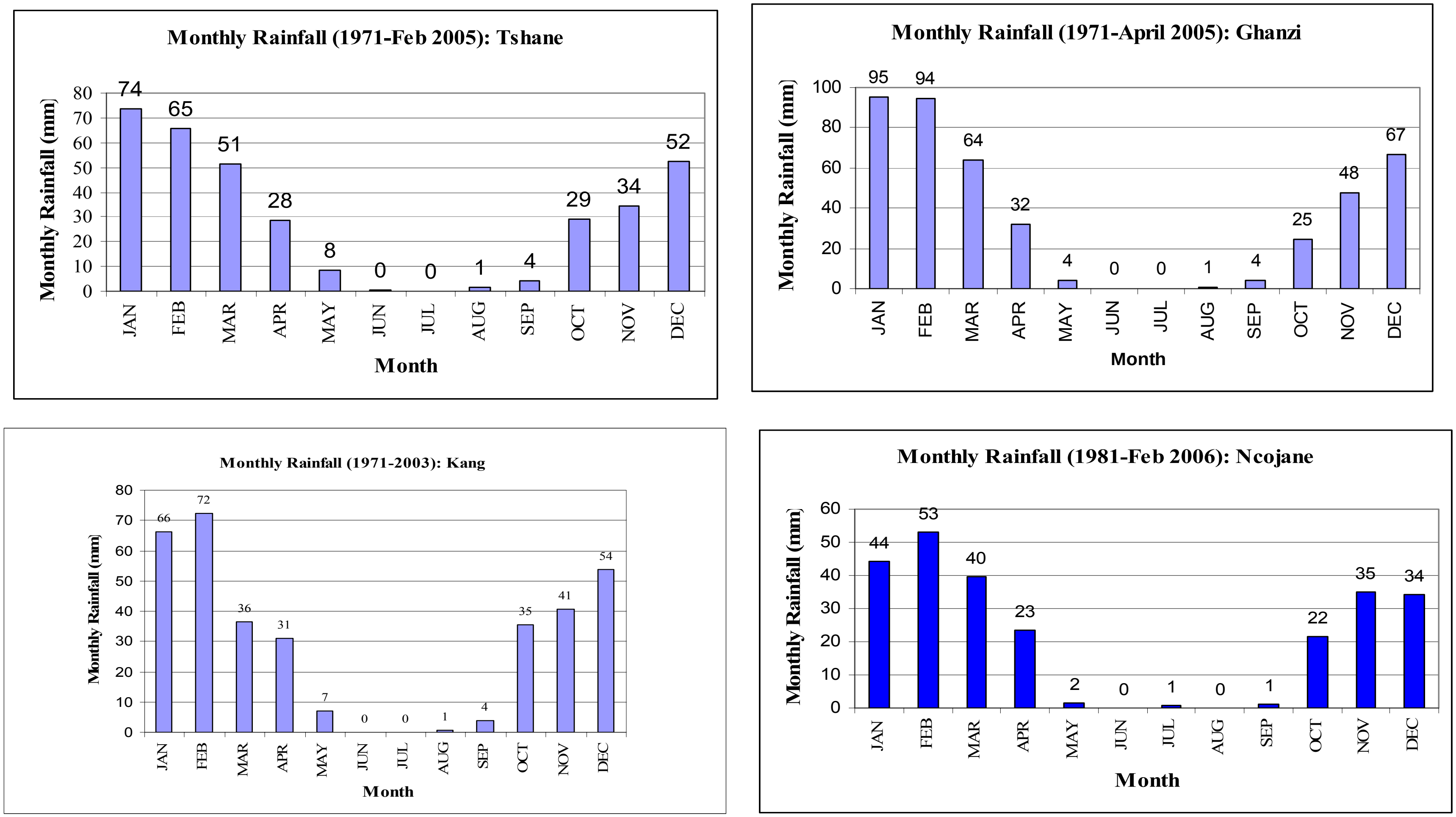

Figure 2.2 Mean Monthly Rainfall

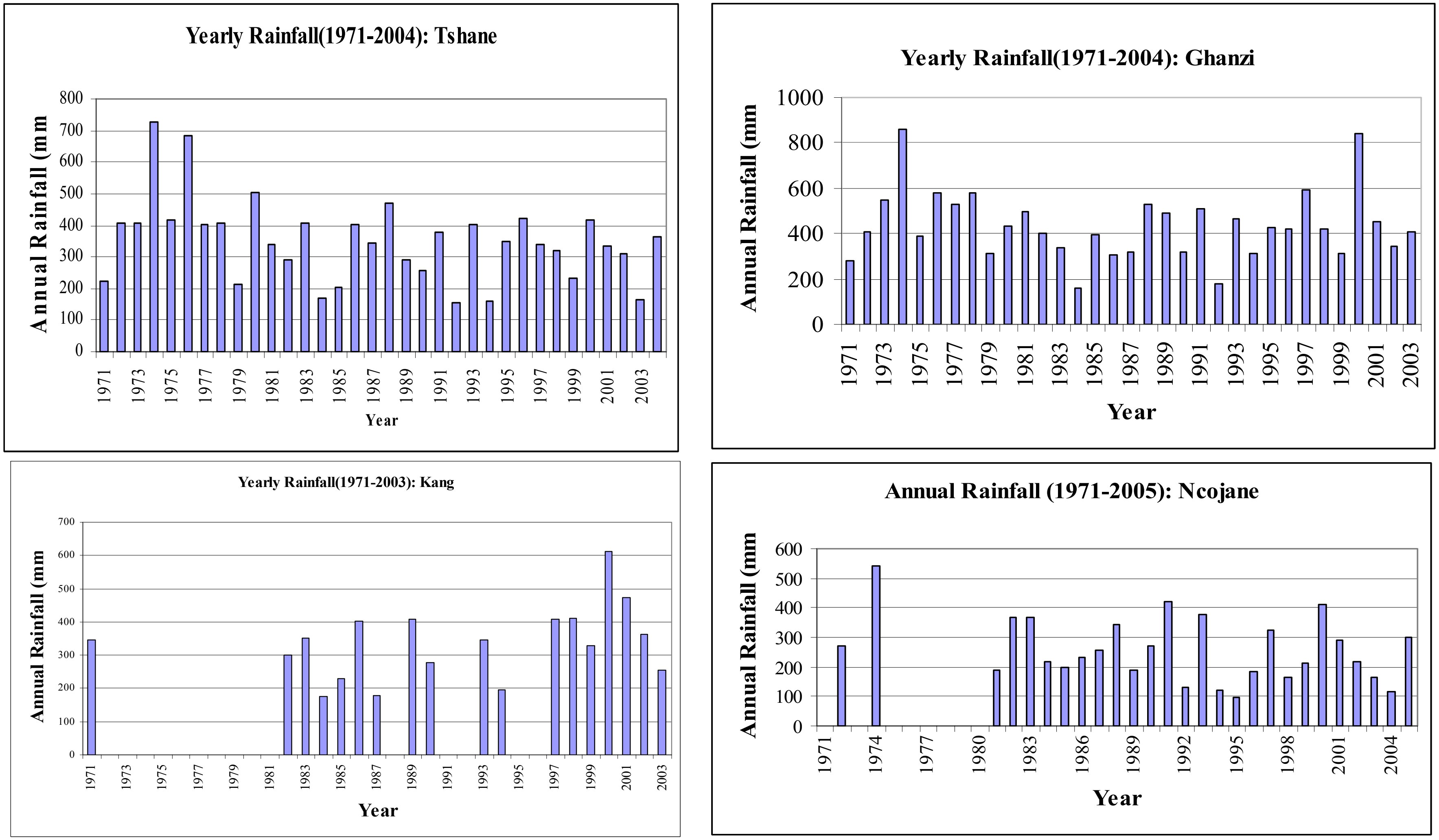

Figure 2.3 Total Yearly Rainfall

Figure 2.4 Geological Map of the Project Area

Figure 2.5 Kalahari Thickness Map

3 OVERVIEW OF PROJECT ACTIVITIES AND PROGRAMME

WRC's overall approach to the execution of the Matsheng Groundwater Development Project, was based on a phased sequence of activities aimed at ultimately achieving the project goal of locating wellfield(s) capable of meeting the water demand for the Matsheng Villages and the Secondary Demand Centres up to the year 2023. The programme was divided into three main Phases of activities which constituted a logical breakdown of the overall project schedule as follows:

Phase 1: Inception Phase
Phase 2: Exploration Phase
Phase 3: Production and Resource Evaluation Phase

This approach allowed for integration and evaluation of results from the various activities resulting in making judicious decisions that ultimately resulted in developing the water supply wellfields. The conclusion of all phases of the project culminated with drafting and submission of the Final Report Volume 1 (Main Report), Five Technical Reports and an Executive summary.

The major activities undertaken in each phase are summarised below.

3.1 PHASE 1 INCEPTION PHASE

The main focus of the activities undertaken during ***Inception Phase*** included the following;

- Review and Interpretation of Existing Data Sets in the Project Area
- Integration of the different data sets to Develop a Conceptual Hydrogeological Model
- Assessment of the water demand for the project area's demand centres which were designated as Primary, Secondary and Other Demand Centres
- Evaluation of suitable geophysical techniques to be deployed for optimal groundwater resources evaluation in the Project Area during the Exploration Phase
- Review of Existing Numerical Models in the Project
- Development of a work plan and time schedule for the Exploration Phase
- Preparation of the Terms of Reference for the Environmental Impact Assessment Study
- Preparation of the Terms of Reference for Drilling and Test Pumping of Exploration Boreholes

The findings of the Inception Phase Activities were summarised in an Inception Report which was submitted to DWA on 22 November 2004.

3.2 PHASE 2 EXPLORATION PHASE

The ***Exploration Phase*** (***Phase 2***) was started in mid May 2005 and was completed in April 2006.

The main activities included:

- Rainfall and Groundwater Level Monitoring
- Ground Geophysical Surveys for Exploration Borehole Siting
- High Precision GPS Surveys
- Drilling of Exploration and Monitoring Boreholes
- Borehole Geophysical Logging
- Pump Testing of Exploration Boreholes
- Numerical Groundwater Modelling

The findings of the exploration Phase were summarised in a Project Review Report which was submitted to the client in April 2006.

3.3 PHASE 3 PRODUCTION AND RESOURCE EVALUATION PHASE

Phase 3, the Production and Resource Evaluation Phase, was started in May 2006 and completed in October 2007. The final reporting was carried out over the period November 2007 and March 2008. It involved among others the following activities:

- Ground Geophysical Surveys for Production Borehole Siting
- Drilling of Production Boreholes
- Test pumping of Production Boreholes,
- Updating of the Numerical Groundwater Model and simulation of Wellfield Abstraction
- Borehole Geophysical Logging
- Resource Evaluation
- High Precision GPS Survey of Production Boreholes

A detailed discussion of the project activities, results, conclusions and recommendations is presented in **Chapters 4** to **14** of this report.

4 REGIONAL AIRBORNE GEOPHYSICAL DATA SETS

4.1 INTRODUCTION

Regional-scale geophysical mapping coverage, within the 230 km (E-W) by 170km (N-S) project area covering the Ncojane and Matlho-a-Phuduhudu Blocks is restricted to the following data sets.

- Aeromagnetic Survey Data (systematic grid coverage)
- Gravity Survey Data (widely-spaced traverses)
- Seismic Reflection Data (four widely spaced traverses)
- Magneto-Telluric Data (widely-spaced soundings along 1 seismic traverse)

These data sets were reviewed (seismics, MT) or interpreted (aeromagnetics, gravity) during the Hunhukwe/Lokalane groundwater survey project (WCS, 2001), whose western extent included the present Matlho-a-Phuduhudu Block. Findings from WCS analysis were that the major information content of the gravity, seismic and magneto-telluric survey data related to a thick Nama Group sedimentary basin overlying deep (~10km) crystalline basement units, and capped by a relatively thin (<1,500 m) succession of Karoo sediments. As little or no detailed mapping information was apparent in these geophysical data sets concerning shallow Karoo strata, which were the focus of this project, they were discounted as being of minimal importance in groundwater exploration. Consequently no further review/interpretation of gravity, seismic and magneto-telluric data sets was deemed necessary.

4.2 AEROMAGNETIC DATA SOURCES

Aeromagnetic data extending beyond the project area was sourced from the following data sets:

- Reconnaissance Aeromagnetic Survey of Western Botswana (Terra Surveys, 1976)
- Kang II Aeromagnetic Survey (Geodass, 1987)
- Block B Aeromagnetic Survey (Geodass, 1988)
- Okwa Aeromagnetic Survey (Geodass, 1987)
- Aeromagnetic Survey of the Ghanzi-Chobe Fold Belt (Geodass, 1993)

Reconnaissance aeromagnetic survey data (1976) along N-S flight lines at a mean terrain clearance of 300 m and a line spacing of 4,000 m constitutes the only available aeromagnetic coverage of the Ncojane and western Matlho-a-Phuduhudu Blocks. The other data were acquired along N-S to NW-SE flight lines at a mean terrain clearance of ~85 m and a line spacing of 250 m, and constitute the 'high-resolution' data set.

All surveys pre-date GPS navigation facilities and airborne survey DTM elevation data are consequently not available. However, NASA shuttle radar DTM data is available for the area was incorporated into an interpretation of ASTER satellite imagery (**Chapter 5**).

Total magnetic field images from low and high resolution aeromagnetic data are optimally rendered with grid cell sizes of 600 m and 60 m respectively, reflecting their widely disparate spatial mapping resolutions. Low resolution data (i.e. over the Ncojane Block) is suitable only for large-scale regional and deep basin mapping, as exemplified in the merged total magnetic field data (**Figure 4.1**). The outlines of shallow dolerite sill sub-crops are well-imaged as continuous features in the high-resolution data over the Matlho-a-Phuduhudu Block and to the east, while their western counterparts appear as discontinuous magnetic noise over the Ncojane Block. Vertical gradient transforms exacerbate aliasing phenomena within the low-resolution data, resulting in high amplitude noise over the Ncojane Block dolerites while resulting in crisp imaging of the equally shallow Ghanzi Group surveyed from the high resolution data **(Figure 4.2).**

A limited litho-structural interpretation of the greater project area was undertaken using the following data transforms:

- Sunshaded total magnetic field images for all data
- Sunshaded vertical gradient and analytical signal images for the high resolution data set
- Sunshaded residual magnetic field data for the low resolution data set

This was generated by upward-continuation of the original TMI data-set to 5000 m and subtraction of same from the TMI. Tight residual field contouring also assisted in interpretation.

Intermittent magnetic modelling was undertaken to confirm and supplement prior depth-to-magnetic basement estimates. Shallow dolerite depth estimates are subject to large error variances where based on the low-resolution aeromagnetic data.

4.3 AEROMAGNETIC DATA INTERPRETATION

The final report for the Hunhukwe/Lokalane Project (WCS, 2001) provides a first pass 'line' interpretation of aeromagnetic data over the present area of interest along with discussions of lithology and structure. Their litho-structural discussion is comprehensive and briefly referenced below. This existing aeromagnetic interpretation has been upgraded to provide better control on:

- Basement contacts
- Faulting
- The aerial distribution of Karoo intrusives
- Hitherto unmapped structural lineaments of possible hydrogeological significance

4.3.1 INTERPRETATION OF LITHOLOGICAL/STRUCTURAL UNITS FROM AEROMAGNETIC DATA

The area of interest lies to the west of the Kalahari Line and within the Southwest Botswana Karoo Basin (Smith, 1984), which contains a modest thickness (<1,200 m) of nearly flat-lying Karoo formations above a succession of Nama Group sediments which have a thickness of up to 10 km. The latter are absent east of the Kalahari Line and truncate in the northwest against the Ghanzi Group on the Ghanzi Ridge. The Karoo of the Western Central Kalahari Basin (Smith, 1984) occupies the area to the east of the Kalahari Line, where up to 1,000 meters of strata are floored by Achaean and Proterozoic basement. In general, magnetically active lithologies within the project area are constrained to Precambrian basement units and late Karoo-age intrusives. An interpretation of lithological and structural units of the project area based on the existing aeromagnetic data is discussed below.

4.3.1.1 THE TSHANE ULTRABASIC COMPLEX/KALAHARI LINE

Total magnetic field data (**Figure 4.1**) is dominated by long wavelength magnetic anomalies (M1 and M2 of **Figure 4.3**) reflecting Precambrian basement lithologies. The most predominant of these relates to the ~12 km to 15 km wide, approximately north-south striking structural corridor (F1) of the Kalahari Line and associated ultrabasic intrusions of the Tshane complex (M2). Large amplitude, predominantly positive, long wavelength magnetic anomalies map out these intrusions as deep-seated, curvilinear to plug-like units at depths of 1,000m to 2,000 meters (exceptionally 3,000 m). The complex appears to bifurcate over the central sector where it is intersected by the NE-striking Makgadikgadi Line (F2), to form western (M2) and eastern (M3) limbs. The former is the more continuous and deeper of the two, and appears to be fault bounded to the west and east, and hosts at least two, parallel, steeply dipping curvilinear intrusive bodies. Individual fault blocks are readily apparent along strike.

The northeast striking magnetic anomaly M2 in the southwest sector maps a deep basement unit whose provenance may be similar to that of the Tshane Complex. It is characterised by ultra-long wavelengths and a 'HI-LO' magnetic signature along its eastern contact. Modelling places its upper surface at ~10 km below surface, where it presumably floors the Nama Group Basin as a slab-like unit with a possible shallow westerly dip.

An up to 50 km wide package of closely spaced, mostly shallow wavelength and predominantly positive magnetic anomalies (M4) falling in the northern sector between the twin limbs of the Tshane Complex, reflects the sub-crop location of the Okwa Basement Complex. This uplifted, fault-bounded block of Achaean basement gneiss is overlain by a thin (~50m) mantle of Kalahari Beds in the north and Stormberg Lava in the south, tapering out further southwards. Internal structures combine folding and shearing, the anastomosing pattern of the latter carving out northeast oriented lozenges of litho-magnetic horizons (**Figure 4.3**).

4.3.1.2 The Ghanzi Group

Tightly folded and faulted metasediments of the northeast striking Ghanzi Group sub-crop and outcrop in the extreme northwest along the Ghanzi Ridge, where they are crisply imaged in the high resolution data (**Figure 4.3**) as continuous belts of weakly magnetic, short wavelength, predominantly positive anomalies (M6) separated by broad, magnetically quiescent zones. Shallow units are barely imaged in the low resolution data, consequently there is no aeromagnetic mapping support for the 'Ncojane Ranches Inlier' of Ghanzi strata (WCS, 2001). Strike-parallel faulting (possibly thrusting) is readily identified from the convergence of litho-magnetic units, and open to closed folds are obviously present. The Tsau Fault Zone (F3) forms the contact between Ghanzi and overlying Nama Group/Karoo strata and its geometry is more complex than shown on the existing interpretation maps.

4.3.1.3 The Nama Group

The Nama Group underlies a large part of the project area but does not outcrop/sub-crop within the present area of interest. Aeromagnetic responses are absent.

4.3.1.4 The Okwa Group

This Group comprises fault-bounded volcanic and sedimentary rocks exposed in the Okwa Valley Inlier and interpreted to be deposited over the Okwa Basement Complex prior to Nama deposition (Carney et al, 1994). No geological maps delineate their distribution, but the magnetic unit M5**,** immediately east of the Okwa Basement Complex, may in part reflect their sub-crop distribution. This unit (M5) is characterised by continuous and thereby locally unique curvilinear horizons of limited aerial extent (**Figure 4.3**).

4.3.1.5 Karoo Supergroup Sedimentary Formations

Karoo Supergroup units from Dwyka through Lebung Groups are magnetically transparent and high or low-resolution aeromagnetic data yields no information concerning their aerial distribution or internal structures.

4.3.1.6 Karoo Age Volcanics

Stormberg Lavas at the top of the Karoo succession are characterised by areally extensive zones of short-wavelength magnetic 'noise' of modest amplitude and internal linear structures reflecting fracturing are occasionally present. The Stormberg Lava is extensively developed (M7) over the extreme northeast of the map area, from which an up to ~14 km wide tongue extends westwards to the locality of Ncojane Ranches and beyond.

4.3.1.7 Late Karoo or Post Dolerite Sills

Late Karoo dolerite sills (M8) occupy most of the southern sector of the area (Ncojane Block), where they are present as multiple intrusions at various levels within the Karoo. On the high-resolution data-set (**Figure 4.3**) they are unambiguously defined as short wavelength, randomly oriented curvilinear magnetic anomalies of modest amplitude and often characterised by distinctive sickle or half-moon shaped strike-traces. These signatures are lost within the low resolution data, where areas of sill activity merely appear as areally extensive zones of magnetic noise. Defining their boundaries in the west is therefore problematic. Over the Ncojane Block, some attempt has been made to outline localities where sill activity may be limited or absent. The low-resolution data do not allow for meaningful modelling of sill depths and thicknesses.

Magnetic anomalies reflect sill discontinuities relating to sill breakthrough phenomena and/or faulting with significant throw. Northwest striking dyke-like units are mapped only over the extreme SE sector, and while they may continue west of the Kalahari Line, they cannot be mapped as such from the present data.

4.3.2 HYDROGEOLOGICAL ASPECTS

Potable aquifers in the region are mainly restricted to Karoo sedimentary units, namely the Ntane sandstones of the Lebung Group and the Otshe sandstones of the Ecca Group. Only the Ecca is present within the Ncojane Block. The existing aeromagnetic mapping data affords no information relating to the distribution of the aquifers.

Karoo intrusive units in the project are hydrogeologically significant, as barriers to groundwater flow, where they can be confidently mapped. Sills within the Ncojane Block act to partition shallow saline Mosolotsane/Kule Formation aquifers from deeper, fresh Ecca aquifers below the sills. However, the low resolution data available for the Ncojane Block does not allow confident identification of sill presence as relatively thin units at shallow depths.

4.3.3 STRUCTURAL INTERPRETATION

The structural setting of the project area was well-documented in the Hunhukwe/Lokalane Project Area Report (WCS, 2001), and only major structural features delineated in the present aeromagnetic interpretation exercise are briefly discussed below.

Aeromagnetic mapping of faults is only feasible where stratigraphic units carry litho-magnetic horizons. The near surface presence of approximately 1,000 meters of magnetically transparent Karoo sedimentary rock restricts confident fault-mapping to locales underlain by the Tshane and Okwa Basement Complexes, the Ghanzi Group and the Stormberg Lava. Less confident fault delineation is often possible over areas of sill activity, most notably to the east of the Kalahari Line along northeast striking lineaments parallel to the Makgadikgadi Line. These cannot be mapped to the west of the Kalahari Line, nor with few exceptions, can possible structures along NW-SE striking dykes be mapped.

The north-south trending Tshane Complex located along the Kalahari Line appears to be fault-bounded (F1, F1A, **Figure 4.3**) to the east and west, and internally dissected by NNW-faulting, most notably in the south. The Complex bifurcates in the central sector where it is locally cross-cut by fault zones (F2) associated with the NE-striking Makgadikgadi Line. A south-westerly extension of the latter may bound the eastern contact of the ~10km deep magnetic basement unit. Strike-parallel faulting and/or thrusting (F3) is readily apparent along the NE-trending Ghanzi Group in the NE-sector. Here the multiple thrust zones of the Tsau Line downthrow Ghanzi metasediments to the south and form the stratigraphic boundary with Karoo and underlying Nama sediments.

Based on the subtle alignment of magnetic lineaments presumably reflecting disruptions along near-surface sills, WNW-striking faults **F4** and **F5** have been interpreted over the Ncojane t Area and to the east as well as NNE Faults **F6** and **F7**.

Interpreted faults **F4**, **F5, F6 and F7** were found to have significant hydrogeological control in the project area as will be discussed in **Chapter 11**. The location of these faults on the ground is, however subject to significant error due the low resolution nature of the data (±3km) and need to be confirmed with ground surveys.

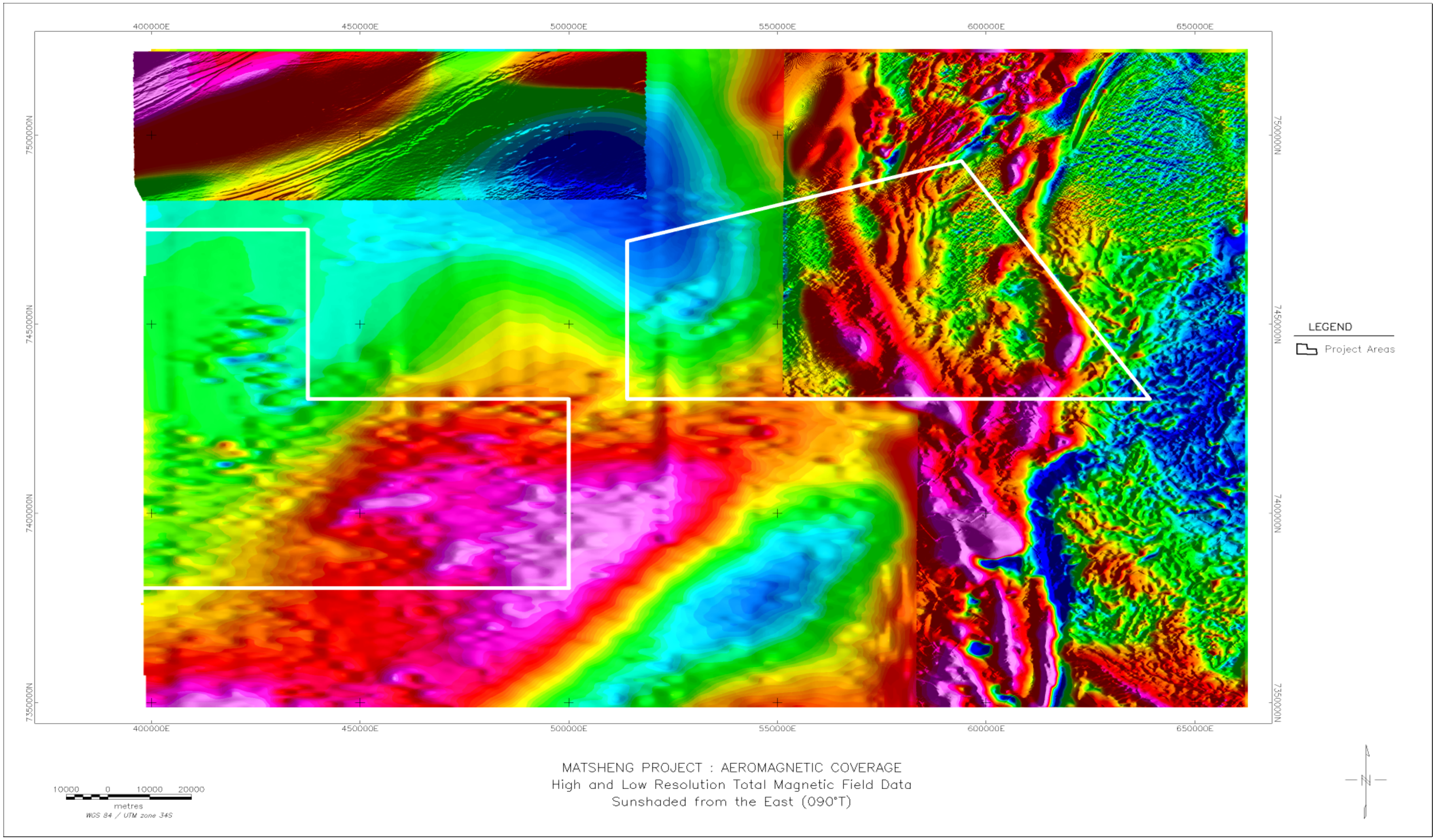

Figure 4.1 Total Magnetic Field Data of the Project Area

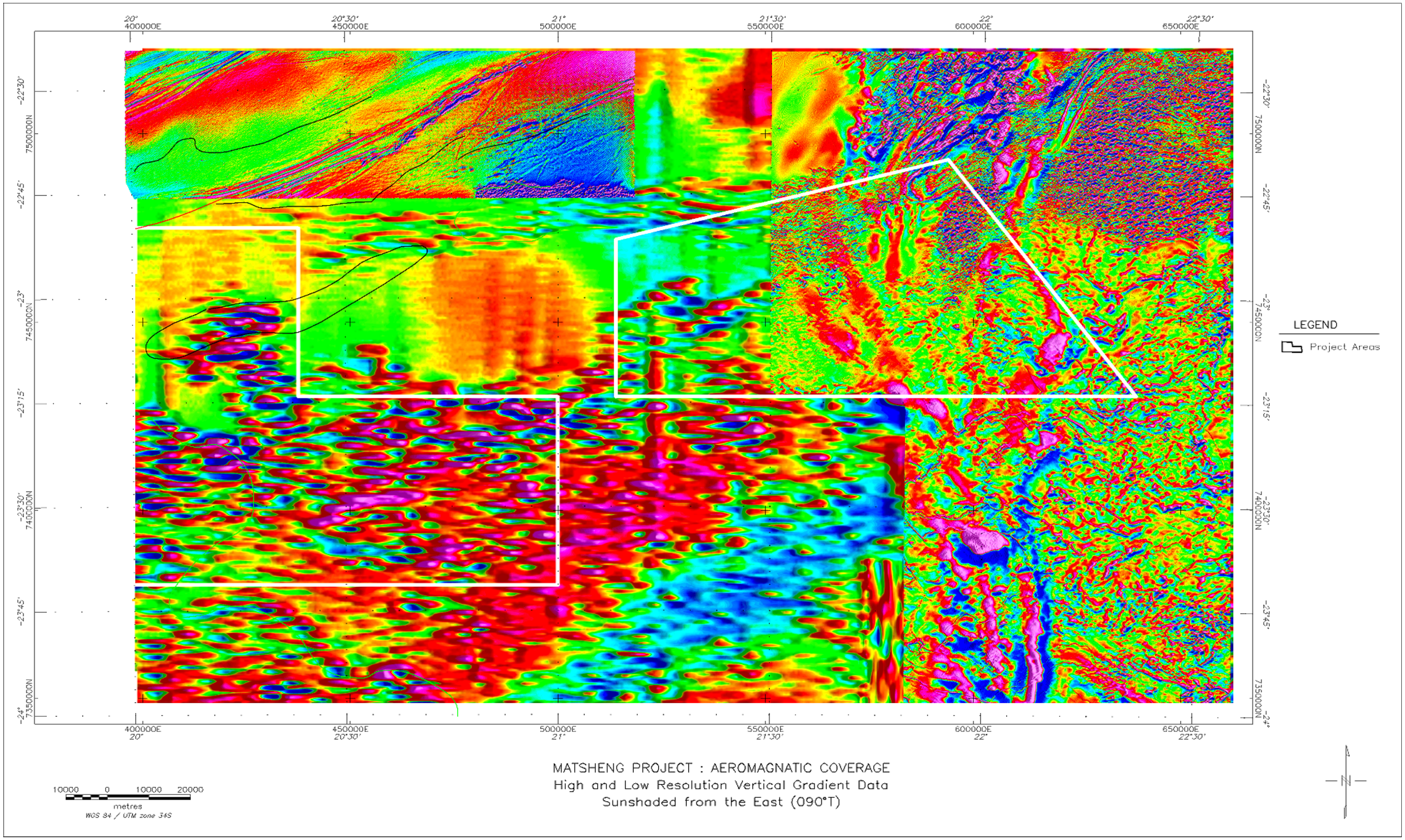

Figure 4.2 Vertical Derivatives of Total Magnetic Field

Figure 4.3 Litho-Structural Map from Aeromagnetic Data Interpretation

5 SATELLITE IMAGERY INTERPRETATION

5.1 OBJECTIVES AND INTRODUCTION

The objectives of satellite imagery interpretation, involving the use of Advanced Spaceborrne Thermal Emission and Reflection Radiometer (ASTER) images supported by ancillary data, was to detect structural lineaments and evaluate the potential of the detected lineaments as targets for groundwater exploration activities. Results of the remote sensing interpretation were collated and compared with the results of the regional aeromagnetic data interpretation to demarcate groundwater exploration targets.

ASTER images were used because of among other reasons, their high spatial resolution (15 m) and their multi-spectral design in the short wave infra red (SWI) and thermal infra red (TIR) spectral regions which allows for better surface soil–regolith discrimination and calculations of surface temperatures respectively. Ancillary shuttle radar topographic mission elevation data were used to detect linear topographic anomalies as indicators of buried structural features. The maps of lineaments derived from remote sensing interpretation were validated against the regional geological map to avoid mapping false lineaments.

It is important to emphasise at the onset that remote sensing data is useful for lineament mapping even in areas covered by thick unconsolidated sand cover. There are several scientific explanations given below as to why fractures, lineaments and fault patterns can be observed even through thick soft-sediment cover:

- Hard-rock fracture patterns and features such as dykes control the topography of the depositional surface on which younger sequences accumulate; they exert control over sedimentary patterns and processes (water and airborne) in the younger sequences, such that these sequences ‘inherit’ the more significant structural features and patterns of the basement on which they are deposited

- The daily flexing of the basement and cover due to earth-tides causes propagation of basement fractures upwards through overlying cover. Thus basement trends are again ‘inherited’ by the unconsolidated to semi-consolidated cover sequences

- Groundwater movement along basement fractures, close to the basement-cover contact, can cause basal erosion of the unconsolidated cover, resulting in subsidence at the surface and thus a surface expression of the buried fracture. Alternatively, upward percolation of groundwater from basement fractures into the younger cover can cause chemical and/or physical differences in the sediments over the fracture compared to those located off the fracture resulting in detectable differences at the surface

- Older structures can be re-activated as preferential zones of weakness during younger tectonic events. For example the younger north-easterly trending lineaments in the study area are parallel to active African Rift Valley structures, which in turn are parallel to older Precambrian structural trends. Since these are active tectonic structures, they will be visible in even the youngest sediments

5.2 DATA

Seven ASTER Level 1B images (scenes) which cover a large portion of the study area were used in this study. The seven images used were acquired on different dates as follows:

Image 1 - ID: AST_108290928 - DATE: 2000-12-29
Image 2 - ID: AST_108290929 - DATE: 2000-12-29
Image 3 - ID: AST_109290769 - DATE: 2001-01-14
Image 4 - ID: AST_109290770 - DATE: 2001-01-14
Image 5 - ID: AST_107151027 - DATE: 2000-11-04
Image 6 - ID: AST_111170503 - DATE: 2001-02-08
Image 7 - ID: AST_204260492 - DATE: 2001-09-11 (cloudy)

Since ASTER is not on a regular acquisition cycle (compared to commercial sensors such as Landsat), a large time separation of images to obtain complete area coverage is often unavoidable. Images 1 to 4 cover the western part (Ncojane Block) of the study area, together with Image 7, which has a large amount of cloud cover. A substitute image was not available within the time frame of the acquisition of the other scenes, so NDVI and Aster temperature maps for the areas close to the cloud cover and their shadows are unreliable.

Although Image 5 covers a large part of the Matlho-a-Phuduhudu Block, a small strip of Image 6 was used to cover the whole area. Since Images 5 and 6 (early summer versus late summer respectively), are from 2 different seasons, extra care was taken while evaluating NDVI image mosaic of this block.

Two Landsat-7 Band-8 images were used to fill the ASTER data gaps for lineament analysis. Details of the 2 images used are provided below.

Image No. 1: **-** Landsat 7, Path 175/ Row 76, Date of acquisition: 13/06/2000
Image No. 2: Landsat 7, Path 176/ Row 76, Date of acquisition: 04/06/2000

5.3 METHODOLOGY

A number of image processing steps were carried out before the ASTER images were converted to useable formats for interpretation purposes. These steps were as follows:

- Conversion from Level 1A to Level 1B
- Image Geo-Referencing & Image Mosaics Production
- Standard Image Composite Production
- De-correlation Image Composites,
- NDVI Production
- Thermal Image Production
- Lineament Analysis

The methodology for each of the above mentioned steps is discussed below.

5.3.1 CONVERSION FROM LEVEL 1A TO LEVEL 1B

ASTER level 1A images were converted to useable Level 1B format using L1A to L1B conversion software. This process performs de-stripping of the data, radiometric balancing, and geodetic geo-referencing of the data to latitude-longitude grid points supplied as ancillary data with the NASA level 1A product. This complex conversion process also registers the short wave infra-red (SWIR) bands to each other (in level 1A the bands are not registered due to offset of the SWIR detector banks on board the ASTER sensor), and also performs a visible near infra VNIR-SWIR-TIR registration, in order to correct for the different pointing directions of the three instrument telescopes on the ASTER sensor.

5.3.2 Image Geo-Referencing & Production of Image Mosaics

Approximately 10 ground control points, located in the field using a Garmin handheld GPS receiver, were used to geo-reference two Landsat-7 Band-8 panchromatic scenes. A LANDSAT-7 band mosaic was then created using these two geo-referenced images. Projection parameters used during the geo-rectification process were as follows.

Projection:	Universal Transverse Mercator (UTM)
Zone:	34S
Ellipsoid:	Clarke 1880
Datum:	Cape.

The ASTER images were then geo-referenced to the Landsat-7 panchromatic referenced image, and re-projected to the UTM projection using above mentioned projection parameters.

For ease of subsequent computation and interpretation, the ASTER images were mosaiced as follows

1. **Images 1 and 2**: same date and flight path (Image Mosaic 1)
2. **Images 3 and 4**: same date and flight path (Image Mosaic 2)
3. **Images 5 and 6**: 3 month date separation (Image Mosaic 3)
4. **Image 7**: treated separately because of cloud cover (Image 4)

In the case of Mosaics 1 and 2, a normalised contrast balancing was applied to all the mosaiced bands in order to balance slight differences in brightness between the images.

5.3.3 Standard Image Composite Production

Following the mosaicing process, band 2 images (red bands) were normalised to band 3NR (near infrared), using linear regression analysis. This ensures that the red band images are in balance with the near-infrared images for subsequent NDVI calculations, and removes potential atmospheric scattering effects (Mie scattering by dust and smoke) from the red band. Mosaic 1 was found to have a large scattering component in band 2, possible due to smoke and dust haze prevailing at the time of acquisition. The following image composites were then produced for each mosaic and for Image-7 independently

- False colour photo-infrared 3N-2-1 RGB
- False colour SWIR 468 as RGB
- False colour VNIR-SWIR 246 as RGB (involved re-sampling of bands 4 and 6 to VNIR 15m using a bilinear interpolation algorithm)
- False colour TIR 10-12-14

5.3.4 De-correlation Image Composites

Because of the limited separation in ASTER's SWIR and TIR wavelengths, these composites have limited colour range, and separation of surface materials is therefore limited. The following composites were therefore produced to enhance the distinction between surface materials.

- Conversion of the 246 RGB combination to Hue-Intensity-Saturation (HIS) colour space (Drury, 2001), and production of a Hue - Band 2 – Saturation image
- Conversion of the 468 RGB combination to Hue-Intensity-Saturation colour space, and production of a Hue - Band 2 – Saturation image
- De-correlation stretching of the TIR bands 10-12-14 combination, using a normalised de-correlation stretch

5.3.5 NORMALISED DENSITY VEGETATION INDEX (NDVI) PRODUCTION

A normalised vegetation density index (NDVI) was produced independently for each of the three image mosaics, and Image-7, from the normalised difference ratio of band 3N and the atmospherically adjusted band 2 ((Band 3N - Band 2)/(Band 3N + Band 2)). For Image-7, a cloud-mask was produced by thresholding out the upper population of reflections, clearly visible in the histograms of the raw VNIR bands. The band 7 NDVI was then masked to eliminate spurious, high NDVI values in the cloud-covered areas.

The 4 NDVI images (3 mosaics plus Image-7) were then combined into a single mosaiced NDVI map image. A statistical analysis of the combined image mosaic was performed, and a classification image produced assigning the area into one of eight NDVI classes, based on +/- 3 standard deviations from the mean (**Figure 5.1**).

5.3.6 THERMAL INFRA RED (TIR) IMAGE PRODUCTION

The seven image's TIR bands were processed independently using thermal processing software that iteratively identifies blackbody radiance values for the scene pixels, using initial seed values for emissivity. Thereafter actual emissivity values for each pixel are determined using the relation

$$R_\lambda = \varepsilon_\lambda B_\lambda$$

Where R is the measured thermal radiance value
ε is the emissivity
B is the blackbody radiance

Thereafter Planck's Law equation was solved for T, the temperature at each pixel.

While this method is not the same as that employed by NASA in the calculation of ASTER product 09T temperature images (Gillespie, et.al.,1999), it yields a relative temperature image that is adequate for the purpose of identifying cooler versus hotter areas although the temperatures derived are not necessarily correct in an absolute sense.

The resulting temperature images were then mosaicked into a single temperature image and statistically analysed. A temperature classification image was produced mapping the area into 8 classes based on +/- 3 standard deviations from the mean (**Figure 5.2)**.

5.4 SHUTTLE RADAR TOPOGRAPHY MISSION (SRTM) DATA ANALYSIS

Raw, non-validated SRTM data is now available for the entire world as a pre-release product from the USGS data archive. For all areas outside of the United States of America, this data is only being released at 90 metre horizontal resolution. Special software was used to fill the data gaps in this raw data (caused by smooth water or sand reflectors and topographic shadows), and compute a 30 meter elevation model by analysing the local terrain shape defined by the 90 meter radar measurement postings.

Raw data from six SRTM degree tiles was obtained for the study area and was subjected to sunshading analysis, as well as a trend removal algorithm, in order to identify both regional topographic gradients and local topographic anomalies.

5.5 LINEAMENT INTERPRETATION

Lineament interpretation was performed on hardcopy prints, as this permits a synoptic overview of the entire area, and viewing of the image obliquely along lineaments. Two sets of lineaments were produced ;

1) by interpretation of the panchromatic image mosaics (seven band 2 images = red reflectance) and

2) the spectrally-enhanced, mosaicked, Hue-Band 2-Saturation images derived from the VNIR-SWIR 246 RGB-HIS transformation.

The second step was undertaken to provide a test of reproducibility in the detection of lineaments by comparison with lineaments detected on the panchromatic image and secondly, to detect linear patterns of different soil-regolith composition, as revealed by either linear patterns of colouration or sharp boundaries between different colourations.

The interpreted lineament maps were then converted to digital format using raster to vector conversion software and the resulting vector maps were then analysed using directional analysis software to determine key directions and groupings of linear trends. These were then independently extracted from the raw interpretations, and simultaneously filtered to remove small-length lineaments (<50 meters) that can be formed by pixelation-effects during scanning of the lineament overlays.

Lineaments were then classified according to strike group. These filtered and classified lineaments were reassembled into single classified vectors, one for the panchromatic and one for the colour-image interpretation (**Figure 5.3**).

In order to identify zones where lineaments of the same strike are more frequent and closely-spaced, as well as areas where lineaments from different strike groupings intersect, a Fracture Spatial Density (FSD) map was produced for each of the lineament interpretations (panchromatic and colour interpretations). The FSD function was proposed by Renshaw 1998 as a method of calculating a fracture density parameter that is un-biased by fracture direction and the shape of the spatial element used to define the area for the density calculation. The FSD is calculated as:

Fracture Spatial Density (2D) = $(\text{SUM}_{i=1 \text{ to } n} (L/2)^2) / A$

Where n = number of fractures in area element
L = Length of fracture in area element
A = area of spatial sampling element

For practicality, the FSD was calculated in this study, for a $2km^2$ grid by;

- superimposing a 2km square grid of polygons (area elements) over the lineament maps
- vector intersection of the lineaments with the polygon grid
- determination of the length in each polygon element of each lineament contained therein
- calculation of the half lengths, squared in each polygon element
- summation of the half lengths squared for each polygon (A-PARAM = $(\text{SUM}_{i=1 \text{ to } n} (L/2)^2$)
- dividing by the area of each polygon

5.6 RESULTS AND DISCUSSION

5.6.1 LINEAMENT INTERPRETATION

Directional analyses of the interpreted lineaments from the Band 2 image and the Bands 2-4-6 composite image are presented as rose diagrams in **Figures 5.4** and **5.5** respectively**.** The general pattern of the two rose diagrams is similar, confirming that similar lineament trends are being detected in the independent interpretations and that the regional lineament pattern is reproducible.

For both sets of interpreted lineaments, the following principal directions are observed, in order of decreasing length frequency:

- **Group 1: 300-120^o (~NW-SE)** strike group; in the case of the colour image interpretation, a divergence to 340-130 degree strike is present

- **Group 2: 330-150^o (~NNW-SSE)** strike group; more prominent on the panchromatic interpretation than on the colour image interpretation

- **Group 3: 215-035^o (~NE-SW)** strike group, on the pan image 210-030, on the colour image 220-040, but elements of both present in both rose diagrams

- **Group 4: 360-180^o (N-S)** strike group, on the panchromatic image, and on the colour interpretation more 355-175

- **Group 5: 265-085^o (~E-W**) strike group, barely mapped on the panchromatic interpretation, but quite strong on the colour image interpretation

- **Group 6: 240-060^o (~ENE-WSW)** strike group, barely mapped on the colour interpretation, but quite distinct on the panchromatic image interpretation

These lineaments were validated as geological features by comparing them to mapped geological structures from the surrounding region. A rose diagram of strike directions for the mapped fault segments (From a 1:1,000,000 digital geological map of Botswana) for an area 320 km E-W by 278 km N-S around the study area was produced (**Figure 5.6)**.

Although the loadings in the different directions are different from those in (**Figures 5.4** and **5.5)**, similar directional groupings exist as follows:

- A 240-060^o to 260-080^o trend (similar to interpreted **Groups 3** and **6**) is dominant. These faults represent the neo-tectonic, quaternary faults aligned with the Ghanzi-Chobe fold belt structures, occurring to the north of the study area. This is why the **Group 3** and **6** lineaments detected are considered real tectonic features, probably representing the youngest fractures in the area, and could be significant in terms of groundwater occurrence in view of their probable extensional nature

- A weak fault strike trend is also apparent in the regional fault pattern, ranging from 290-110^o to 310-130^o. This corresponds to the dominant **Group 1** (NW-SW) lineament set detected on both image sets. While this trend is thus confirmed as being associated with known fault trends in the area, it is also the dominant strike direction of dolerite dykes in Botswana, as illustrated in **Figure 5.7**. Thus **Group 1** lineaments could probably represent surface linear disturbances over buried dykes, associated dyke-parallel faults, and extensional subsidence structures in the overlying sediments as these “drape” over basement ridges caused by dolerite dykes.

A comparison of lineaments detected in this study with mapped geological features indicates that the majority of these lineaments are related to geological structural features. When comparing the geological map with the lineament maps it was observed that some of the interpreted lineaments are actual physical extensions into the study area of mapped faults and their pattern is in agreement with the surrounding mapped fault pattern.

The computed FSD maps serve three purposes: they aid in the identification of broader fracture zones, assist in simplifying the overall fracture pattern for visual analysis, and help to locate areas where several lineaments of different strike directions intersect, creating areas of probable higher secondary permeability. FSD factors range from 0 to 0.71 for the colour image set and up to 0.83 for the panchromatic image set.

A weights-of-evidence GIS layer was computed to provide a fracture-density and fracture-intersection component in the exploration target model by summation of the two FSD models, and re-classing the result into weight groupings according to the mean and standard deviation statistics of the summation layer. The re-classed layers were re-sampled to 30 meters using nearest-neighbour interpolation. Summation of the FSD layers incorporates a factor for extra weighting of those areas in the final model where lineaments were detected on both the panchromatic and colour image interpretations. The statistics of the FSD summation layer and the weightings assigned to standard deviation classes are given below.

Mean FSD = 0.14, STD DEV = 0.20

- Class 1 – all values less than or equal to FSD mean: weighting = 1
- Class 2 – FSD values less than or equal to 1 sigma above mean: weighting = 2
- Class 3 – FSD values 1 to 2 sigma above mean: weighting = 3
- Class 4 – FSD values 2 to 3 sigma above mean: weighting = 4
- Class 5 – FSD values greater than 3 sigma above mean: weighting = 5

5.6.2 TOPOGRAPHIC ANALYSIS

The project area is characterised by limited topographic variation, with a total elevation range of 405 metres for the full area of the DEM (**Figure 5.8)**. The prominent topographic features of the area are the wide fossil Okwa River Valley to the north, a 100 meter high fault scarp in the extreme northeast (part of the Ghanzi-Chobe Fold Belt fault system) and an elevated area in the Ncojane Block. Closer investigation reveals subtle structural control on the local topography. The boundaries of the elevated area (coloured yellow through red to pink) are seen to be linear, and trend approximately NW-SE and NE-SW. Narrow ridges in the topography extend south-eastwards from this elevated area, and also have a bearing of 300 to 310 degrees. These directions correspond to lineament directional **Groups 1** and **2** interpreted from ASTER images. The NW-SE trend corresponds to the dominant trend of dolerite dykes in Botswana, and it is therefore significant that subtle topographic ridges with this direction are observed. The NE direction corresponds with the neo-tectonic, Ghanzi Chobe Fold fault directions, and the detection of this direction in the topography indicates that these structures are actively disrupting the present topographic surface.

There is regional topographic slope towards ~ENE which is parallel to the Ghanzi Chobe Fault alignment and Group 6 lineaments. The residual of first order trend surface from topographic surface reveals subtle local deviations in the topography from the regional surface. Prominent in this image is a residual ridge trending roughly 290 degrees (~WNW) in the eastern portion of the study area and is parallel to the direction of dolerite dykes in Botswana (**Figure 5.9**). It is interpreted as being the product of a buried dolerite dyke and has been offset in several places along a 060 (~ENE) direction, coincident in some instances with interpreted lineaments. This observation confirms the 060 (**Group 6**) fault direction as being younger than the 300 (~WNW) direction (**Group 1**). It also supports the interpretation that **Group 6** lineaments are related to the active Ghanzi Fold Belt system.

Based on the observations made on the analysis of the topography of the area, together with the conclusions reached as to the probable geological origins of the mapped image-lineaments, a weights-of-evidence GIS layer was modelled (at 30m resolution) for each filtered lineament map. Lineaments were assigned weightings as follows;

- Group 1 (**~NW-SE)**: weight = 5: parallel to dykes and at near right-angles to the regional topographic gradient: probably significant as local groundwater transfer structures especially where they occur alongside dykes.
- Group 2 **(~NNW-SSE)**: weight = 2: sub-parallel to dykes, local transfer in a NE direction only expected along these from one NE trending fracture to another.
- Group 3 **(~NNW-SSE)**: weight = 8: obliquely down topographic gradient. Possibly act as pathways across local topographic highs / dykes
- Group 4 **(N-S)**: weight = 6: north-south striking, very oblique across topographic gradient, Also transect NW striking topographic barriers / dykes
- Group 5 **(~E-W**): weight = 8: 20 degrees off the regional topographic gradient; Possibly

associated with the neo-tectonic, Ghanzi Fault system

- Group 6 (**~ENE-WSW**): weight = 10: strike down the topographic gradient, parallel to the Ghanzi Fold Belt system observed north of the study area, and are probably extensional in nature
- Background = 1

These relative weightings are based on simple logical assumptions regarding hydraulic gradients and proposed origins of the lineament groups. Without data characterising the actual physical properties of these lineaments (origin, fault type, aperture width, hydraulic conductivity, flow rates and volumes, etc) it is not possible to calculate empirical weightings.

5.6.3 NDVI MAPPING AND ANOMALIES

The patterns on the regional NDVI map **(Figure 5.1)** are significantly disturbed by human activity, as many of the low NDVI areas tend to be circular and centred around rural settlements. Other low NDVI areas are clearly related to recent burn scars. Despite these interfering patterns, linear trends in the high NDVI values can be discerned, particularly in a north-easterly direction, and are often co-incident with mapped photo lineaments. Weaker north-westerly and north-north-westerly trends in high NDVI are also visible. The strong north-easterly alignment of high NDVI areas may be a confirmation that the **Group 3** and **6** and lineaments are indeed the primary pathways for groundwater movement down the regional topographic gradient.

The sigma-class ranked NDVI map was used as is, as a weights model in the prospectivity analysis function. Weightings values of 6 to 8 were assigned to fractures along which significant vegetation anomalies occur which may be an indication of near surface groundwater, and weightings of less than 5 to other areas and fractures not exhibiting high vegetation anomalies.

5.6.4 ASTER TEMPERATURE MAPPING

Comparison of the lineament maps against the ASTER temperature maps computed from the emissivity calculations indicates that the lineaments have a very variable thermal signature along their lengths. Several, are however, associated with linear lows and alignments of low temperature patches, possibly indicative of local cooling of the surface by near surface groundwater in these areas. Still other lineaments are associated with high gradients from high temperatures adjacent to the lineament, to low temperatures on the lineament (**Figure 5.2**).

5.7 INTERPRETED AREAS OF HIGHEST GROUNDWATER POTENTIAL

An infinite number of permutations exist for combining the weightings for the data sets to generate potential target areas, especially since no information yet exists to quantify the relative importance of these parameters. A simple summation of the weights for topographic, panchromatic photo-lineaments, colour photo lineaments, NDVI and temperature weights-of-evidence rasters, multiplied by the FSD weightings, was used to produce a potential target area index map, which was referred to a prospectivity model. That is;

PROSPECTIVITY = (TOPO weight + PANF weight + 246F weight + NDVI weight + TEMP weight) * (FSD weight)

This has the effect of setting areas with no detected lineaments (zero FSD) NULL or very low prospectivity, which is desirable. The undesirable result of this equation is that areas not covered by the ASTER scenes have low indicated prospectivity because of a combination of low FSD and no NDVI or temperature weightings in the ASTER data gaps. It also results in a blocky model due to the 2 km size of the FSD models, but since the goal of this analysis was to identify approximate areas of improved groundwater potential where ground geophysics can be focussed, the coarse resolution was considered acceptable.

From the prospectivity model, a groundwater potential map was generated **(Figure 5.10)**. Blocks with shades of red colour have the highest potential and other colour areas within these blocks narrow the identified areas down to positions on ideally oriented lineaments possibly with high NDVI and low temperature signals. On this map, areas of highest interpreted potential lie along or are defined by two major northwest (300^o) striking lineaments with the best areas located where north-easterly striking lineaments transect the north-westerly trend. These high potential areas are immediately to the southwest of the topographic ridge anomaly or immediately to the northeast of this ridge. On the ridge itself, the only prospective areas lie along northeast trending lineaments that offset the ridge. The groundwater potential as interpreted from this method drops off southwest of the Ncojane Block even though favourable lineament directions exist. Outside of the blocks, favourable lineament directions are highlighted as linear strips of varying colours. These zones lack a high lineament density loading and provided that the narrow zone of "faulting" and / or fracturing can be pinpointed, they may still give good yielding water strikes.

These high groundwater potential areas were identified purely on the basis of remote sensing data and are based on interpretation and modelling of favourable physical properties detectable at surface or near-surface as possible indicators of groundwater occurrence. These identified areas formed a crucial input during conceptualisation of the hydrogeology of the area and for the selection of target areas for the Exploration Phase.

Figure 5.1 Classified NDVI Image

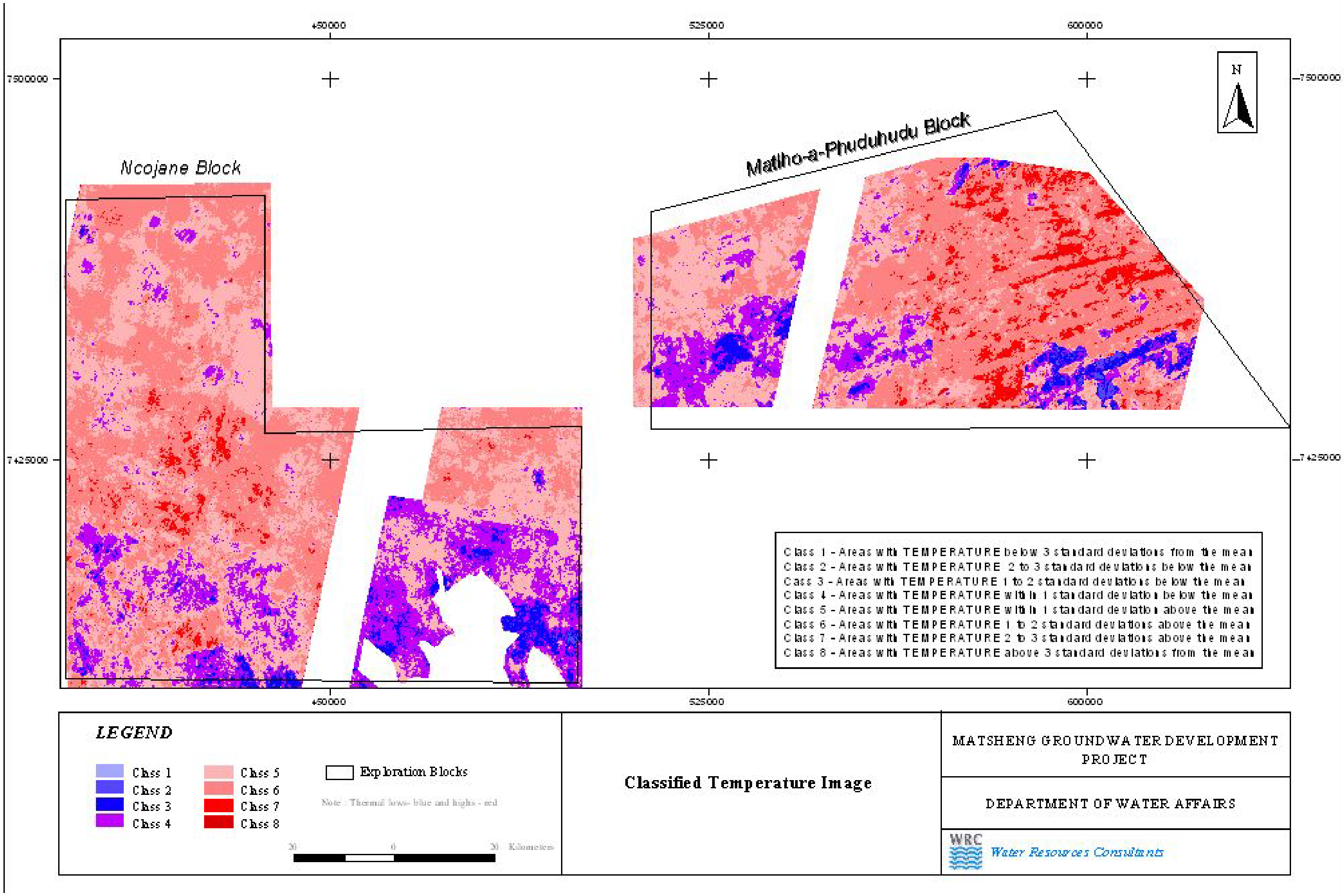

Figure 5.2 Classified Temperature Image

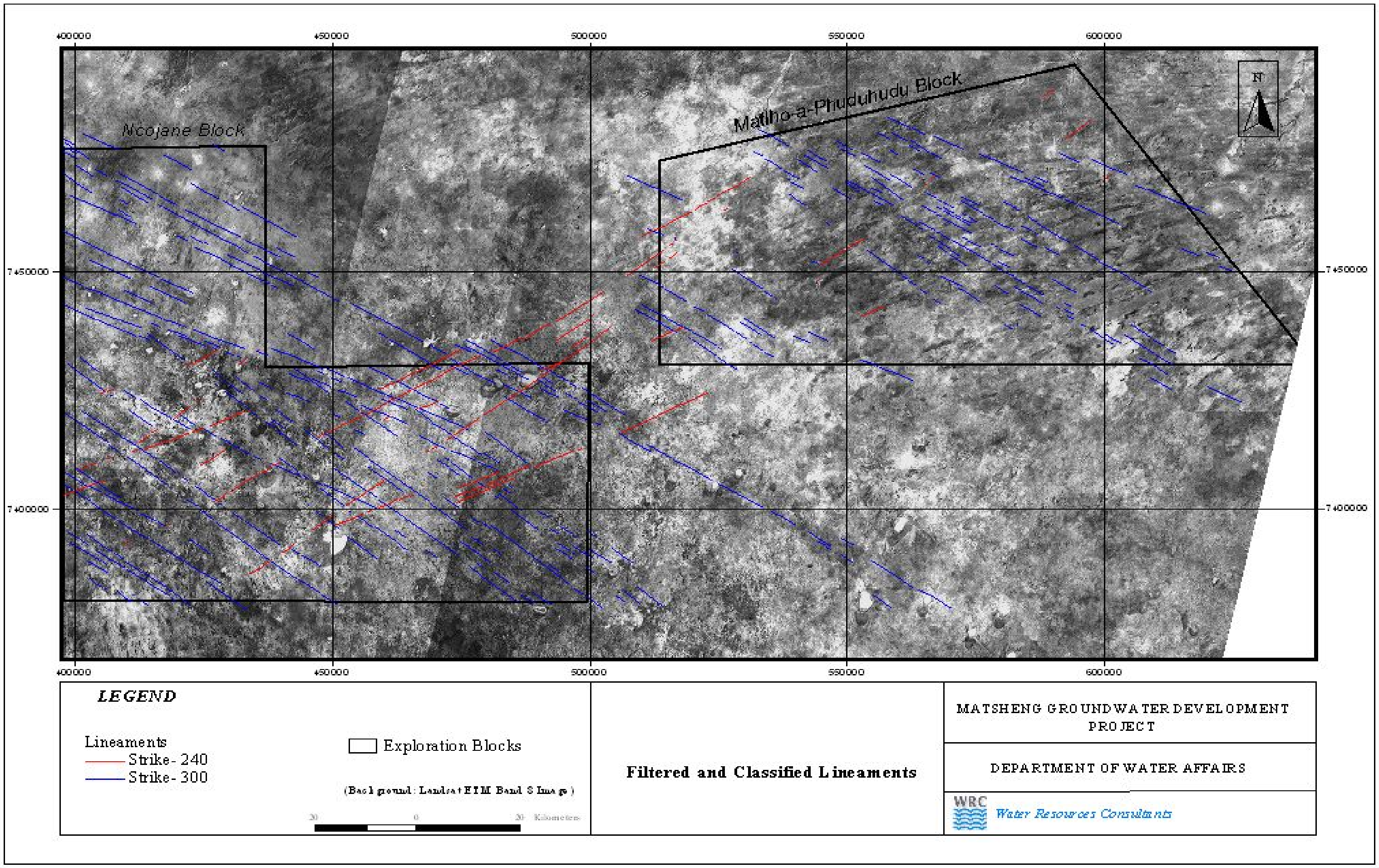

Figure 5.3 Filtered and Classified Lineaments

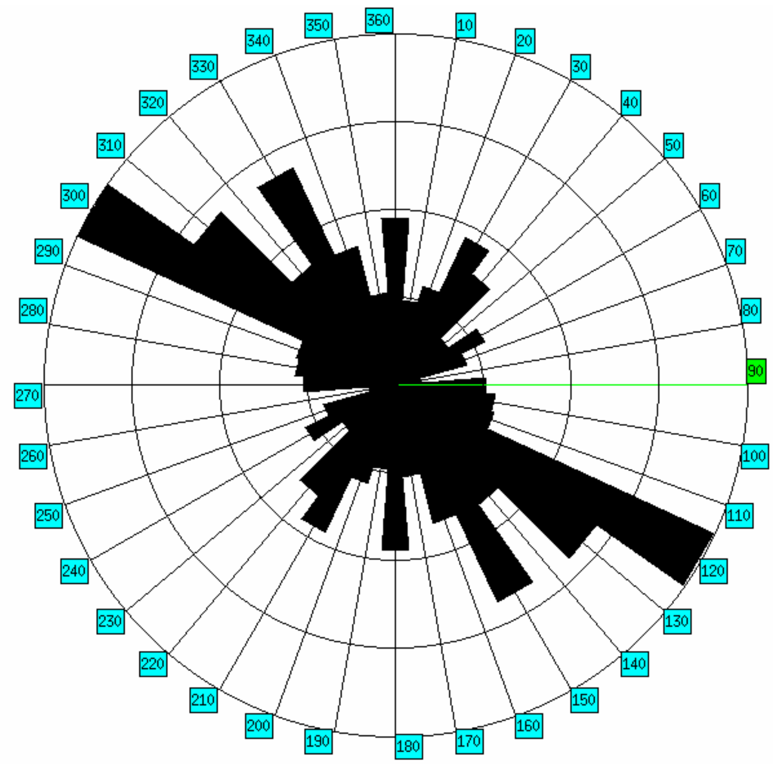

Figure 5.4 Rose Diagram of Lineaments Interpreted from Panchromatic Aster Band 2 Images

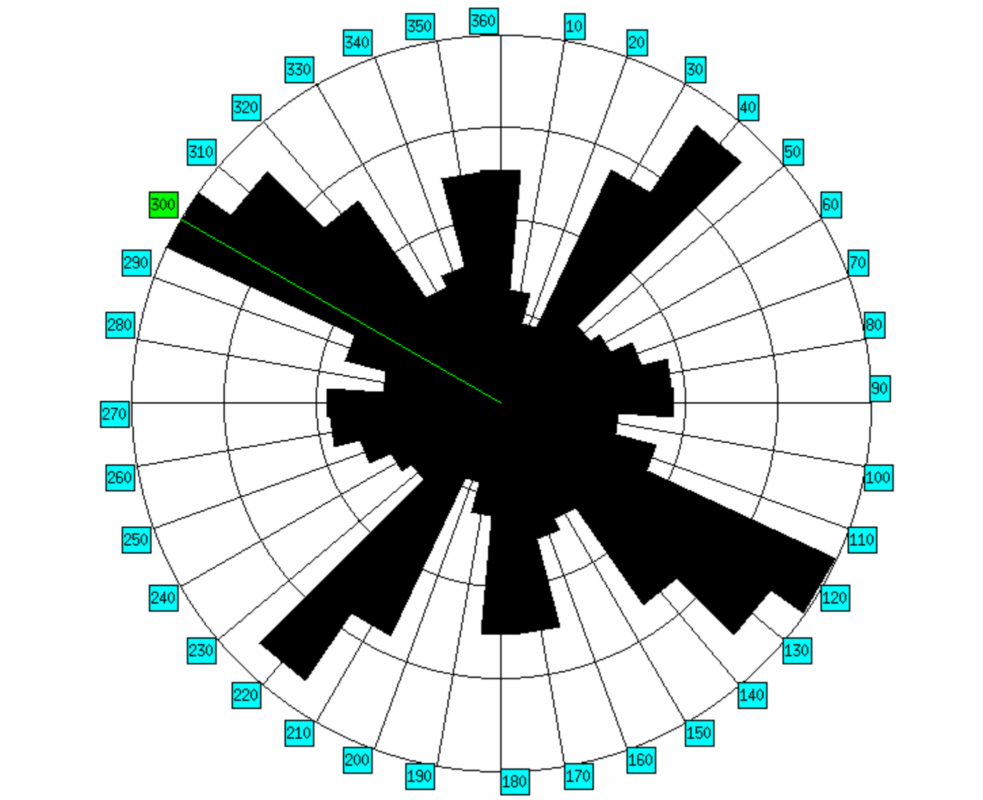

Figure 5.5 Rose Diagram of Lineaments Interpreted From Aster 246 Colour Image

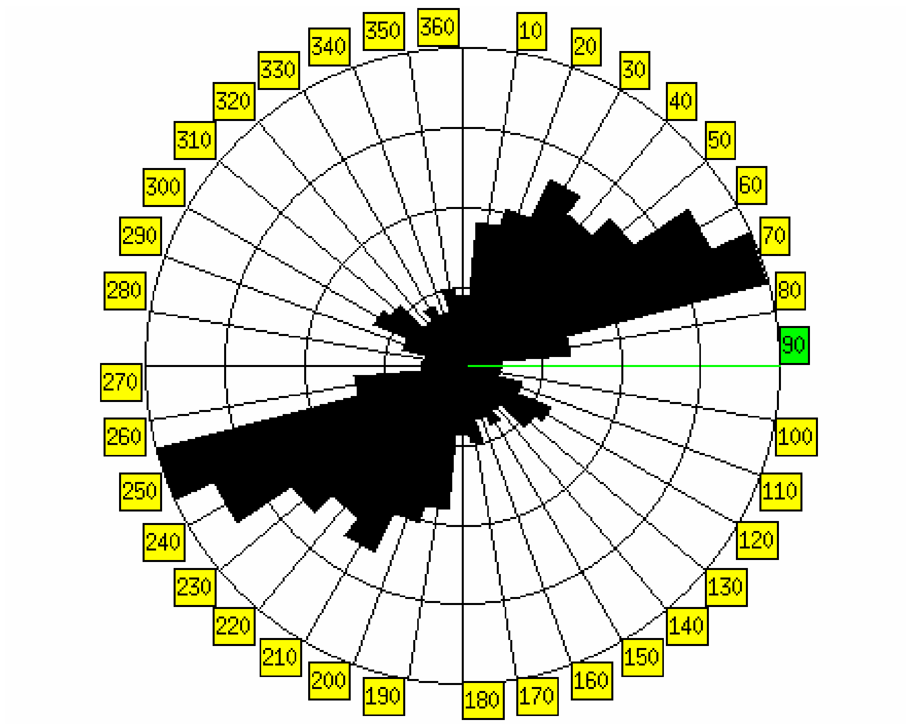

Figure 5.6 Fault Segment Rose Diagram for Mapped Faults from the 1:1 000 000 Geological Map of Botswana, For an Area Surrounding the Study Area

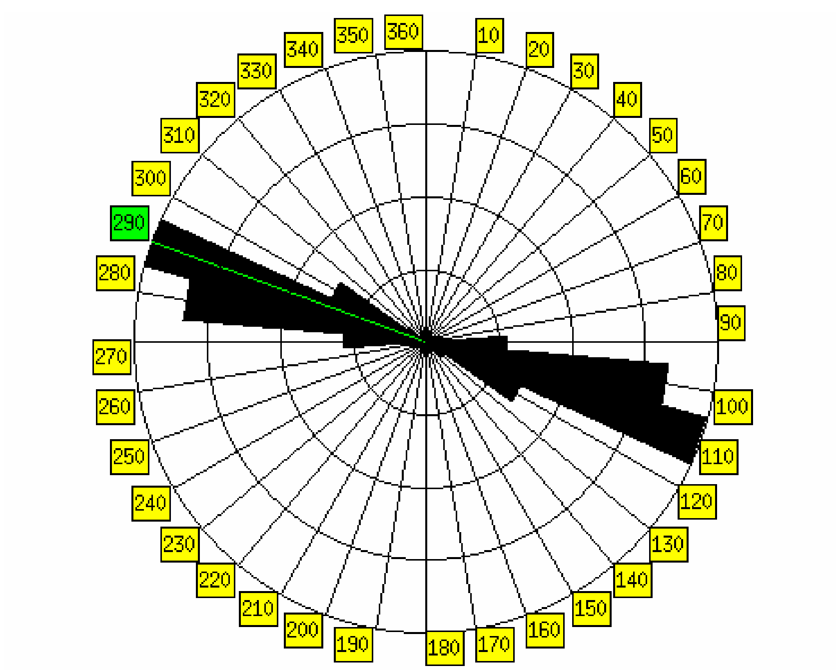

Figure 5.7 Strike Directions of Mapped Dolerite Dyke Segments, for the Entire Botswana

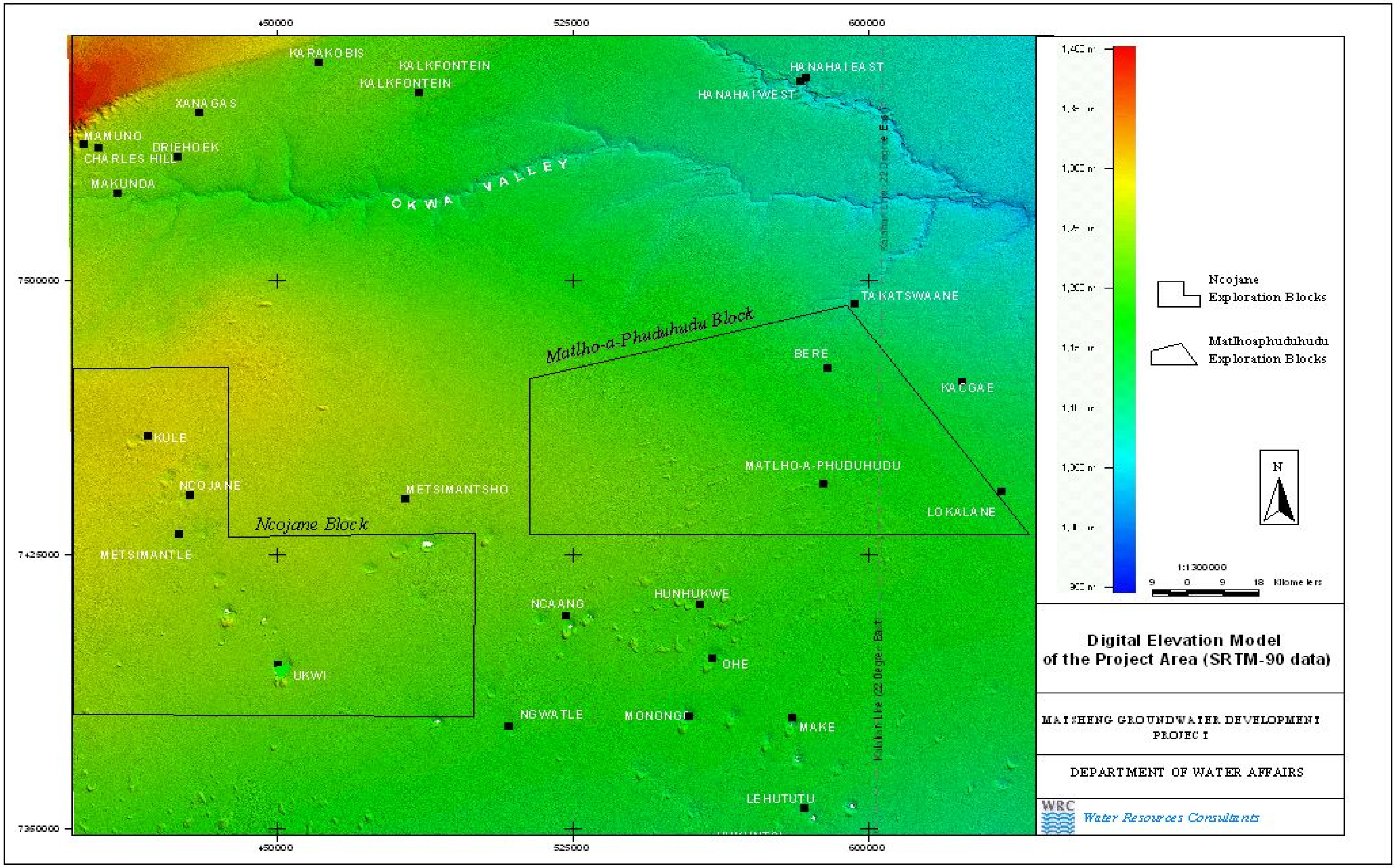

Figure 5.8 Digital Elevation Model of the Project (Srtm-90 Data)

Figure 5.9 First Order Trend Surface from Topographic Surface

Figure 5.10 Location Of Potential Target Areas Based On Remote Sensing Interpretation

6 GROUND GEOPHYSICS

6.1 OBJECTIVES

The objectives of the ground geophysical surveys were as follows;

- Locating/confirming structural features such as faults, lineaments and dolerite intrusions identified from aeromagnetic and remote sensing data interpretation
- Inferring subsurface lithological units and groundwater quality variations with depth
- Siting of exploration monitoring and production boreholes

6.1.1 DELINEATION OF STRUCTURAL FEATURES

Structurally two important issues had to be addressed, the possible presence of block faulting in the project area and the role of dolerite sills as hydraulic boundaries. Large scale block faulting has been interpreted throughout the Karoo basin in eastern Namibia, with offsets sufficient to isolate some aquifer units. In the project area, previous studies have inferred that there is no block faulting in the Botswana portion of the basin, but if present it could have important implications on aquifer geometry, hydraulic properties, groundwater flow as well as quality. Aeromagnetic and remote sensing data interpretations carried out during the project indicated that some of the NE-SW and NW-SE trending faults in the project area parallel the structural trend of the Ghanzi–Chobe fold belt and the main Dyke swarm of eastern Botswana respectively and might exert some control on the aquifer geometry and hydraulic characteristics of the aquifer units (**see previous sections 4 & 5**)

Also relevant to the possible aquifer boundaries are the extent and geometry of dolerite intrusions which are well developed towards the south and western parts of the Ncojane Block. For borehole siting, locating areas with significant dolerite intrusions was critical for three reasons;

1. Controlling drilling depths in such a way that boreholes are not sited in areas underlain by thick dolerite sills as this will result in deep boreholes and hence increased drilling costs
2. To determine the hydraulic role of these intrusions either as areas of increased hydraulic conductivity or as barriers to groundwater flow (aquifer compartmentalisation)
3. Evaluate their effect on groundwater quality

Accurate location of these structures on the ground (faults, lineaments dolerite dykes/sills) was therefore, one of the key objectives of the ground geophysical surveys. Drilling in the vicinity or away from these structures was important to verify and assess their hydrogeological role either as zones of enhanced groundwater potential (fracturing) or groundwater flow barriers.

6.1.2 INFERRING SUBSURFACE LITHOLOGICAL CONDITIONS

Aquifers in the project area are developed in sandstones units of the Lebung and Ecca Groups (Ntane and Otshe Formations). These two aquifers are separated from each other (if both present) by argillaceous units of the Mosolotsane and Kule (Kwetla) Formations. In the absence of the Ntane Sandstone Formation, the Ecca aquifer is overlain by Kalahari Beds, Mosolotsane and Kule (Kwetla) Formations. In the Ncojane Block, particularly in the western and southern parts, existing low resolution aeromagnetic data indicates that multiple dolerite sill intrusions are present (**Figures 4.1** and **4.2**). Ground geophysical surveys were therefore critical in differentiating areas likely to be underlain by lithological units with good groundwater potential from those with poor groundwater potential. Areas with good groundwater potential include areas underlain by faulted/fractured or non faulted thick sandstone units. Critical in the choice of ground geophysical method(s) is its ability to differentiate areas underlain by various lithological units.

For example based on the known stratigraphy of the project area and review of project and existing data, a typical resistivity sequence in an area underlain by Kalahari Beds, unsaturated Ntane Sandstone, Mosolotsane/Kule (Kwetla) Formations, Ecca and Upper Dwyka Formations in the Ncojane Block would be as given in **Table 6.1**.

Table 6.1 Resistivity Sequence in Ncojane Block

Layer 1	Resistive	Kalahari Beds/Unsaturated Mosolotsane/Kule (Kwetla) Mudstone Formations
Layer 2	Conductive	Mosolotsane/ Kule (Kwetla) Mudstone Formations
Layer 3	Resistive	Fresh Water Saturated Ecca Group Sandstone (Otshe)
Layer 4	Conductive	Saline Ecca Group Sandstone (Otshe) or Kobe Formations
Layer 5	Resistive	Upper Dwyka (quartzitic sandstones)

Within this sequence, dolerite intrusions will appear as zones of very high resistivity.

In the Matlho-a-Phuduhudu Block, however because of the presence of saturated Ntane Sandstone Formation, a typical resistivity sequence would be as given in **Table 6.2.**

Table 6.2 Resistivity Sequence in the Matlho-a-Phuduhudu Block

Layer 1	Resistive Formation	Kalahari Beds/Unsaturated Ntane Sandstone
Layer 2	Moderately Resistive to Resistive Beds	Saturated Ntane Sandstone Formations
Layer 3	Conductive	Saline Mosolotsane/ Kule (Kwetla) Mudstone Formations
Layer 4	Resistive	Fresh Water Saturated Ecca Group Sandstone (Otshe)

6.2 SURVEY METHODOLOGY AND PARAMETERS

Ground geophysical surveys consisting mainly of magnetic profiling and Time Domain Electromagnetic (TEM) soundings (200 x 200 m loop) together with limited horizontal loop electromagnetic profiling (HLEM) were conducted in the project area.

Magnetic profiling assisted in differentiating areas underlain by dolerite intrusions (although flat and thick dolerite sills are not pronounced) from those without intrusions as well as locating the structural features interpreted from regional aeromagnetic and remote sensing data, while TEM soundings assisted in inferring subsurface lithologies and groundwater quality variations both laterally as well as vertically. During the surveys, the total magnetic field was recorded at station intervals of 20 m while TEM soundings along profile lines were conducted at station spacing of between 1 km (predominant) to 4 km. A total of 291 (200x200 m loop size) TEM soundings were conducted along profile lines (**Figure 6.1**). In addition to TEM soundings along profile lines, 104 spot soundings were also conducted at various locations in order to assist in delineating the regional distribution of the different geological units (aquifers). Ten of these soundings were conducted using a loop size of 400x400m (ultra deep) while the rest were conducted using a loop size of 200x200 m. Horizontal Loop Electromagnetic (HLEM) profiling at 20 m intervals was carried in locations around Ncojane and Kule Villages and near Metsimantsho, along profile lines, **R1, R2, R3, R9 and R10** where this method was considered likely to provide useful information (thinner Kalahari) on vertical and sub-vertical structural features as well as geological contacts between different formations. HLEM was not applied during the production phase as it was found not ineffective after the exploration phase.

A summary of the equipment used is given in **Table 6.3** while ground geophysical survey quantities are provided in **Table 6.4**.

Table 6.3 Survey Method, Equipment and Survey Parameters

Survey Method	Equipment	Survey Parameters
Line Preparation	Garmin 12XL Hand Held GPS	Pegging at 20 m interval
Magnetic profiling	GEM GSM-19 and Geotron G5 total magnetic field magnetometers	Total magnetic field recording at 20 m station intervals
HLEM Profiling	Apex maxmin I-10 and II EM units	Reading at 20m station interval using 200 m coil spacing at three frequencies 880, 1760 and 3520 Hz.
TEM Soundings	Geonics Protem D Receiver with TEM57 MK2 transmitter	In-loop soundings (200 x 200 m loop & 400x400) with 25, 6.25 and 2.5 Hz frequencies.

Table 6.4 Summary of Ground Geophysical Survey Quantities (Exploration and Production)

Profile Line	Co-ordinates *				Line Cutting	Magnetic Profiling	HLEM Profiling	TEM soundings (200m x 200 m)
	Zero Point		End Point					
	Easting	Northing	Easting	Northing	(km)	(km)	(km)	(nos.)
R1	417837	7458619	421857	7467675	10	10	10	10
R2	427160	7439519	420838	7412342	28	28	28	29
R3	452734	7444474	437397	7432264	20	20	19	21
R4	448675	7395688	437280	7413199	21	21	NP	23
R5	455984	7395915	477806	7398325	22	22	NP	23
R6	434890	7398102	437031	7384295	14	14	NP	14
R7	472281	7433169	480656	7419556	16	16	NP	17
R8	490415	7432042	491156	7418116	14	14	NP	15
R9	513004	7427008	511316**	7429250**	17	17	16	14
R10	464580	7431283	474348	7406270	27	27	27	28
R11	398067	7420861	443336	7421080	0	NP	NP	28
L1	437040	7429770	450432	7440230	17	17	NP	18
L2	437050	7424560	452700	7436970	20	20	NP	21
L3	438420	7420780	452608	7431816	18	18	NP	19
L4	444805	7420595	452545	7426660	10	10	NP	11
Line Clearance for Spot Soundings					10			
Spot Soundings								104
Total					**264**	**254**	**100**	**395**

Notes
* UTM Zone 34, Clark 1880, Cape Datum
** Co-ordinate of 15000 m station
NP = Not planned

6.3 CALIBRATION SURVEYS AND DATA PROCESSING

6.3.1 CALIBRATION SURVEYS

Calibration surveys comprising of TEM soundings were conducted near six existing boreholes, BH8469, BH8470, BH8364, BH8363, BH8346 and BH8645 (**Figure 6.1**) prior to conducting the surveys in the rest of the project area. These surveys were conducted in order correlate lithostratigraphic units and groundwater quality with resistivities obtained from TEM soundings inversions at known locations. All the boreholes in which calibration surveys were conducted are tapping aquifers in Ecca and contain fresh groundwater with TDS values ranging between 500 and 900 mg/L. In the Ncojane Block, the Ntane Sandstone is missing and does not constitute an aquifer.

Resistivity ranges of the main lithostratigraphic units as obtained from the calibration surveys are summarised in **Table 6.5**.

Table 6.5 Resistivity Range of Major Litho-Stratigraphic Units of the Project Area

Lithostratigraphic Unit	TEM Resistivity (Ω-m)
Kalahari Beds	11 – 90
Dolerite	40 – > 400
Mosolotsane Formation/Kule (Kwetla) Formation (saturated)	5 – 40 (mostly < 10)
Ecca Group (Fresh)	10– 70 (mostly 10 to 30)
Saline Ecca Group or Kobe	< 5

From **Table 6.5,** it is observed that sandstones in the Ecca, which form the main aquifer units in the Ncojane Block, contain mostly fresh groundwater and is commonly characterised by TEM resistivities in the range of 10 to 70 Ω-m. However, the resistivity range of this unit is commonly observed to be between 10 to 30 Ω-m. The Mosolotsane and Kule (Kwetla) Formations have resistivities which are generally less than 10 Ω-m. Kalahari Beds are characterised by similar resistivities which range from 11 to about 90 Ω-m.

Magnetic and HLEM profiling data were plotted using Jendel Scientific Sigma Plot software. Inversion of TEM sounding data was undertaken using Interpex's Temix-XL software based on a 1-Dimensional horizontally stratified earth model. The inversion results provide a resistivity-depth model, which gives resistivity variation with depth based on a number of layers characterised by step wise changes in resistivity.

After inversion of TEM sounding data, geo-electric sections were generated using Surfer 7 software and example plots representing typical responses are presented in **Figures 6.2** through **Figure 6.9** and a summary of geophysical interpretations of all profile lines is given in **Table 6.6.** Full interpretations of the ground geophysical survey data are given in **Volume 3A**, **Airborne and Ground Geophysics Report**.

In addition to the geo-electric sections along profile lines, regional resistivity contours maps at depths of 100 m, 150 m, 200 m, 250 and 300 m were also generated (**Figures 6.10 through 6.14**). These maps provide an aerial picture of the subsurface distribution of the different lithological units at various depths. These figures also indicate borehole locations together with the lithology at that particular depth as well as aeromagnetic data interpreted lineaments.

This information together with drilling results was used to improve the understanding of the aquifer geometry, assist in aquifer modelling and optimising wellfield locations

6.4 SURVEY RESULTS

An integrated interpretation of the acquired data was undertaken in conjunction with borehole information, geological and structural maps. The main objectives of the interpretation were:

- Verification of structural features and lineaments identified from aeromagnetic and remote sensing data interpretation
- Mapping of subsurface lithologies and inferring groundwater quality
- Correlation of the Geophysical Interpretations with drilling Results

The results of the surveys are discussed in the following section.

6.4.1 DRILLING SITES

A total of 26 drilling sites were recommended for drilling of exploration and production boreholes after completion of the ground geophysical surveys. Sites were selected in different geological and hydrogeological environments of the project area bearing in mind the principal objectives of the exploration and production phases which were:

- Delineation of structural features such as faults, lineaments and dolerite intrusions and evaluation of their hydrogeological significance as hydraulic barriers or areas with increased groundwater potential
- Inferring subsurface lithological units and groundwater quality variations with depth as well as spatially.
- Drilling production boreholes in the most potential areas in terms of borehole yields, water quality and the potential for future wellfield expansion

The exploration surveys were focused in the Ncojane Block, where the Ecca Group Sandstones (Otshe Formation) constitute the main aquifer units and the groundwater potential has not been extensively explored in previous projects.

To fully evaluate the groundwater potential of the different geological environments and the identified structures, drilling sites were selected on different features such as:

- Structurally undisturbed areas which are characterised by uniform magnetic and or HLEM responses (where applicable) together with uniform resistivity layering on TEM sections.
- Structurally disturbed (fractured) areas which are characterised by magnetic and HLEM (where applicable) anomalies as well as discontinuities in the TEM resistivity sections coinciding with remote sensing and aeromagnetic data interpreted structures.

Information from these drilled sites together with ground geophysical and borehole geophysical logging data interpretations are summarised in **Table 6.6**. Interpretations of selected profile lines are given in the following chapter and the rest of the interpretations are given in **Volume 3A**.

Table 6.6 Summary of Geophysical Interpretations

6.4.2 PROFILE LINE R2

Profile Line **R2** was orientated to demarcate various NW-SE trending lineaments interpreted from remote sensing and airborne magnetic data. Magnetic and HLEM profiling data together with the TEM section for Line **R2** is presented in **Figure 6.2**. The aeromagnetic data interpretation shows that this line is located at the edge of a regional dolerite intrusive body (**Figure 6.1**).

Ground magnetic profiling data confirms that the area underlying Line R2 is intruded by several dolerite sills and dykes as seen from several short wavelength anomalies. Three zones can be observed from magnetic profiling data which are described as follows:

Zone 1 Zone 1 occurs between 0 to 10000 m and is characterised by several short wavelength magnetic anomalies suggesting that this zone is dominated by dolerite intrusions.

Zone 2 Zone 2, occurring between 10000 m to 26000 m is characterised by relatively uniform ground magnetic background and a few magnetic anomalies. Significant dyke type anomalies occur between 19000 and 20000 m stations and 23000 to 25000 m stations. Overall the magnetic data indicates that this zone has less shallow dolerite intrusions as compared to the area underlying Zone 1.

HLEM profiling shows a significant change in IP signatures at 16000 m suggesting a fault or lithological contact near this station.

Zone 3 This zone occurs between 26000 and 28000 m and is characterised by a distinctly high magnetic field, which coincides with the location of a dolerite body as observed in **Figure 6.2**.

On the TEM section (**Figure 6.2**), a resistive layer (20 to > 50 Ω-m) occurring in the top 20 to 60 m (yellow to red) is interpreted as unsaturated Kalahari Beds. Below Kalahari Beds, a conductive layer with a resistivity of < 10 Ω-m is interpreted as mostly saturated Mosolotsane and Kule (Kwetla) Formations, and the upper argillaceous units of the Ecca Group rocks (light green to dark blue). The bottom of this conductive unit increases from 140 m in northeast to about 300 m in the southwest. The thickness of this unit also increases significantly from the northeast where it is less than 80 m to the southwest where it is over 200 m thick. Towards the end of the profile line (between 26000 and 28000 m stations), this unit is intruded by dolerites at ~ 80 to 300 m below ground level. Below the interpreted Mosolotsane and Kule (Kwetla) Formations, is a moderately resistive (10 to 25 Ω-m) unit which has been interpreted as Ecca Formation units (green to yellow colour). The top of this unit ranges from 140 m in the northeast to about 300 m in the southwest. Northeast of the 16000 m station, the bottom of this unit, generally occurs at around 340 m depth, while to the southwest of this station, its bottom is poorly constrained on the TEM data (**Figure 6.2**). A distinctly higher resistivity zone (15 to 35 Ω-m) occurs between the 3000 and 12000 m stations within this layer at a depth of 140 to 300 m. This zone is interpreted to represent either coarse sandstones within Ecca or weathered dolerite intrusions. Between 0 and 16000 m stations, the interpreted Ecca is underlain by a high resistivity layer interpreted as dolerite sill (red to pink).

On this profile line, three major discontinuities are observed (indicated as dotted lines on **Figure 6.2**), near 2000 m, 16000 m and 26000 m stations from magnetic profiling data. On the HLEM profiling data and the TEM section, significant discontinuities are observed near 12000 m and 16000 m stations. All these anomalies are likely to represent faults in the subsurface formations.

One Site, (BH10215, Site S2) was originally located on this profile line at TEM 10 peg 8000 m but was later moved to a different location (TEM 18, peg 16000) based on drilling results from BH10221 (Site S13) to avoid drilling through thick dolerites before reaching the target aquifer (Otshe Sandstones) (**Figure 6.2**). A good correlation between TEM geoelectric layers and litho-stratigraphic units was obtained at this site. From drilling and geophysical logging data it was confirmed that the top 27 m is Kalahari Beds overlying the Kule/Kwetla units to their interpreted base of 107 m. The low to moderate unit interpreted from TEM was confirmed to be freshwater bearing Ecca Group (Otshe Formation) aquifers.

6.4.3 Profile Line R3 (Ncojane Wellfield Block)

Profile Line **R3** was oriented to cut across various NW-SE trending lineaments interpreted from remote sensing data and a regional fault interpreted from aeromagnetic data (**Figure 6.1**). It also intercepts a geological boundary between the Ntane and Mosolotsane Formations. Magnetic and HLEM profiling data together with the TEM section for Line **R3** are presented in **Figure 6.3**.

In general, the magnetic field on this line is observed to be uniform with no indication of shallow dolerite intrusions except towards the end (SW) of the profile line. HLEM profiling data does not show any significant anomalies along this profile line.

The TEM resistivity section suggest a major discontinuity near the 10000 m station, which coincides with the location of the aeromagnetic data interpreted fault, **F4** (**Figure 6.1**). This discontinuity divides the profile line into two major zones on either of fault **F4**. On the basis of TEM resistivities, the formations underlying Line **R3** can be classified into four main geo-electric layers northeast of **F4** (**Zone 1**) and five main geo-electric layers southwest of fault **F4** (**Zone 2**) as described below.

Zone 1 (North East of Fault F4)

Layer 1 Layer 1, a resistive layer (20 to > 100 Ω-m) occurring in the top 120 m along this profile line northeast of station 10000 m (fault **F4**) has been interpreted as Kalahari Beds (red to pink).

Layer 2 Layer 1 (Kalahari Beds) is underlain by a thin moderately resistive layer (>10 to 20 Ω-m) northeast of fault **F4** (yellow to green). This layer is interpreted as unsaturated Mosolotsane/Kule (Kwetla) Formations as well as the upper argillaceous units of Ecca Group. The top of this unit occurs around 120 m with its base occurring at around 140 m.

Layer 3 A moderately low resistivity layer (10 to 15 Ω-m) underlies the interpreted Mosolotsane/Kule (Kwetla) Formation and has been interpreted as Ecca Group (blue and green). The top of this unit occurs around 140 m while its base ranges from 300 m to 450 m. Borehole logs of (W3 and BH10210/211) confirmed this layer to be Ecca Formations.

Layer 4 Layer 4 which is the bottom most unit, is characterised by high resistivities (15 to 80 Ω-m) and generally occurs below 300 to 450 m (yellow to red). This layer may represent the upper units of the Dwyka Group (Malogong Formation).

Zone 2 (South West of fault F4)

Layer 1 Layer 1, a resistive layer (20 to > 100 Ω-m) occurring in the top 60 to 120 m along this profile line southwest of fault **F4** has been interpreted as Kalahari Beds (red to pink).

Layer 2 Layer 1 (Kalahari Beds) is underlain by a reasonably thick moderately resistive layer (>10 to 20 Ω-m) south west of the fault **F4** (yellow to green). This layer is interpreted as unsaturated Mosolotsane/Kule (Kwetla) Formations as well as the upper argillaceous units of Ecca Group. The top of this unit occurs between 60 m and 120 with its base occurring at around 140 m.

Layer 3 A high resistivity layer (20 to 60 Ω-m) underlies the interpreted Mosolotsane/Kule (Kwetla) Formation and has been interpreted as Ecca (Otshe) Formations (yellow to red). The top of this unit occurs around 140 m while its base ranges from 260 m to 280 m. Borehole logs of **BH10227/228/402** confirmed this layer to be the Ecca (Otshe) unit (target aquifer for production boreholes in the Ncojane Block).

Layer 4 A moderately low resistivity layer (10 to <15 Ω-m) underlies the interpreted Ecca (Otshe) Formations and has been interpreted as Ecca (Kobe) Formation (light blue and green). The top of this unit occurs between 260 m to 280 m while its base ranges from 420 m to 460 m. Borehole log of **BH10227/402** confirmed this unit to be unsaturated Ecca (Kobe) Formations and a bit of Ecca (Otshe) sandstones.

Layer 5 Layer 4 which is the bottom most unit, is characterised by high resistivities (15 to 80 Ω-m) and generally occurs below 420 to 460 m (yellow to red). This layer may represent the upper units of the Dwyka Group (Malogong Formation).

A discontinuity observed on the TEM section near the 10000 m station, coincides with the location of fault, **F4** interpreted from aeromagnetic data (**Figures 6.1** and **6.3**). This fault appears to be controlling the Ecca lithologies as a moderately high resistivity layer (originally interpreted as coarse sandstone units in Ecca, but later confirmed to be weathered dolerite as well as coarse sandstones). These weathered dolerites/sandstones are very thin on the north-eastern side of the fault **BH10402**.

Two Exploration boreholes, Site S3, TEM 69 (BH10227/BH10228), Site S4, TEM 63 (BH10210/10211**)** were drilled on either side of fault **F4** (**Figure 6.1**) during the Exploration Phase. During the production Phase, three Sites P01 (BH10402), P02 (BH10404) and P03 (BH10405) were drilled along this profile line all of which had high yields and very good groundwater quality.

In general a fair correlation between TEM geoelectric layers and litho-stratigraphic units is observed on either side of the fault. However, two differences between the original interpretation and drilling results are as follows;

- Mosolotsane and Kwetla formations (BH10210 and BH1028, 45-149m) are characterised by much higher resistivities (<10 to 40 Ω-m) as compared to the originally interpreted values of <10 Ω-m. This is probably due to their unsaturated nature.

- A moderately high resistivity layer found Southwest of Fault **F4** (**Figure 6.3**) which was originally interpreted as coarse sandstones was confirmed by drilling to be combined weathered dolerites and course sandstone units (Otshe Aquifer). This indicates that the resistivity of weathered dolerite and sandstone is very similar and these two units can not be resolved on resistivity data alone.

6.4.4 Profile Line R7 (Ncojane Block)

Profile **Line R7** was oriented to cut across an area where several NE-SW and NW-SE trending remote sensing and aeromagnetic lineaments intersect. It also intercepts regional faults interpreted from aeromagnetic data (**Figure 6.1**) as well as a geological boundary between the Lebung and Ecca Group rocks. Magnetic profiling data together with the TEM section for **Line R7** is presented in **Figure 6.4**.

Interpretation of ground magnetic profiling data indicates three zones along this line as follows;

Zone 1 Zone 1 which occurs between 0 to ~ 5000 m is dominated by short wavelength magnetic anomalies indicating presence of shallow dolerite intrusions.

Zone 2 Zone 2 which occurs between 5000 to ~15000 m is characterised by very flat magnetic response indicating that there are no dolerite intrusions in this zone.

Zone 3 Zone 3 which occurs between 15000 to ~16000 m coincides with the start of short wavelength magnetic anomalies, indicating possible presence of shallow dolerite intrusions.

A magnetic anomaly observed near the 5000 m station has been interpreted as fault and close to the location of an aeromagnetic data interpreted fault **F4** as well as the geological boundary between the Lebung and Ecca Group Rocks. Another magnetic anomaly observed near the 15000 m station, is close to the location of a regional NE-SW trending remote sensing lineament.

Correlation of the magnetic profiling data and TEM data inversions suggests that there is a dolerite intrusion at relatively shallow depths {40 to 100 m (pink)} between 0 to 5000 m stations. Another dolerite intrusion is also likely to be present between 15000 to16000 m stations in the depth range of 180 to 320 m (yellow).

Based on the TEM section, the top high resistivity (30 - >100 Ω-m) layer on this section (**6.5**) between 0 to 5000 m stations is interpreted as a relatively shallow dolerite intrusion (pink colour) and between 5000 m to the end of the profile line this layer is interpreted Kalahari Beds (red to green). The thickness of this unit is about 40 m in the southeast and gradually increases to about 80 m towards the northwest. This resistive layer is underlain by a conductive layer (< 10 Ω-m) which is interpreted as Mosolotsane/Kule (Kwetla) Formations (dark blue colour). The top of this unit occurs at depths of between 60 to 80 with its base occurring at approximately 140 to 160 m. Below this layer, a moderately resistive (10 -15 Ω-m) layer (light green) with a depth to top of between 140 to 160 m is interpreted as Ecca Group (Otshe Formation). The base of this unit occurs at approximately 300 m above a conductive layer (< 10 Ω-m) which could represent the Kobe Formation or saline water saturated Ecca sandstones (blue).

Two boreholes were drilled along this profile line BH10222 (Site S10, TEM111) and BH10229 (Site S5, TEM 114). In general a good correlation between the TEM geoelectric layers interpretation and litho-stratigraphic units was obtained particularly the interface between Kalahari Beds, Mosolotsane/Kwetla Formations and the Ecca Group. The low resistivity layer below 300 m was confirmed as the Kobe Formation by drilling and borehole geophysical logging data at BH10229. It appears that BH10222 is uplifted relative to BH10229, probably due to faulting associated with fault, **F6**.

6.4.5 PROFILE LINE R9 (NCOJANE BLOCK)

Profile Line **R9** was oriented to demarcate several regional NE-SW trending remote sensing and aeromagnetic lineaments. It also crosses a geological boundary between the Ntane and Mosolotsane Formations Magnetic and HLEM profiling data together with the TEM section for Line **R9** is presented in **Figure 6.5**.

The magnetic profiling data on this profile line is characterised by two distinct zones as follows;

Zone 1 This zone, located between 0 to ~ 6000 m stations, is characterised by extremely flat magnetic response indicating absence of dolerite intrusions in this zone.

Zone 2 This zone, occurring between the 6000 m to ~ 17000 m stations, is characterised by short wave length relatively high amplitude magnetic anomalies superimposed on relatively high magnetic background, indicating possibly uplifted magnetic basement and shallow dolerite intrusions.

Anomalies observed on both the magnetic and HLEM profiles near the 6000 m station (TEM 81) have been interpreted as a fault and coincides with the location of an aeromagnetic data interpreted fault **F6** (**Figure 6.1**). A contact type magnetic and HLEM anomaly is observed near the 11000 m station, and closely matches with the location of the geological contact between Ntane and Mosolotsane Formations.

Based on the TEM section, the top high resistivity (20- >110 Ω-m) layer on this section is interpreted to be Kalahari Beds to the northwest of the 6000 m station. Southeast of the 6000 m station, the interpreted Kalahari Beds are expected to be intruded by a shallow dolerite sill, based on magnetic profiling data. The thickness of this unit ranges between 80 m to about 110 m. A conductive layer (resistivity <10 Ω-m) occurring below the top resistive layer is correlated with the Mosolotsane/Kule Mudstone Formations and the upper argillaceous units of the Otshe Formation (dark blue to green). The top of this unit occurs at ~ 80 m in the northwest and gradually increases to about 110 m in the southeast. Its base ranges from 140 m in the northwest to about 240 m in the southeast. Underlying this conductive layer, is a well developed resistive (10-60 Ω-m) unit which occurs at a depth of approximately 140 m in the northwest to about 240 m in the southeast (green to red). The bottom of this unit occurs between 400 to 480 m. This resistive unit is interpreted as Ecca Group (Otshe Formation). The interpreted Ecca Group (Otshe Formation) is underlain by a conductive layer (< 10 Ω-m) interpreted as Ecca (Kobe) Formation or saline water saturated sandstones of the Ecca Group.

Two boreholes BH10220, (Site 20, TEM 77) and BH10315 (Site 12, TEM 84) were drilled on this profile line. TEM, Drilling and Geophysical Logging Data sets at these borehole sites were interpreted as follows:

- The top high resistivity layer (20 - 110 Ω-m) observed on the TEM section is correlated with Kalahari Beds whose thickness is 65 m at BH10220 and 40m at BH10315.
- The conductive layer (resistivity <10 Ω-m) occurring below the top resistive layer interpreted as Mosolotsane/Kule Formations on TEM model was intercepted as expected at both BH10220 and BH10315. The interpreted dolerite southeast of 7000 m station was also intercepted as expected at BH10315.

The TEM interpreted Ecca Group (Otshe Formation), underlying the Mosolotsane/Kule Formations was encountered at 132 and 209m at BH10220 and BH10315 respectively. Both boreholes were terminated within the Otshe Formation.

6.4.6 PROFILE LINE L1 (NCOJANE WELLFIELD BLOCK)

Profile Line **L1** was oriented to cut across various NW-SE trending lineaments interpreted from remote sensing data and a regional fault interpreted from aeromagnetic data (**Figure 6.1**). It also intercepts a geological boundary between the Ntane and Mosolotsane Formations. Magnetic profiling data together with the TEM smooth model section for Line **L1** are presented in **Figure 6.6**.

In general, the magnetic field on this profile line gradually decreases from southwest to northeast with an indication of shallow dolerite intrusions particularly between the 7000 m and 9000 m stations. Between stations 3000 m and 5000 m, a few weak anomalies are observed which may be associated with deep dolerite intrusions. The magnetic anomaly observed at 11000 m station coincides with the Ntane-Mosolotsane geological boundary while the anomaly at 14000 m coincides with fault **F4**.

The TEM resistivity section shows a major discontinuity near the 14000 m station, which coincides with fault **F4** (**Figures 6.6**). This discontinuity divides this profile line into two major zones on either side of fault **F4**. On the basis of TEM resistivities, the formations underlying Line **L1** can be classified into five main geo-electric layers southwest of **F4** (**Zone 1**) and three main geo-electric layers northeast of fault **F4** (**Zone 2**) as described below.

Zone 1 (South West of fault F4)

Layer 1 Layer 1, a resistive layer (20 to < 60 Ω-m) occurring in the top 40 to 110 m throughout the whole profile line has been interpreted as Kalahari Beds (light orange to red). Within this layer high resistive zones in pink colour (>60 Ω-m) are probably dolerite intrusions.

Layer 2 Layer 1 is underlain by a conductive to moderately resistive layer (10 to <20 Ω-m) interpreted as units of the Mosolotsane/Kule (Kwetla) Formations throughout the whole profile line (blue to green). The top of this layer occurs at a depth of 40 m in the southwest which increases to around 110 m near the fault **F4**. Its base occurs at depths of 140 m southwest of the fault **F4**.

Layer 3 A moderately resistive to resistive layer (25 to <50 Ω-m) interpreted as Ecca (Otshe Formation) underlies Layer 2 (yellow to red). The top of this unit occurs at a depth of approximately 140 m to the southwest of **F4** while its base occurs at 260 m in the same zone. This unit was the main target aquifer for construction of production boreholes. Borehole logs of **BH10407** and **BH10411** confirmed this unit to be the resistive Ecca (Otshe) aquifer and also some weathered dolerites were intercepted within these units.

Layer 4 Layer 3 is underlain by conductive (< 10 to 20 Ω-m) units interpreted as saline water saturated Kobe Formation Units (dark blue to green). The top of these units occurs at around 260 m while the base occurs at depths of between 420 to 430 m. These Kobe Formation Units were intercepted at a depth of 247 m at borehole **BH10407**.

Layer 5 Layer 5, which is the bottom most unit, is characterised by high resistivities (35 to > 60 Ω-m) and generally occurs below 420 m to 430 m (yellow to pink). This layer may represent the upper units of the upper Dwyka Group (Malogong Formation),

Within these layers, zones of higher resistivities (pink colour) are interpreted as dolerite intrusions.

Zone 2 (North East of Fault F4)

Layer 1 Layer 1, a resistive layer (20 to < 60 Ω-m) occurring in the top 40 to 110 m throughout the whole profile line has been interpreted as Kalahari Beds (light orange to red). Within this layer zones in pink colour (>60 Ω-m) are probably dolerite intrusions.

Layer 2 Layer 1 is underlain by a conductive to moderately resistive layer (10 to <20 Ω-m) interpreted as units of the Mosolotsane/Kule (Kwetla) Formations throughout the whole profile line (blue to green). The top of this layer occurs at a depth of 40 m northeast of **F4** and its base occurs at depths of 430 m in Zone 2. This layer seems to be a merge of the Mosolotsane/Kule (Kwetla) Formations and the Kobe Formations after they were faulted by fault **F4**.

Layer 3 Layer 3, which is the bottom most unit, is characterised by high resistivities (35 to > 60 Ω-m) and generally occurs below 420 m to 430 m (yellow to pink). This layer may represent the upper units of the upper Dwyka Group (Malogong Formation)

Within these layers, zones of higher resistivities (pink colour) are interpreted as dolerite intrusions.

A major discontinuity observed on the TEM section near the 14000 m station, coincides with the location of fault, **F4** (**Figure 6.6**) where the Mosolotsane, Otshe and Kobe Formations seems to merge.

Three sites, **P04**, TEM 296 (BH10407), **P05**, TEM 302 (abandoned borehole BH10406**),** and Site P**06**, TEM 294 (BH10411) were drilled along this profile line (**Figure 6.6**) during the Production Phase.

There is a very good correlation between TEM geoelectric layers and litho-stratigraphic units from drilled boreholes.

6.4.7 PROFILE LINE L2 (NCOJANE WELLFIELD BLOCK)

Similar to Line 1, profile Line L2 was oriented to cut across various NW-SE trending Remote Sensing lineaments and a regional fault interpreted from aeromagnetic data. It also cuts the geological boundary between the Ntane and Mosolotsane Formations. Magnetic profiling data together with the TEM section for Line **L2** is presented in **Figure 6.7**.

In general, the magnetic field on this line is observed to be gradually decreasing from the southwest to the northeast with the major change observed at station 13000m interpreted as the Ntane/Mosolotsane geological boundary. A few weak magnetic anomalies between stations 5000m and 8000m are signatures from deep dolerite dykes. The sudden drop in magnetic field observed at station 17800m coincides with fault **F4**.

The TEM resistivity section suggests a major discontinuity near the 17800 m station, which is coincident with the location of fault, **F4** (**Figure 6.7**). Beyond this station (17800m) and fault, the Mosolotsane/Kule, Otshe and Kobe Formations seem to have similar (low) resistivities and are not clearly defined on TEM smooth model sections. This discontinuity divides this profile lines into two major zones on either of fault **F4**. On the basis of TEM resistivities, the formations underlying Line **L2** can be classified into five main geo-electric layers southwest of **F4** (**Zone 1**) and three but not well pronounced geo-electric layers northeast of fault **F4** (**Zone 2**) as described below.

Zone 1 (South West of fault F4)

Layer 1 Layer 1, a resistive layer (25 to <60 Ω-m) occurring throughout the whole profile line has been interpreted as Kalahari Beds (yellow to red). The depth to the bottom of this unit increases gradually from approximately 60 m in the southwest to 120 m in the northeast. This layer is possibly intruded by dolerite sills (pink colours) between stations 8000 m to 10000 m and between 12000 m and 14000 m stations.

Layer 2 Layer 1 is underlain by a conductive to moderately resistive layer (10 to <20 Ω-m) interpreted as Mosolotsane/Kule (Kwetla) Formations southwest of **F4** (blue to green). The top of this layer occurs at depths of 60 m to the southwest and at about 120 m in the northeast. Its base occurs at approximately 140 m in the southwest of **F4**.

Layer 3 A moderately resistive to resistive layer (25 to <60 Ω-m) underlies Layer 2. This layer is interpreted as Ecca (Otshe Formation) Group. The top of this unit occurs at a depth of approximately 140 m to the southwest in Zone 1 while its base occurs at approximately 280 m through in Zone 1. Production boreholes were drilled to a terminal depth within this layer as it was the main target aquifer. Borehole log of **BH10410** confirmed this unit to be the resistive Ecca (Otshe) aquifer with some weathered dolerites at the top.

Layer 4 Layer 3 is underlain by a conductive (< 10 to 20 Ω-m) unit interpreted as saline water saturated Kobe Formation Units (green to blue). The base of this unit occurs at depths of between 420 to 510 m in the southwest to the northeast respectively.

Layer 5 Layer 5, which is the bottom most unit, is characterised by high resistivities (35 to > 90 Ω-m) and generally occurs below 420 m to 510 m (yellow to pink). This layer may represent the upper units of the Dwyka Group (Malogong Formation).

Zone 2 (North East of Fault F4)

Layer 1 Layer 1, a resistive layer (20 to < 60 Ω-m) occurring in the top 110 m northeast of **F4** has been interpreted as Kalahari Beds (light orange to red).

Layer 2 Layer 1 is underlain by a conductive to moderately resistive layer (<10 to <20 Ω-m) interpreted as a merge of Mosolotsane/Kule (Kwetla), Otshe and Ecca Formations (blue to green) due to faulting at **F4**. The top of this layer occurs at a depth of 110 m northeast of **F4** and its base occurs at depths of 430 m within Zone 2.

Layer 3 Layer 5, which is the bottom most unit, is characterised by low to moderate resistivities (<10 to <20 Ω-m) (green to yellow). This layer may represent the upper Kobe Formation.

Although two Sites **P07**, and **P08** were recommended for drilling production boreholes along this profile line, only Site **P07**, TEM 313 (BH10410) was drilled. This was due to lengthy delays in the drilling progress and also due to the high yields of the boreholes which resulted in achieving the required yield after successfully drilling only 6 boreholes.

- There is a very good correlation between TEM geoelectric layers and litho-stratigraphic units from BH10410.

6.4.8 PROFILE LINE L3 (NCOJANE WELLFIELD BLOCK)

Profile Line **L3** was oriented to cut across various NW-SE trending lineaments interpreted from remote sensing data. It also intercepts a geological boundary between the Ntane and Mosolotsane Formations. Magnetic profiling data together with the TEM section for Line **L3** is presented in **Figure 6.8.**

In general, the magnetic field on this line is observed to be uniform with no indication of shallow dolerite intrusions except near the 6000m station where there is an indication of a shallow dolerite dyke.

On the basis of TEM resistivities, the formations underlying Line **L3** can be classified into five main geo-electric layers, as described below.

Layer 1 Layer 1, a resistive layer (25 to <60 Ω-m) occurring at depths of 40 m to 100 m has between interpreted as Kalahari Beds (yellow to red). This layer is possibly intruded by dolerite sills occurring as zones of higher resistivity (pink zones) particularly between the 4000 m to 7500 m stations and 10000 m and 15000 m stations.

Layer 2 Layer 1 is underlain by a conductive to moderately resistive layer (10 to <20 Ω-m) throughout the whole profile line (blue to green). The top of this layer occurs at depths of 40 to 100 m in the southwest and the north-eastern parts of the profile line. Its base occurs at depths of 140 m to 160 m. This layer is interpreted as Mosolotsane/Kule (Kwetla) Formations.

Layer 3 A moderately resistive to resistive layer (20 to <70 Ω-m) underlying Layer 2 is interpreted as Ecca (Otshe Formation) Group. The top of this unit occurs at depths of 140 to 160 m while its base occurs at around 320 m. This unit is intruded by a possible dolerite sill (pink colour) between the 1000 m and 5500 m stations.

Layer 4 Layer 3 is underlain by a conductive (< 10 Ω-m) unit interpreted as saline water saturated Kobe Formation Units. The base of this unit occurs at depths of between 420 to 440 m.

Layer 5 Layer 5 which is the bottom most unit, is characterised by high resistivities (35 to <80 Ω-m) and generally occurs below 420 m to 440 m (red to pink). This layer may represent the upper units of the Dwyka Group (Malogong Formation).

No borehole was recommended for drilling along this profile line.

6.4.9 PROFILE LINE L4 (NCOJANE WELLFIELD BLOCK)

Profile Line **L4** was oriented to cut across various NW-SE trending lineaments interpreted from remote sensing data (**Figure 6.1**). Magnetic profiling data together with the TEM section for Line **L4** is presented in **Figure 6.9**.

In general, the magnetic field on this line is observed to be gradually increasing from the southwest to northeast with major anomalies observed at stations 2500 m, 6750 m and at 8400 m. All these anomalies coincide with areas where remote sensing data lineaments are crossing.

On the basis of TEM resistivities, the formations underlying Line **L4** can be classified into four main geo-electric layers, as described below.

Layer 1 Layer 1, a resistive layer (20 to < 40 Ω-m) occurring in the depth range 40 m to 60 m to the southwest and northeast respectively is interpreted as Kalahari Beds (yellow to red).

Layer 2 Layer 1 (Kalahari Beds) is underlain by a conductive to moderately resistive layer (10 to 20 Ω-m) throughout most of the profile line. This layer is interpreted as the Mosolotsane/Kule (Kwetla) Formations. The top of this unit occurs at around 40 m to 60 m with its base occurring at around 120 m in the southwest and at about 180 m in the northeast.

Layer 3 A moderately resistive to resistive layer (20 to 60 Ω-m) interpreted as Ecca (Otshe Formation) Group (green to red) underlies Layer 2. The top of this unit occurs at a depth of approximately 120 m in the southwest and at around 180 m in the northeast. The base of this unit occurs at approximately 280 m throughout the profile line. This unit comprises the main target aquifer for construction of production boreholes

Layer 4 Layer 3 is underlain by a conductive to moderately resistive (< 10 to 30 Ω-m) unit interpreted as saline water saturated Kobe Formation Units. The base of this unit occurs at depths of between 460 to 500 m.

No borehole was recommended for drilling along this profile line

6.4.10 RESISTIVITY DISTRIBUTION WITH DEPTH

As mentioned earlier, in addition to presentation of the TEM data in the form of resistivity sections, regional resistivity contours maps at various depths were generated. These maps provide an aerial picture of the subsurface distribution of the different lithological units at various depths. Contour maps were generated at depths of 100 m, 150 m, 200 m, 250 m and 300 m and are presented in **Figures 6.10** through **6.14**. These figures also indicate borehole locations together with the lithology at that particular depth as well as aeromagnetic data interpreted lineaments. A discussion of the resistivity distribution at various depths is given below.

6.4.10.1 RESISTIVITY DISTRIBUTION AT 100M DEPTH

As per borehole lithological logs, resistivities at 100 m depth represent unsaturated units of the Mosolotsane and Kule Formations in the Ncojane Block (**Figure 6.10**). Different resistivity ranges are represented by different colours and correlation of these resistivities with borehole lithologies at 100 m depth suggests the following:

- **Blue zones** (< 10 Ω-m) generally represent mudstones of Mosolotsane and Kule Formations (Boreholes e.g. BH10220, BH10229, BH10227, BH10314) and also weathered dolerites at borehole BH10214. These zones predominantly occur on the eastern side of Metsimantsho and southwest of Metsimantle.
- **Green zones** (10 – 20 Ω-m) represents unsaturated Kule (Kwetla) mudstones in the Ncojane Wellfield area (BH10402, BH10404, BH10405, BH10407 etc) and also at BH10216, BH10215 and BH10227. These zones mainly occur south and southeast of Ncojane and around Metsimantsho.
- **Yellow to Red zones** (20 – < 50 Ω-m) represents saturated basal sandstone units of Kule (Kwetla) and mostly weathered dolerite sills (BH8364 and BH10210).
- **Red to Pink zones** (> 50 - < 200 Ω-m) represent dolerite sills (Boreholes BH9184, BH9183, BH4939, BH10219). These zones predominantly occur to the south and southwest of the Ncojane Block and around Ukwi.

6.4.10.2 RESISTIVITY DISTRIBUTION AT 150M DEPTH

The resistivities at 150 m (**Figure 6.11)** generally represent the upper units of the Ecca Group where there are no dolerites, but within the Ncojane Wellfield area the formation intercepted is mostly dolerites. In general the lithologies at 150 m depth have a uniform resistivity (greenish) ranging between 10 to 20 Ω-m. However moderate to relatively high resistivities formations (orange to pink) are present in the southwestern and northwestern parts of the Ncojane Block and also within the Ncojane Wellfield are. Different resistivity ranges are represented by different colours and correlations of these resistivities with borehole lithologies at 150 m depth suggest that:

- **Blue zones** (< 10 Ω-m) predominantly represent the saline water saturated basal sandstones of the Kule Kwetla Formation or the upper Otshe mudstones (BH10314, BH10315 and BH10215). These units mainly occur in the southern part of Ncojane and southeastern part of Metsimantsho.
- **Green zones** (10–20 Ω-m) correlate predominantly with sandstone units of the Otshe Formation (e.g. BH10220, BH10212, BH10221, and BH10229) however mudstones were also intercepted in this zone (e.g. BH10210, BH10316 and BH10220). These zones cover a large part of the Ncojane Block particularly in the northeast.
- **Yellow to Orange zones** (20-40 Ω-m) correlate with weathered dolerite (BH10227, BH10402, BH10405, BH10407, BH10410, and BH10411) and may be sandstones although very few boreholes were drilled in this zone outside the Ncojane Wellfield area. These zones are mainly developed southwest and south of Ncojane block and also partially to the west of Kule Village.
- **Red to Pink zones** (50 - < 200 Ω-m) represent possible fresh dolerite sills and mainly occurs in the southern part of the Ncojane Block but no boreholes were drilled in this zone.

6.4.10.3 RESISTIVITY DISTRIBUTION AT 200M DEPTH

Resistivities at 200 m depth (**Figure 6.12**) predominantly represent mudstone 2 of the Ecca (Otshe) formation within the Ncojane Wellfield but outside the Ncojane Wellfield it represents the first sandstone units of the Ecca Group (Otshe Formation) towards the north and north-eastern part of the Ncojane Block. This change in formation is due to the dipping of the layers (formation) towards the northeast.

The various resistivity ranges are represented by different colours and correlations of these resistivities with borehole lithologies at 200 m depth suggest that:

- **Blue zones** (< 10 Ω-m), represent mudstone units of the Otshe Formation (BH10314). This zone is generally missing throughout the Ncojane Block except in southeastern part of Metsimantsho.
- **Green zones** (10-20 Ω-m) correlate with the first sandstone units of the Otshe Formation towards the north and north-eastern part of the Ncojane Block (BH10229, BH10210, BH10221, BH10315, BH2240, BH9184, BH10216, and BH10219) and are present in most parts of the Ncojane Block. This sandstone unit forms one of the main aquifers within the Ecca Group and occurs in a large part of the area including areas around Metsimantsho, southwest of Ncojane and northeast of Ukwi (between F6 and F7).
- **Yellow to Orange zones** (20- < 50 Ω-m) correlate with the second mudstone (the mudstone separating the two target aquifers) of the Ecca (Otshe) Formations within the Ncojane Wellfield area (BH10402, BH10404, BH10405, and BH10407) and also with the basal sandstone units of Otshe Formation towards the south and south western part of the Ncojane Block (BH10316, BH10216, BH10214, BH10411 and BH10410). Boreholes which intercepted Otshe Sandstones in this zone had ground water with TDS which was much lower than the sandstones in the green zones. These zones are mainly developed around Ncojane and Metsimantle, towards Ngwatle as well as northeast of Metsimantsho. Due to similar resistivities of coarse sandstone and weathered dolerite, orange zones may also represent dolerite sills.
- **Red to Pink zones** (50 - < 200 Ω-m) represent dolerite sills and mainly occurs in the south-western part of the Ncojane Block. No boreholes were drilled in this zone.

6.4.10.4 Resistivity Distribution at 250m Depth

Resistivity at 250 m depth (**Figure 6.13**) represents the second (basal) sandstone units of the Ecca Group (Otshe Formation) within the Ncojane Wellfield area also in some limited portions of the Ncojane Block. However in some areas, particularly in the southwest resistivities at 250 m represents the mudstones of the upper Kobe, this is due to the uplifting of the Ecca (Otshe) towards the western side of the Ncojane Block.

The various resistivity ranges are represented by different colours and correlations of these resistivities with borehole lithologies at 250 m depth suggest that:

- **Blue zones** (< 10 Ω-m), may represent mudstone units of the Ecca (Kobe) Formation as this formation was encountered at depths nearly 200m particularly towards the western part of the Ncojane block (BH10314 and BH10215).
- **Green zones** (10-20 Ω-m) correlate with sandstone units of the Otshe Formation (BH10229, BH10210, BH10221, BH10315, BH2240, BH9184, BH10216, and BH10219) and are present in most parts of the Ncojane Block. This sandstone unit forms the second aquifer within the Ecca Group and occurs in a large part of the area including areas around Metsimantsho, southwest of Ncojane and northeast of Ukwi (between F6 and F7).
- **Yellow to Orange zones** (20- < 50 Ω-m) correlate with the basal sandstone units of Otshe Formation within the Ncojane Wellfield area (BH10227/10402, BH10220, BH10410, BH10411, and BH10405). Boreholes which intercepted Otshe Sandstones in this zone had ground water with TDS which was much lower than the sandstones in the green zones. These zones are mainly developed around Ncojane and Metsimantle, towards Ngwatle as well as northeast of Metsimantsho. Due to similar resistivities of coarse sandstone and weathered dolerite, orange zones may also represent dolerite sills.
- **Red to Pink zones** (50 - < 200 Ω-m) represent dolerite sills and mainly occurs in the south-western part of the Ncojane Block. No boreholes were drilled in this zone.

6.4.10.5 Resistivity Distribution at 300 m Depth

The resistivity values at 300 m depth (**Figure 6.14**) represent resistivity characteristics of the lower Ecca units, Ghanzi Group Rocks and dolerite intrusions. Limited borehole lithological information is available at this depth since only few boreholes were drilled to this depth. The various resistivity ranges are represented by different colours and correlations of these resistivities with borehole data suggests that:

- **Blue zones** (< 10 Ω-m) may represent saline mudstones of the Kobe Formations. They occur mostly around the northern and southern side of Ukwi. No borehole was drilled in this zone.
- **Green zones** (10 – 20 Ω-m) are likely to represent the basal sandstones of the Ecca Formations. These zones mainly occur in the southeastern, southwestern, and the central part of the Ncojane Block.
- **Yellow zones** (25 -<30 Ω-m) are likely to represent coarse basal sandstones of the Otshe Formation. This zone is mainly developed in the southwestern part of Ukwi.
- **Red to Pink zones** (50 - < 200 Ω-m) occur in a large portion of the area particularly in the northwestern, eastern and north of Ukwi. Sandstones (BH10229 and BH10221), and mudstones (BH10315, BH10314, BH10227 and BH10217) were intercepted in this zone instead of the expected dolerites probably due to the poor resolution of TEM data at this depth. The pink zone to the north of the area probably represents the Ghanzi Group Rocks while in other areas it may be represent dolerite sill intrusion. No borehole was drilled through this range of resistivities (pink zone) at this particular depth

6.5 SUMMARY AND CONCLUSIONS

In general a good correlation between borehole lithology and TEM resistivities was observed, except at boreholes drilled between sounding points. At these locations dolerites were intercepted where they were not expected due to the poor horizontal resolution of TEM data and the weathered nature of these dolerites. The TEM interpreted depths of the Otshe Formation, which is the main aquifer in the Ncojane Block, correlates well with drilling and borehole geophysical logging results. At depths of more than 300 m however, TEM sounding have poor vertical resolution of the different lithological units, as sandstones and mudstones were intercepted during drilling instead of the expected lithologies (dolerites). Only a few boreholes were drilled to these depths bearing in mind the poor vertical resolution of TEM data at these depths. Above 300 m TEM smooth models provided very critical information about the resistivity variation with depth for mapping saline and fresh water bearing aquifers.

Ground magnetic profiling assisted in locating aeromagnetic and remote sensing data interpreted lineaments and faults, some of which have major control on the aquifer geometry and water quality. Magnetic profiling was also very instrumental in locating some dolerite sills, though not always due the horizontal and weathered nature of these dolerites.

HLEM profiling was found to be ineffective because a large portion of the project area is underlain by thick conductive units overlying the target aquifer, except near Ncojane and Kule villages where Kalahari Beds, Mosolotsane and Kule Mudstones are thinner and more resistive.

TEM soundings together with magnetic profiling were found to be the most effective methods for hydrogeological investigations in the project area should constitute the main ground geophysical techniques employed for siting water supply boreholes in the area.

Figure 6.1 Detailed Geophysical Survey Plan

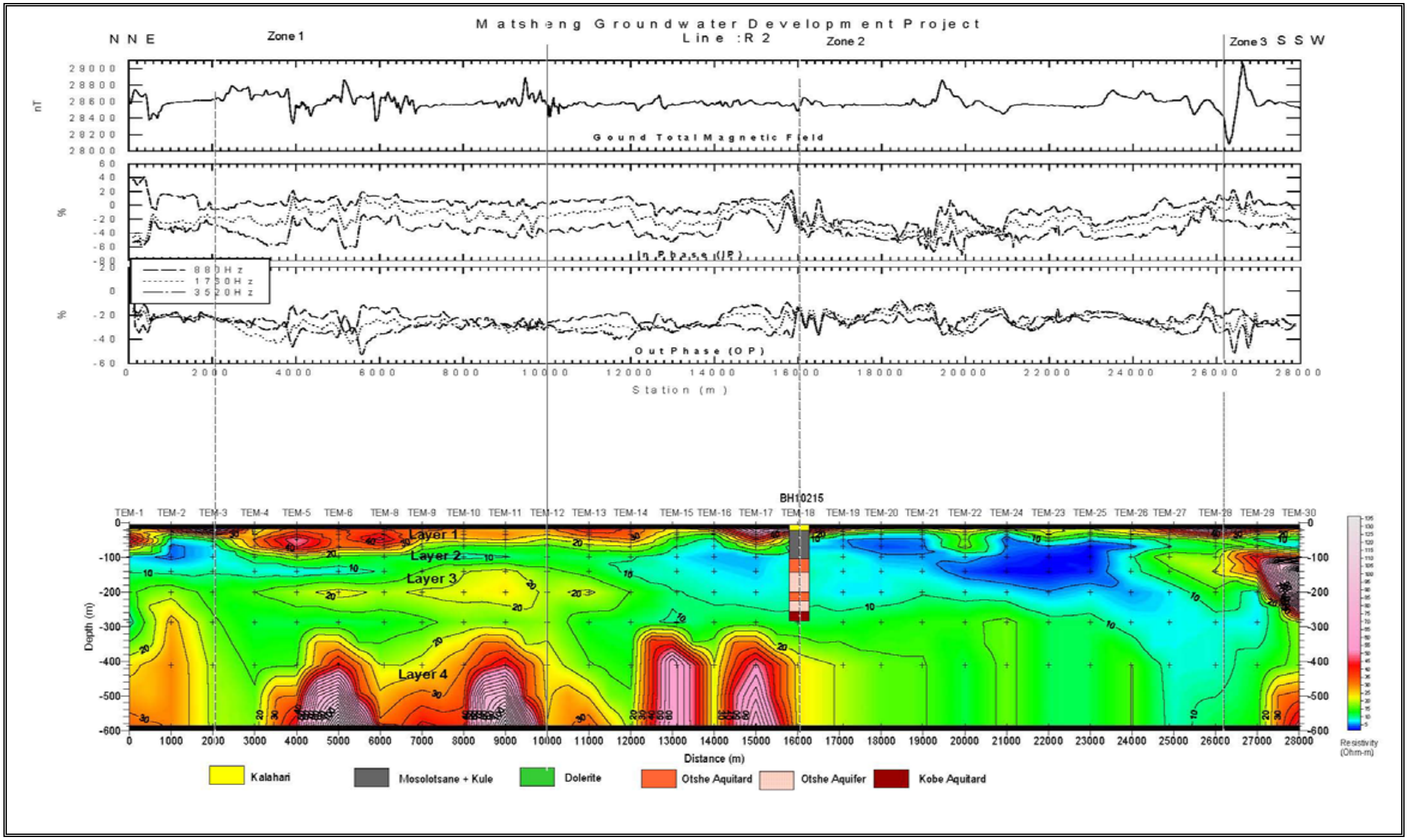

Figure 6.2 Magnetic, HLEM and TEM (Smooth Model) Plots Along Line R2

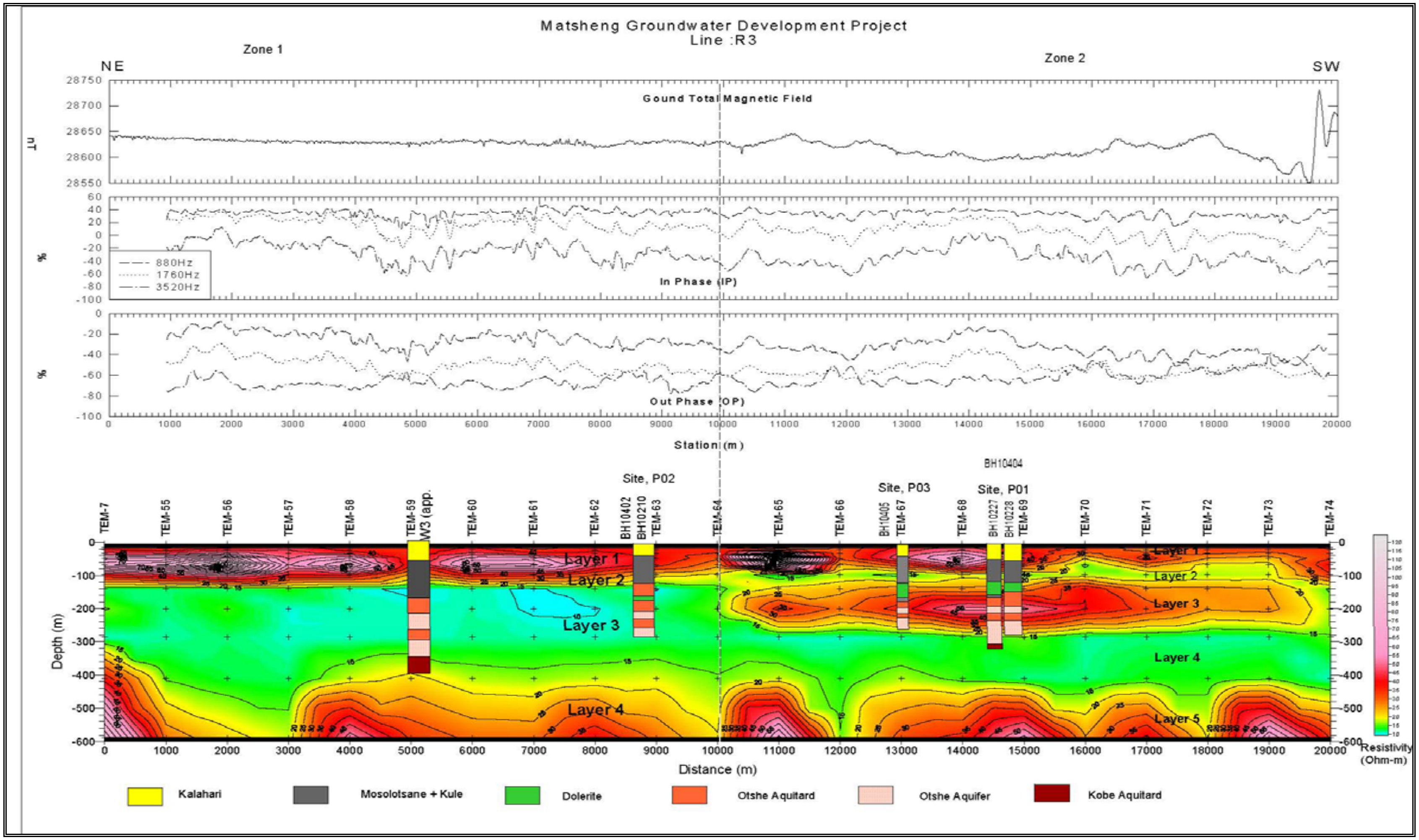

Figure 6.3 Magnetic, HLEM and TEM (Smooth Model) Plots Along Line R3

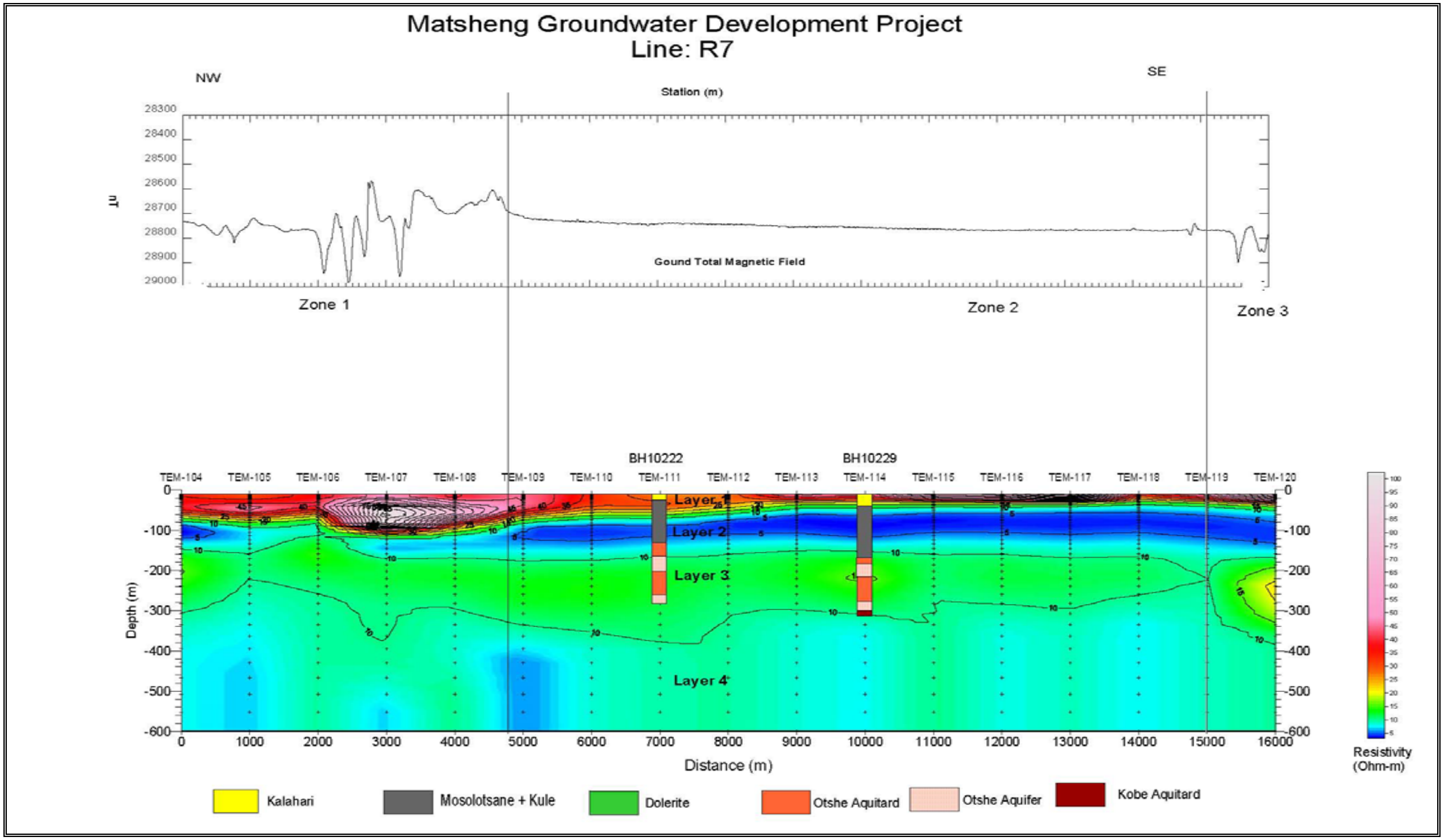

Figure 6.4 Magnetic and TEM (Smooth Model) Plots Along Line R7

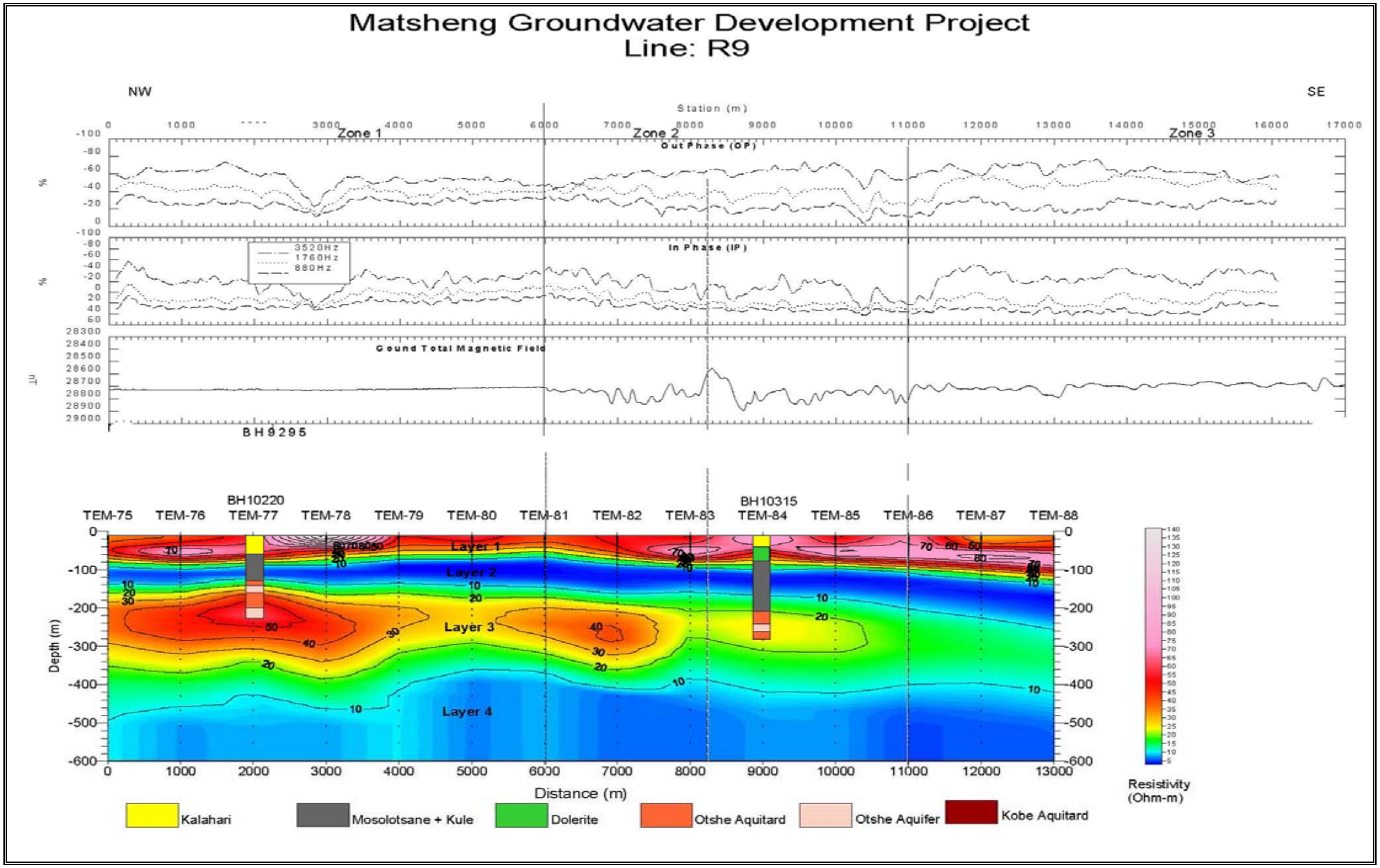

Figure 6.5 Magnetic, HLEM and TEM (Smooth Model) Plots Along Line R9

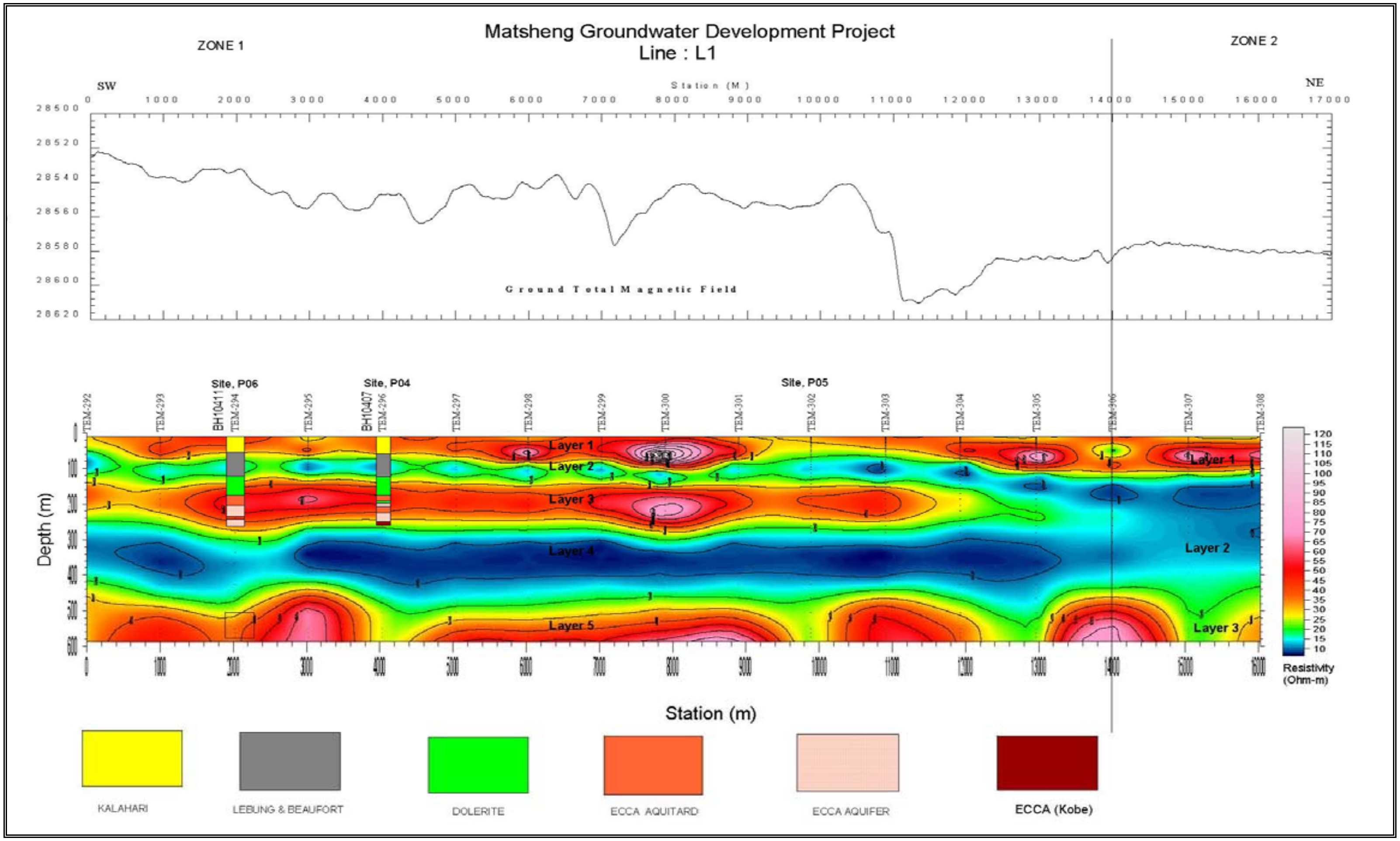

Figure 6.6 Magnetic and TEM (Smooth Model) Plots Along Line L1

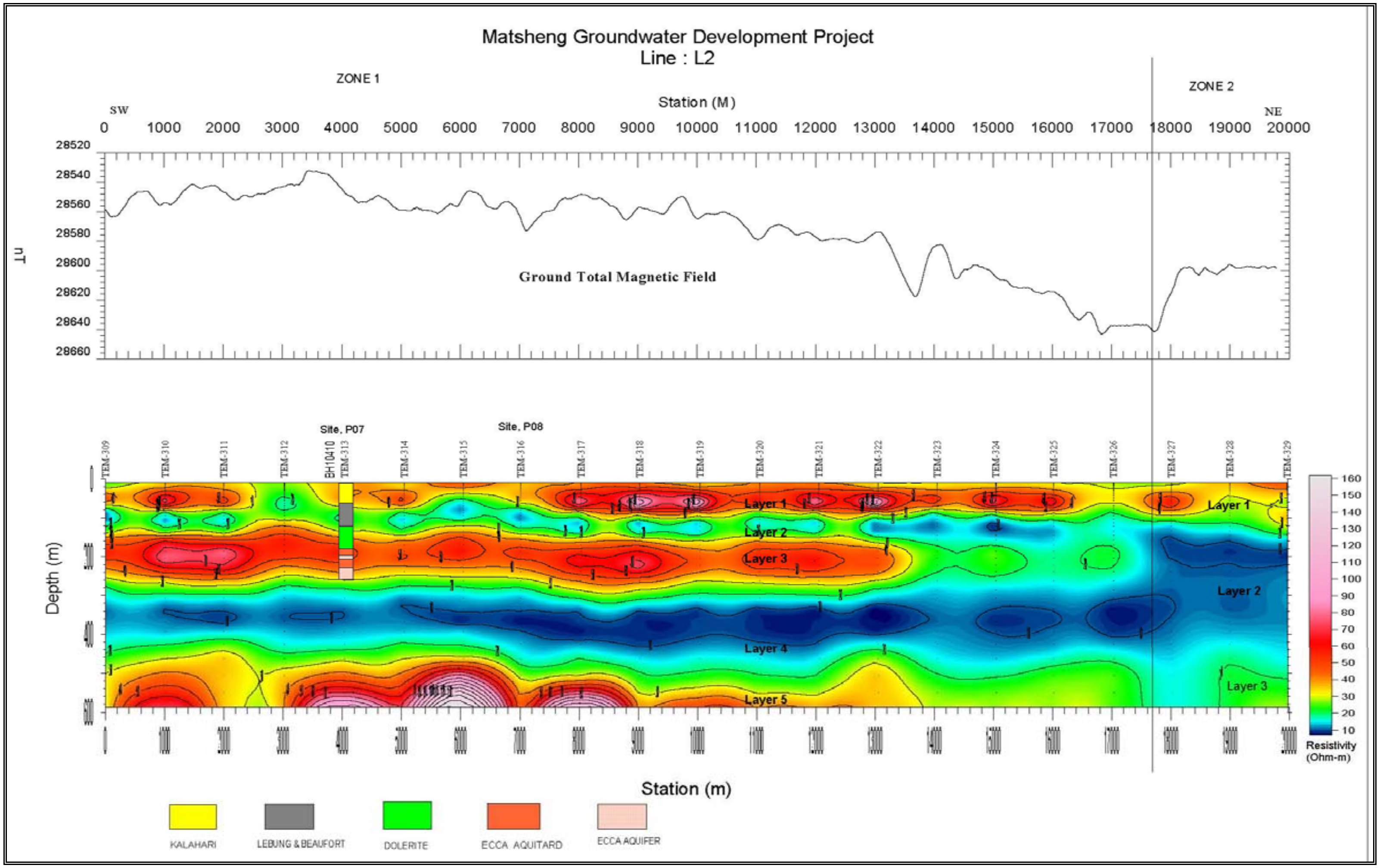

Figure 6.7 Magnetic and TEM (Smooth Model) Plots Along Line L2

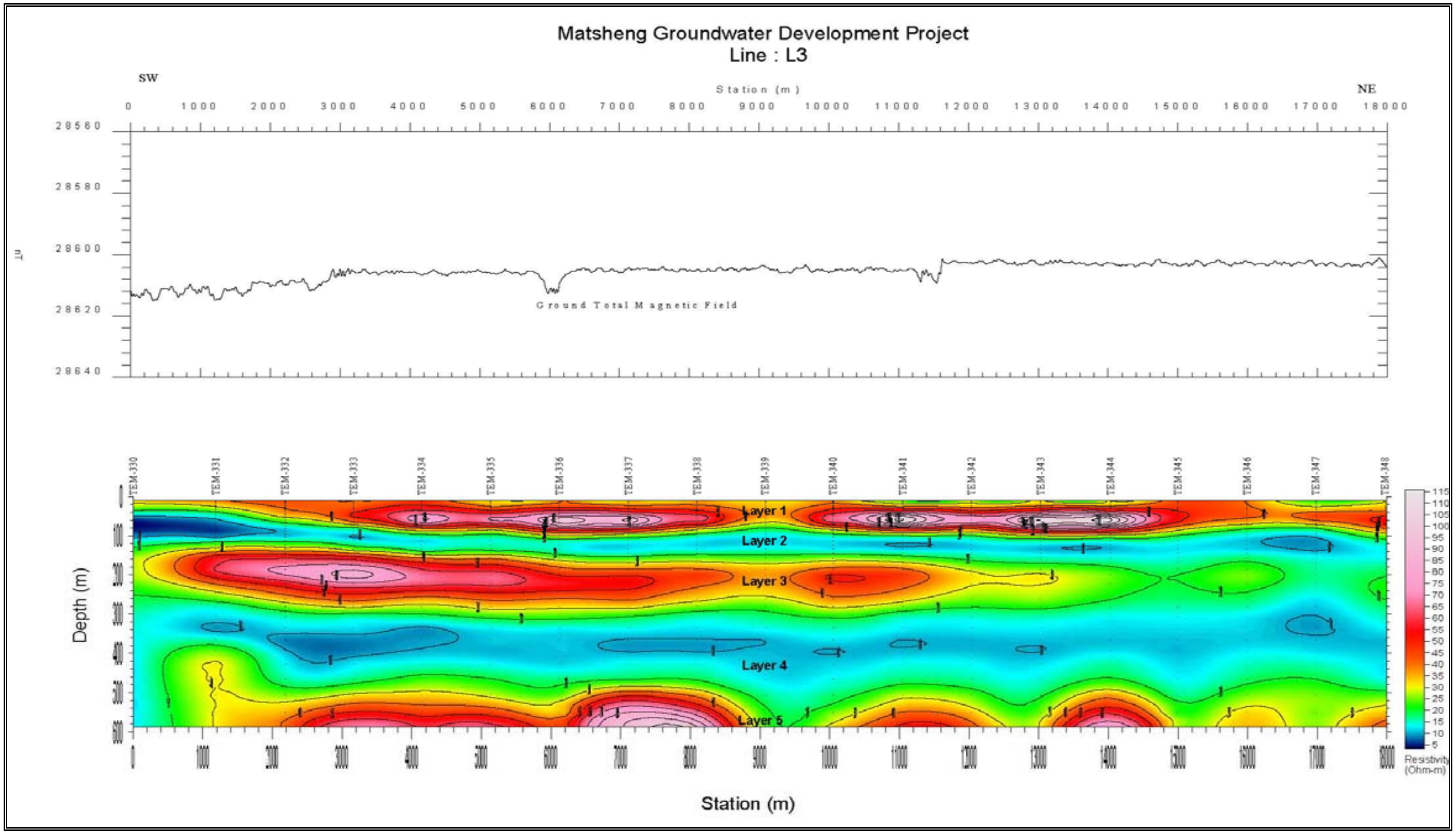

Figure 6.8 Magnetic and TEM (Smooth Model) Plots Along Line L3

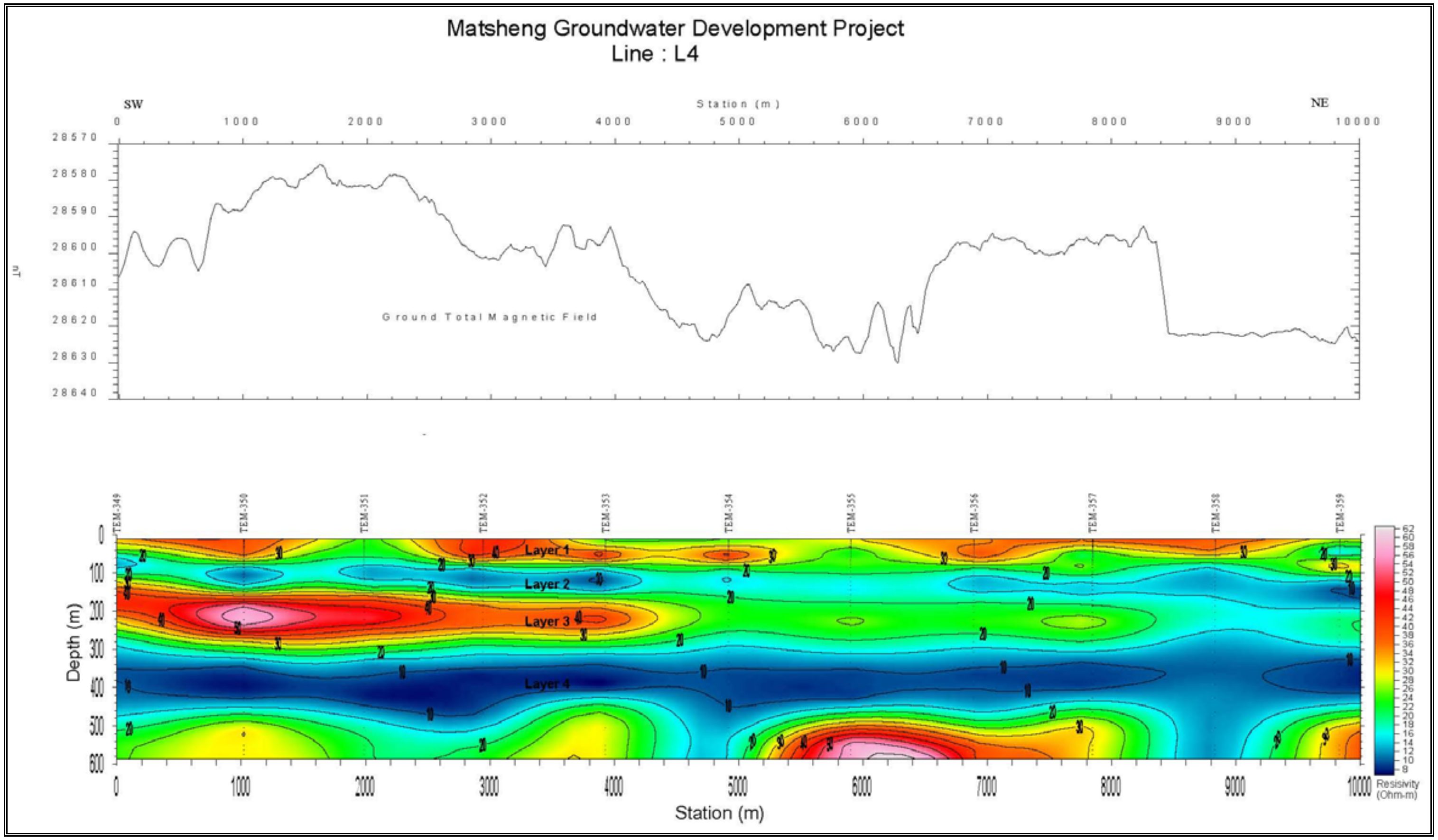

Figure 6.9 Magnetic and TEM (Smooth Model) Plots Along Line L4

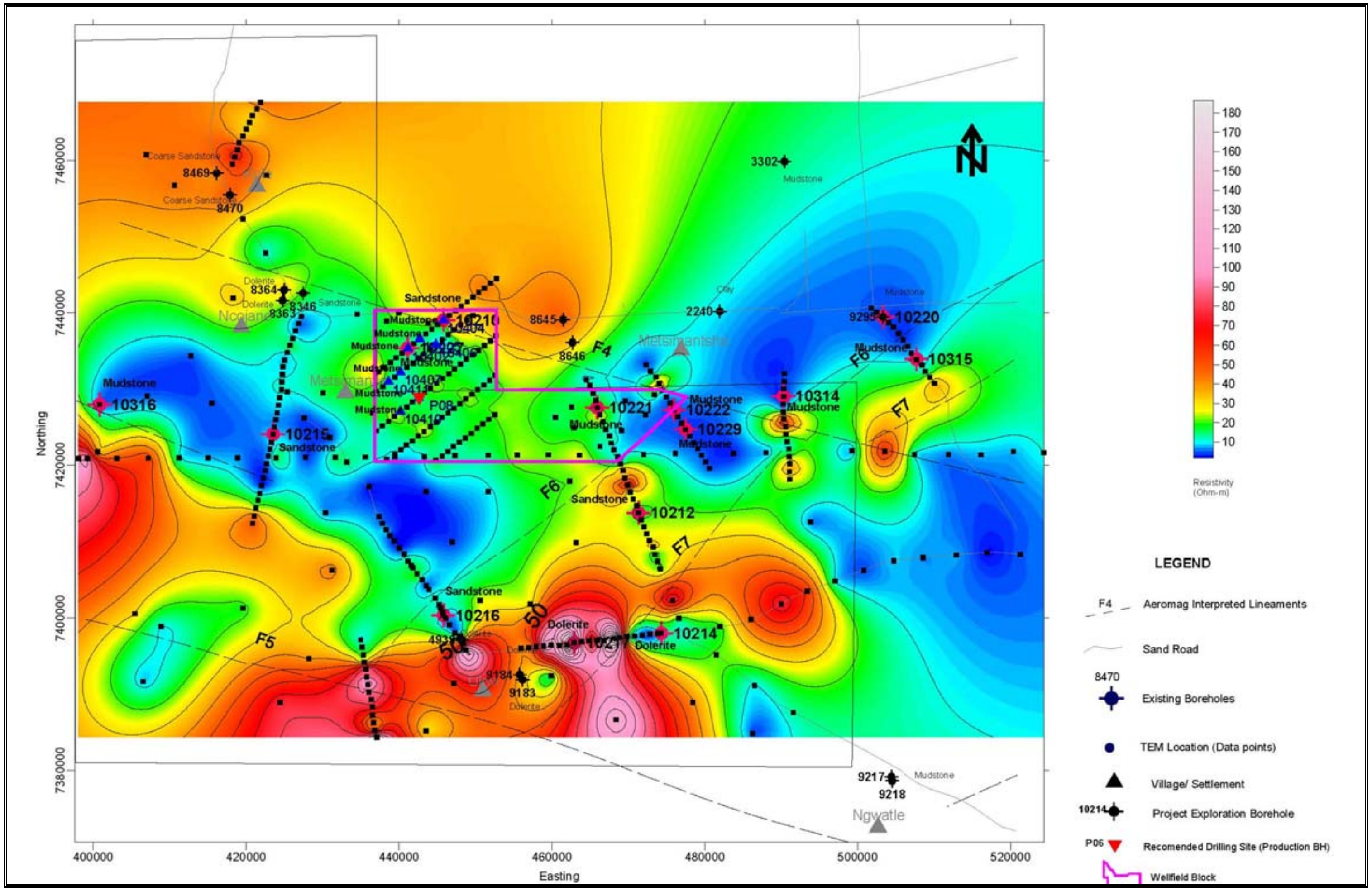

Figure 6.10 TEM Resistivity Contour at 100 m Depth

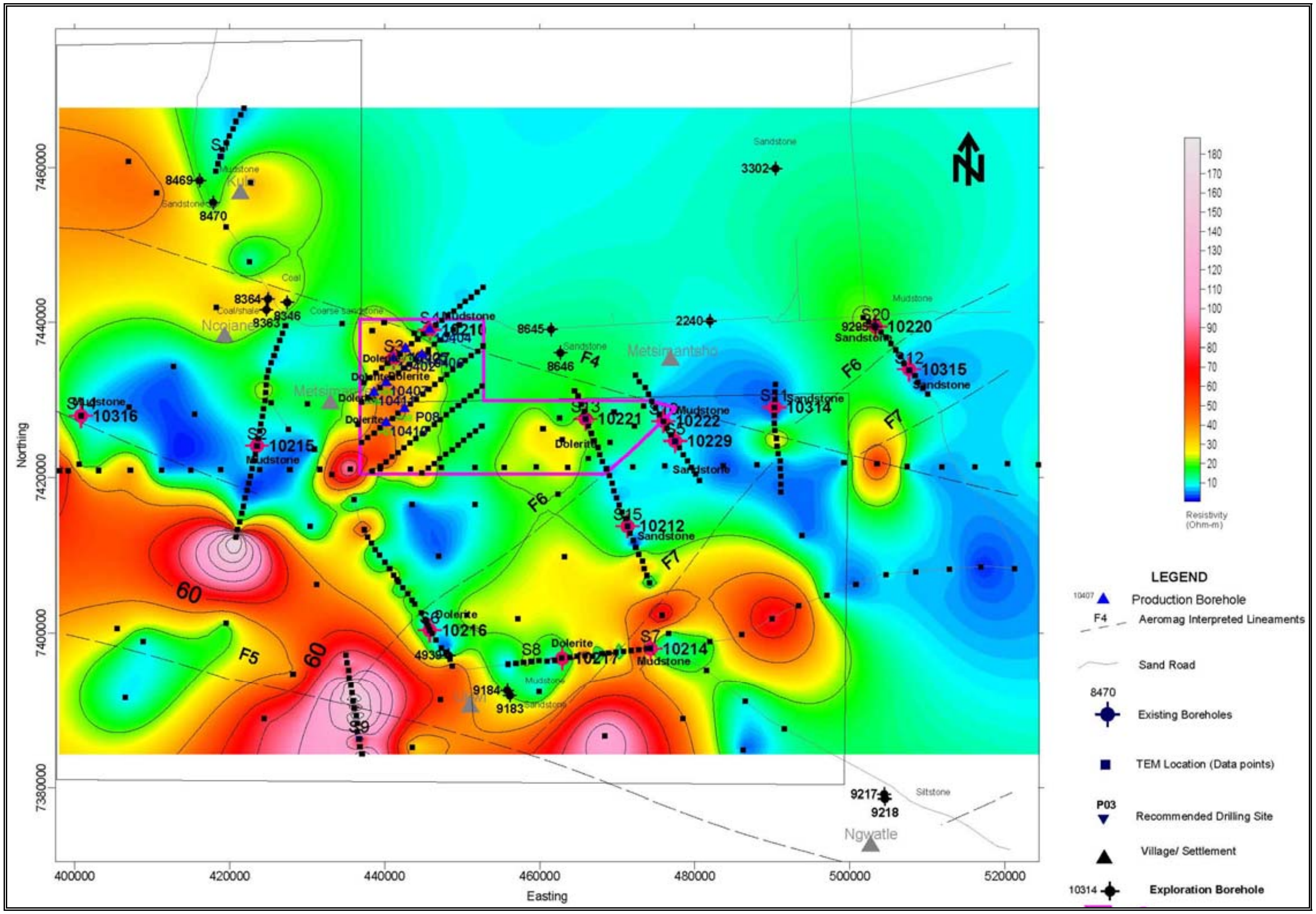

Figure 6.11 TEM Resistivity Contour at 150 m Depth

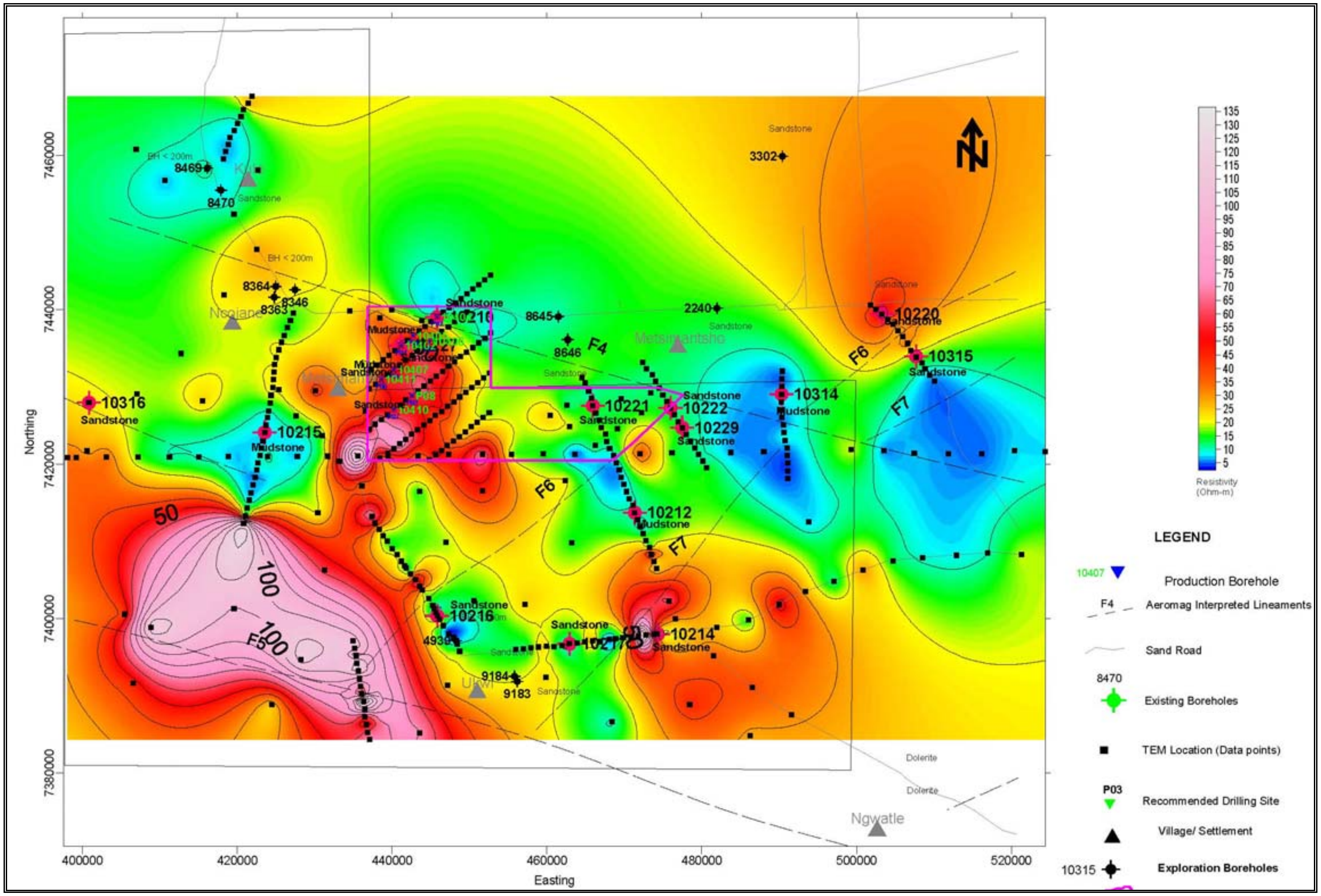

Figure 6.12 TEM Resistivity Contour at 200 m Depth

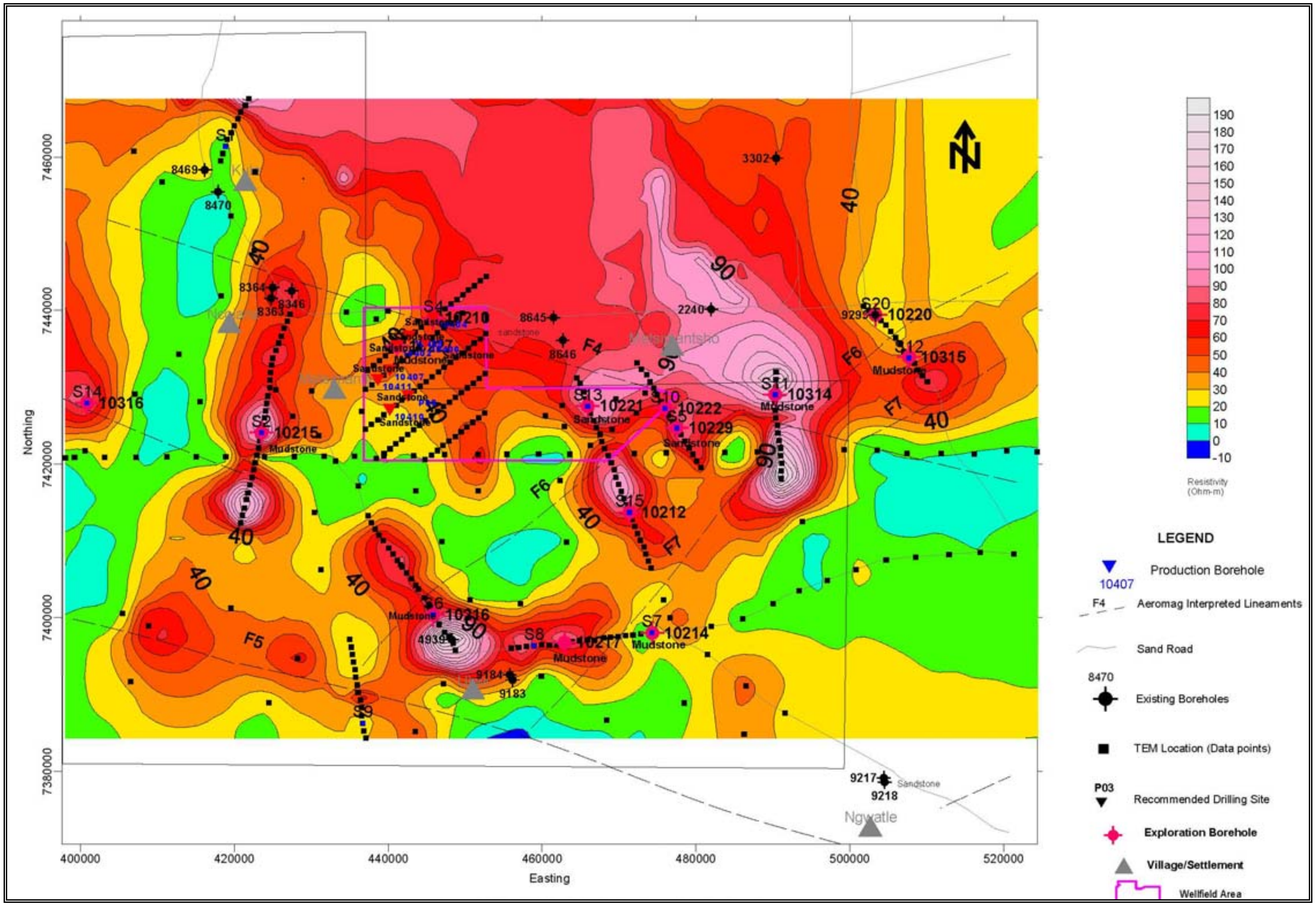

Figure 6.13 TEM Resistivity Contour at 250 m Depth

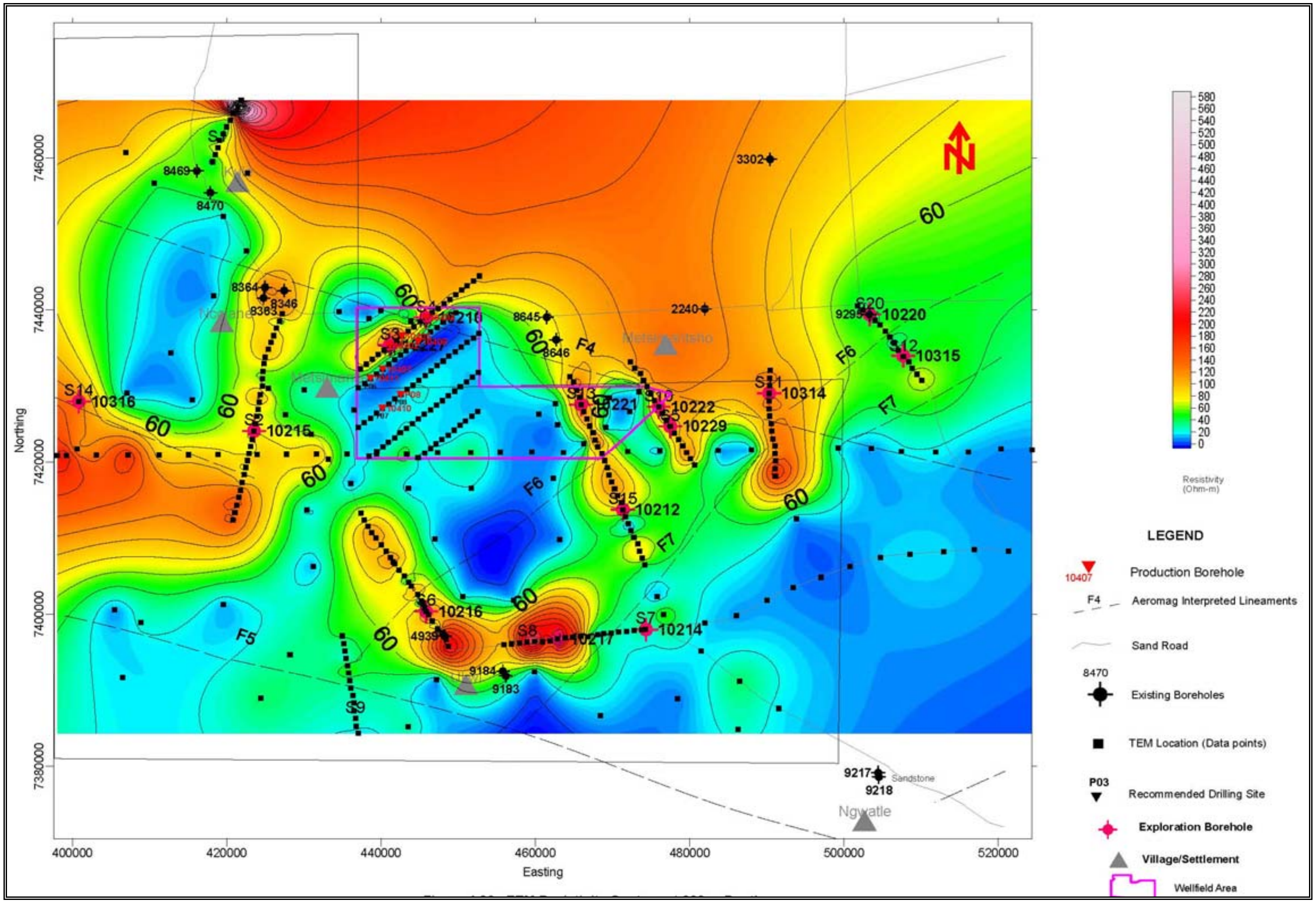

Figure 6.14 TEM Resistivity Contour at 300 m Depth

7 DOWNHOLE GEOPHYSICAL LOGGING

7.1 OBJECTIVES OF LOGGING

The objectives of conducting borehole geophysical logging during the Matsheng Groundwater Development Project were as follows;

- To delineate and refine depths to contacts of the different stratigraphic units intercepted during drilling
- To correlate the lithology intercepted during drilling with the interpreted TEM smooth model layers
- To examine the water quality of the aquifer zones in the area
- To guide casing and screen placements to help in maximizing borehole yields
- To correlate the intercepted lithologies between boreholes to assist in delineating aquifer geometry

7.2 METHODOLOGY AND EQUIPMENT

During the exploration and production phases, borehole logging was conducted using the latest of Century's logging tools called System VI. It represents Century's sixth generation of logging equipment, and it is conceptually a peripheral device to the users desktop or laptop computer. All logging specific hardware/electronics are packaged into a single small box and connected to the user's computer via a standard Ethernet cable connection. System VI automatically identifies the connected logging probe and it comes equipped with all software and hardware necessary to log, edit, process, interpret and print data.

Three downhole probes listed in **Table 7.1**, all allowing for measurements of several parameters were used during the project's logging operations (exploration and production phases). Each sensor within the probe measures the appropriate parameter at the selected sampling interval which was 1 cm for this project.

Table 7.1 Logging Probes used During the Exploration Phase

Probe Number	Parameters measured
8074A	Diameter Calliper (3-arm)
8057A	Natural Gamma Neutron and neutron porosity Temperature and delta temp Point Resistance Self Potential Lateral Resistivity 16 inch Resistivity 64 inch Resistivity
9041A	Natural Gamma Fluid Resistivity Temperature and delta temp Point Resistance Self Potential Lateral Resistivity 16 inch Resistivity 64 inch Resistivity Fluid Conductivity

7.2.1 DATA ACQUISITION AND QUALITY CONTROL

Data was acquired with a total of three probes for all boreholes during the course of the project. All logging tools were run in the upward direction with the 8057A or the 9041A probes run as a first probe to record temperature in a relatively stable environment. Logging was performed at the recommended speed of 6 m/minute.

In order to provide the highest possible data quality and integrity of the collected data one existing borehole BH8346, with known lithological information was chosen as a calibration borehole. This borehole was logged several times (4 times) during the course of the project and the logs are shown in **Figure 7.1**. This calibration exercise was undertaken prior to, during and on completion of the exploration and production phases logging. It was noticed that all parameters remained within acceptable limits as no significant shifts were observed during the entire logging operations.

7.2.2 BASIC PRINCIPLES AND APPLICATION OF LOGS

All applied geophysical logging devices can be divided into four categories as follows

- Radioactive (Natural Gamma and Neutron) Logs
- Electric (Resistivity) Logs
- Mechanical Logs
- Passive Logs

A brief discussion of the principles for the above logs is presented below.

7.2.3 RADIOACTIVE LOGS (NATURAL GAMMA AND NEUTRON LOGS)

The natural gamma radiation measured with the probe originates from radioactive isotopes of Potassium-40, Uranium and Thorium, which are common components of shales (clays). The gamma ray measurements therefore permit differentiation between shales and other lithologies with low clay contents. In general shales (clays) are characterized by high gamma counts and sandstones (sands) by relatively low counts, depending on the content of clayey minerals within them. Natural gamma is generally expected to be very low for all intrusive rocks (e.g. dolerite) as well as coals. Relatively high gamma counts are also expected from mica and feldspars rich sandstones and in some coals that are enriched with radioactive elements.

The neutron tool comprises fast neutron source (Americium Beryllium) which emits neutrons into the formation. The main application of this tool is to directly measure the formation porosity. The neutron log response thus largely represents the amounts of hydrogen in a formation. Low or sudden decrease in neutron counts thus represent high hydrogen concentration and therefore high porosity values (in a saturated sandstone layer), as the majority of hydrogen is present as water or hydrocarbons. This enables direct measurements of porosity within a particular formation. Corrections for borehole diameter and borehole fluid as well as for lithology are automatically applied by the logging software, eliminating the need for correction during processing. A sudden decrease in neuron count is expected as the probe enters the borehole fluid. Above the water table the neutron log can be viewed only in a qualitative sense. An increase in neutron porosity accompanied by a decrease in neutron counts indicates the presence of porous sandstone. The neutron log can also be used to identify coal seams and dolerites where a decrease in neutron porosity accompanied by in increase in neutron counts is observed.

7.2.4 ELECTRIC (RESISTIVITY) LOGS

All resistivity logs investigate the resistivity of the formations surrounding the borehole and are influenced by the matrix material as well as the pore fluids and the borehole itself. The radius of investigation is considered approximately twice the electrode spacing; therefore it is 32 and 128 inches for 16 and 64 inches respectively. The deeper penetration tools (long normal, lateral) do, however have poor resolution on thin layers which are highly resolved on tools with a small radius of investigation (short normal and point resistance) hence the tools compensate each other. A single electrode point resistant is commonly used to achieve the best resolution in thin bed environments, although it does not provide the resistivity values of the formation (it is solely resistance). The electric logs complement the natural gamma log and are of assistance in lithology interpretation since clays are more conductive than sands. Electric log can only be run in water filled boreholes because they need to make contact with the formation through the borehole fluid. Consequently they cannot be conventionally run in cased holes (either PVC or metallic casing). Electric logs are also the main means of monitoring the pore water salinity. While it is difficult to differentiate between clay rich sediments and sandstone containing saline ground water by means of ground geophysics, it is possible in downhole geophysical logging with the use of the fluid conductivity probe.

7.2.5 MECHANICAL LOGS

Under this category, is a calliper tool, which measures deviations in borehole diameter hence providing information on borehole construction and indirectly on lithology (caving in unconsolidated or fractured formations and very smooth on mudstones/shales). An accurate borehole diameter is often required in order to correct some of the logs (e.g. density).

7.2.6 PASSIVE LOGS

These tools measure the properties of the formation without inducing any field or emitting radiation into the formation. The temperature and differential temperature sondes fall under this category.

Air (above the water level) or borehole fluid temperature is measured by use of a thermistor. The differential or delta temperature is automatically calculated from the original temperature log by the logging software and is used to enhance small changes in temperature not visible on the temperature log. The temperature log most often registers a sudden change in temperature when it enters a borehole fluid, and therefore it is one of the tools with an accurate measurement of the static water level a borehole.

7.3 DATA PROCESSING AND INTERPRETATIONS

On completion of logging of each borehole, the raw unprocessed data was backed up to diskettes and converted to LAS format using the Analytical Compu Log (ACL) software, which accompanies the Portable Compu Log (PCL) logging software. The converted data was then imported into VIEWLOG (V1.0) software for interpretation purposes. Geophysical logging data interpretations were correlated with lithological information obtained from drilling chip samples. All the measured parameters (natural gamma, density, neutron, resistance, normal resistivity, fluid conductivity, and calliper) were utilized for the interpretation.

Typical responses of the measured parameters used in differentiating different lithological units are summarised in **Table 7.2**.

Table 7.2 Typical Responses of the Measured Parameters Used to Differentiate Lithologic Unit

Parameter		SANDSTONE		MUDSTONE	DOLERITE
		Clean	Micaceous		
Natural Gamma (API)	Cased	10 - 40	20 - 100	40 - 150	5 - 20
	Open	20 - 80	40 - 160	60 - 300	5 - 50
Resistivity (Ohm-m)	16 inch	5 - 50	50 - 200	0 - 20	60 - 150
	64 inch	10 - 60	50 - 200	0 - 20	100 - 400
	Lateral	0 - 60	50 - 200	0 - 20	60 - 150
Resistance (Ohm)	Point resistance	0 -40	0 - 80	0 - 10	5 - 50

All geophysical logs were interpreted individually and interpretations concentrated on the identification of lithologic units and water quality in the logged boreholes. While each log carries some information about the traversed lithology, the use of multiple parameters (logs) improves the accuracy and the certainty of the interpretation, as the marker horizons do not always appear clearly on all lithological logs. The interpretation for each logged borehole is summarized in **Table 7.3**.

In the sandstone/siltstone/mudstone environment of the project area, the various logs were expected to respond in the following manner:

- Natural Gamma - increases with increasing clay content and very low in dolerites
- Neutron-Neutron - increasing neutron porosity with increasing silt content and water saturation.
- Resistivity - decreasing with increasing salt content, it is also generally high in fresh water sandstones and dolerites
- Calliper – Smooth in mudstone and shale stones, spiky in cavities, washouts, fractures, sandstones and siltstones

Table 7.3 Interpretation of the Logged Boreholes

Borehole Number	Depth Logged	Lithostratigraphic Interpretations						
		Base of Kalahari (m)	Base of Ntane (m)	Base of Mosolotsane (m)	Base of Beaufort (m)	Base of Ecca (Otshe) (m)	Top of ECCA (Upper Kobe) (m)	Dolerite (m)
BH10216	249.2	13	Absent	Absent	126	212	212	58-71 84-99 137-165
BH10212	198.08	27	Absent	107	159	196+		27-69, 121 -136
BH10215	249.77	15	Absent	Absent	106	226	226	Absent
BH10228	252.14	25	Absent	65	163	256+		119-159
BH10229	320	33	Absent	117	160	306	306	Absent
BH10315	282	37	Absent	153	209	300+		40-80
BH10314	300	20	Absent	120	157	292	292	Absent
BH10211	250.5	33	Absent	81	134	250+		160-165
BH10227	247.39	25	Absent	65	163	298	298	121-161
BH10220	226	64	Absent	77	129	253+		Absent
BH10221	295.28	42	Absent	81	235	327++		120 - 177
BH10222	282.8	30	Absent	127	166	290	290+	Absent
BH10214	318	37	Absent	Absent	55	246	246	55-144 313+
BH10219	297	14	Absent	Absent	71	290	290	68-149
BH10316	243	17	Absent	Absent	92	220	220	Absent
BH10317	349	93	202	216	289	347	Absent	345-349+
BH2412	87	20	87+					Absent
BH8346	163	27	Absent	69	109	163+		NE
BH6188	43	10	Absent	34+				34 - 43(+)
BH9218	365	37	Absent	120	231	365+		120 - 200, 231 - 242
BH7832	365	69	Absent	97	257	365+		257 - 267
BH7829	365	82		166	263	365+		
BH9297	365	148		277	365+			
BH7871	110	30	Absent	Absent	110+			
BH10402	265	25	Absent	65	127	264+		127 – 169
BH10404	250	33	Absent	81	144	250+		154 – 157
BH10405	257	47	Absent	86	169	257+		127 – 155
BH10407	251	55	Absent	91	118	246	246+	118 – 170 171 - 176
BH10410	265	60	Absent	88	135	265+		135 – 183
BH10411	262	50	Absent	77	119	262+		119 – 169

The results for each measured parameter are discussed in the following chapters.

7.3.1 NORMAL RESISTIVITY (16 INCH AND 64 INCH) AND POINT RESISTANCE

Both normal resistivity and point resistance were able to delineate contacts between sandstones (high resistivity) and mudstones (low resistivity) as observed in **Figure 7.2** (BH10220).

7.3.2 NATURAL GAMMA

The natural gamma log was able to delineate contacts between sandstones, mudstones and dolerite as illustrated in **Figure 7.3** (BH10219). However, natural gamma alone failed to distinguish between micaceous sandstone (high gamma counts) and mudstones. In this case, conjunctive interpretation of the natural gamma and resistivity logs assisted in delineating such contacts as observed in **Figure 7.4** (BH10316) at depths **172-243** m.

7.3.3 FLUID RESISTIVITY AND FLUID CONDUCTIVITY

Fluid resistivity logs were able to distinguish between saline and freshwater aquifers. The data obtained during geophysical logging correlates with the drilling electrical conductivity (EC) values with an error of ±5 %. There was, however one borehole BH10315 where no correlation between the drilling EC values (700 µS/cm) and the geophysical logging EC values (1780 µS/cm) was obtained (from 240m) as observed in **Figure 7.5.** This is probably due to leakage of poor quality water from overlying Kule/Kwetla seeping down into the Otshe Formation.

7.3.4 TEMPERATURE LOG

The temperature logs were able to pickup the static water level as well as water inflow zones in some boreholes particularly during the production phase as can be seen in **Figure 7.6 (**BH10402**).**

7.3.5 NEUTRON-NEUTRON POROSITY LOG

Neutron logs were able to delineate porous sandstones from mudstones and dolerites as observed in **Figure 7.7** (BH10228). The unusually higher porosity values observed in the mudstone layer shown in **Figure 7.2** (BH10220) at depths 132-140 m is due to fracturing as indicated by the spikes in the calliper log.

7.4 SUMMARY AND CONCLUSIONS

Geophysical logging provided valuable information about the subsurface conditions in the project area, and supplemented information obtained during drilling and interpretation of TEM smooth model plots. Water inflow zones were also recognized in some boreholes, but generally they are difficult to infer from the geophysical logs probably indicating that the aquifers in the area are primary (not fractured). To best delineate contacts a combination of electrical parameters, natural gamma and neutron logs are very useful since they compensate each other.

From the review of existing logging data and interpretation of the logging data acquired during the project, it is can be concluded that:

- Natural gamma, resistivity and porosity together with the observed lithology provided very useful information on aquifer properties and assisted in interpretation of various lithological units
- Resistivity logs provided useful information on water quality variations with depth since a good correlation between groundwater electrical conductivity (EC), fluid conductivity, and formation resistivity was obtained
- Water temperature was found to be useful in identifying water inflow zones only in a limited number of cases mainly because the aquifer is primary, however the water temperature logs picked up the static water level in all the boreholes.

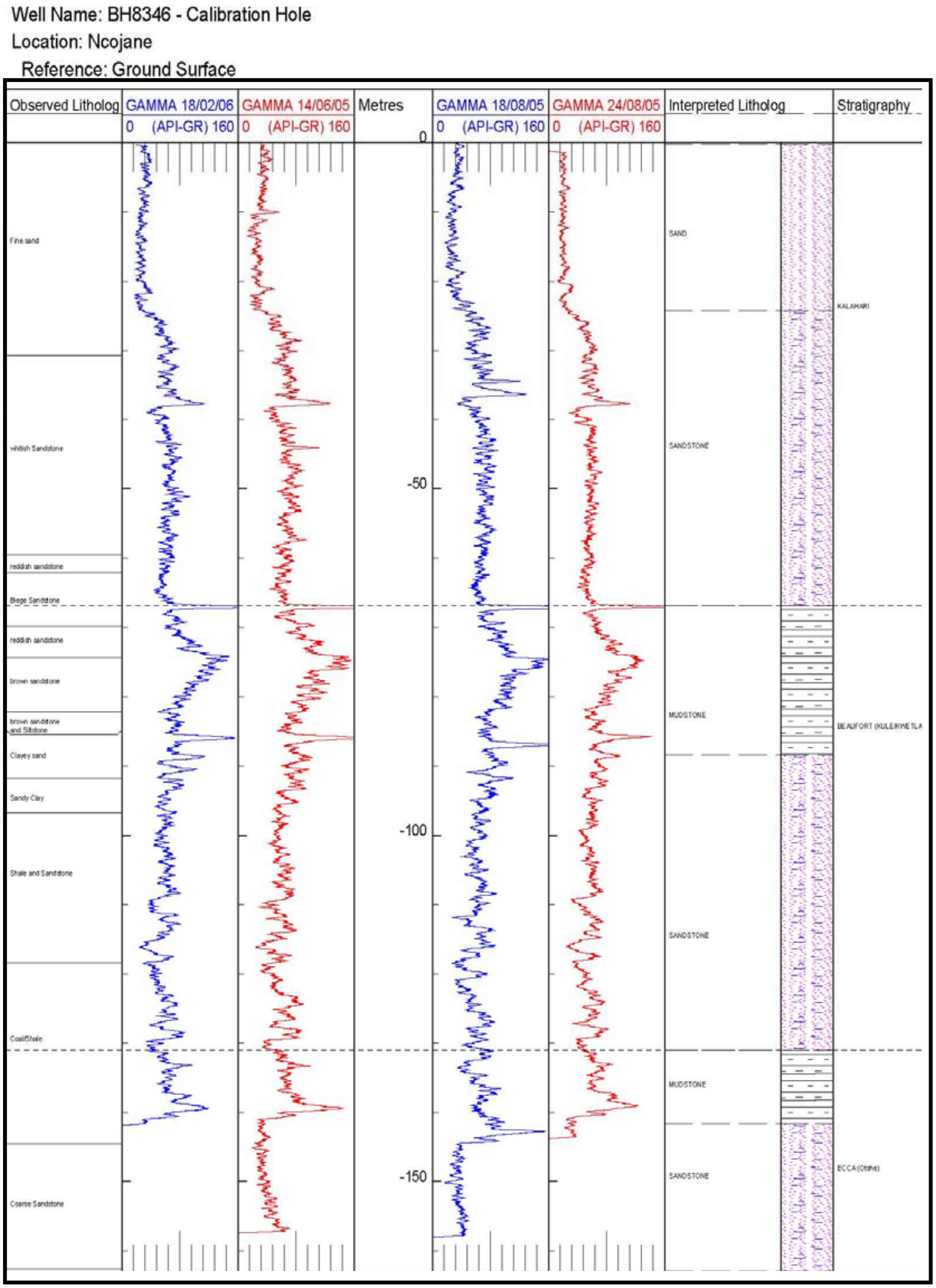

Figure 7.1 Calibration Borehole Showing Consistency of the Probes Used

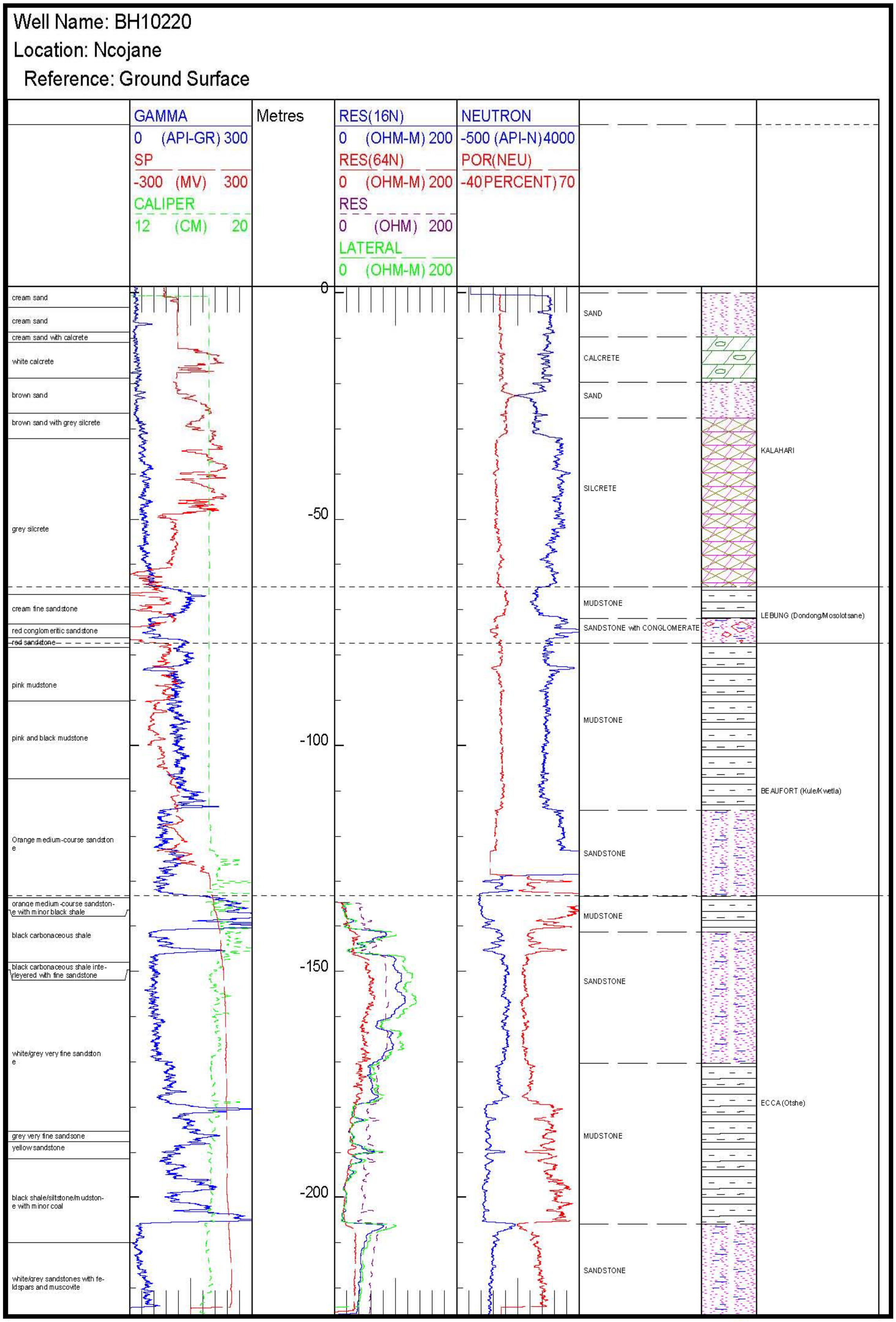

Figure 7.2 Normal Resistivity Delineating Sandstones and Mudstones Beds

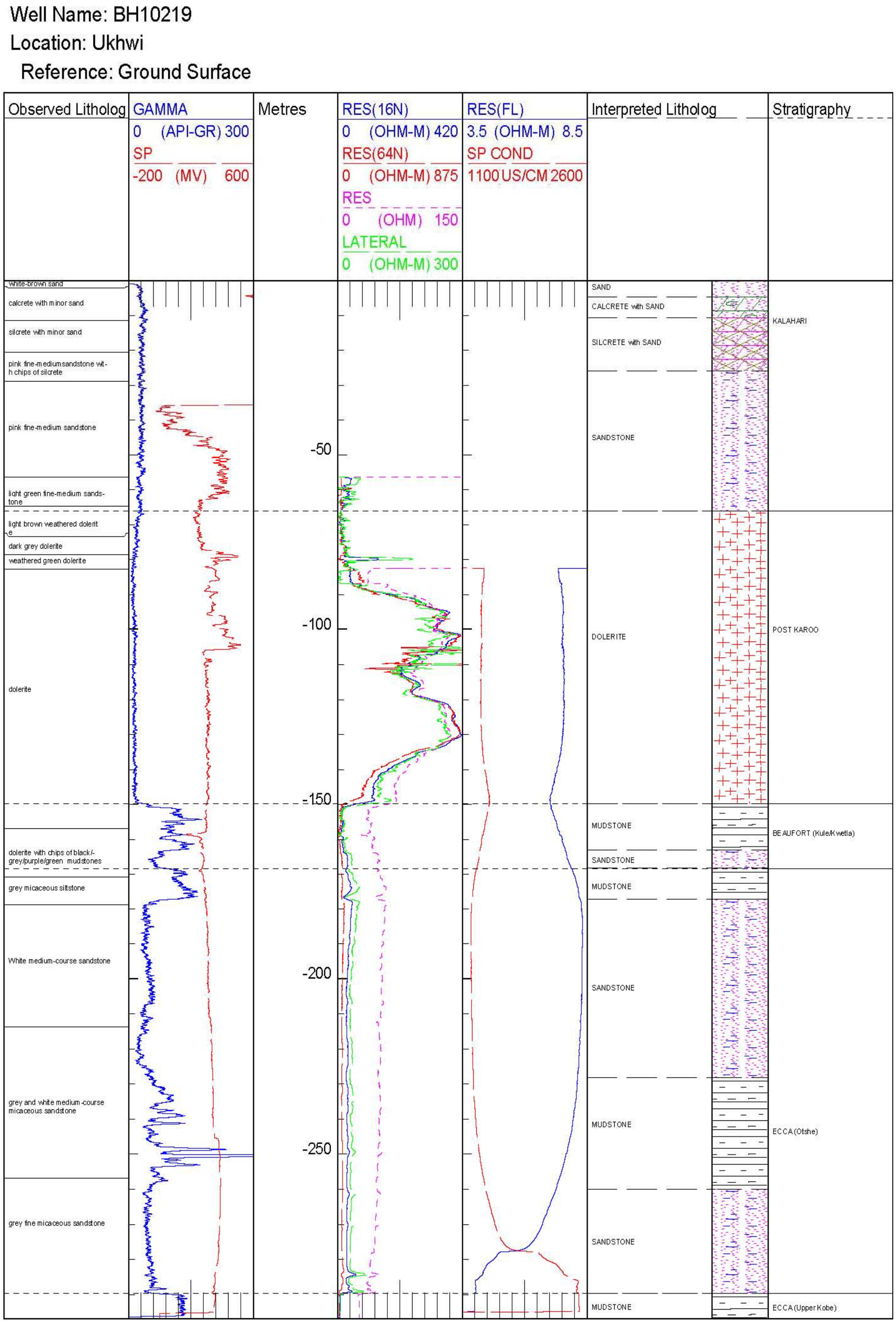

Figure 7.3 Natural Gamma Delineating Sandstones, Mudstones and Dolerite Contacts

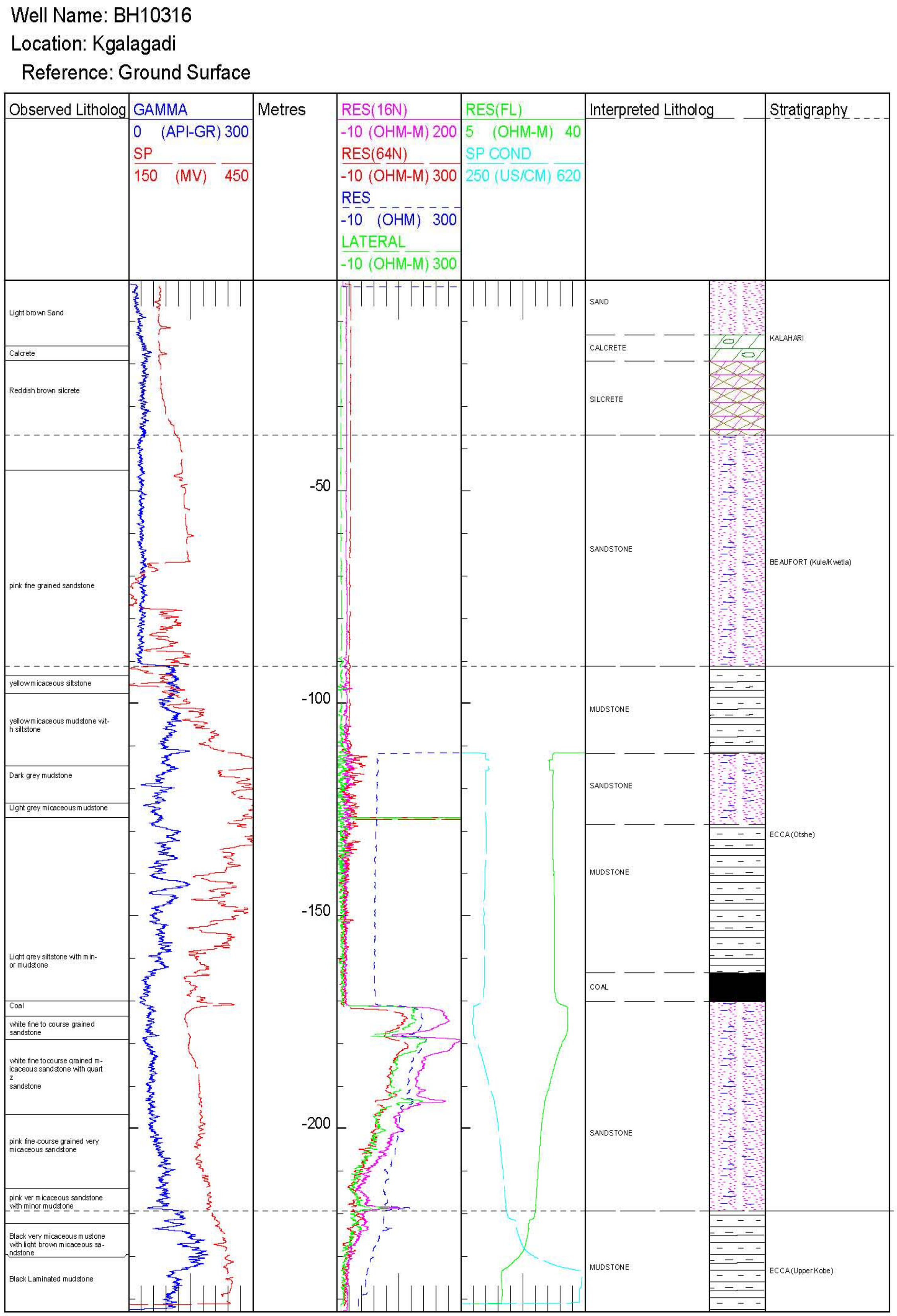

Figure 7.4 Resistivity with Natural Gamma Differentiating Micaceous Sandstones & Mudstones

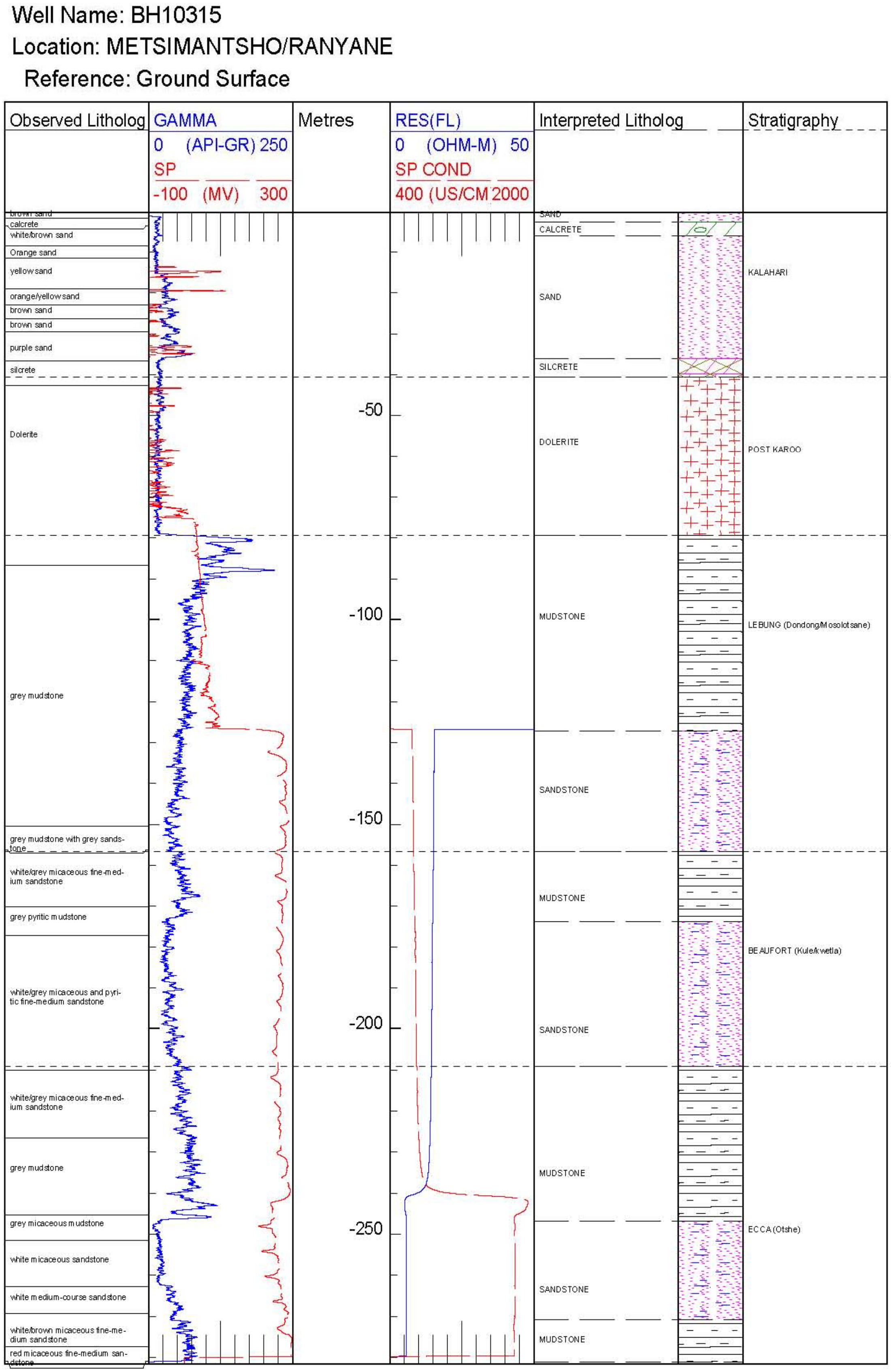

Figure 7.5 Fluid Conductivity Identifying Leakage of Poor Quality Water

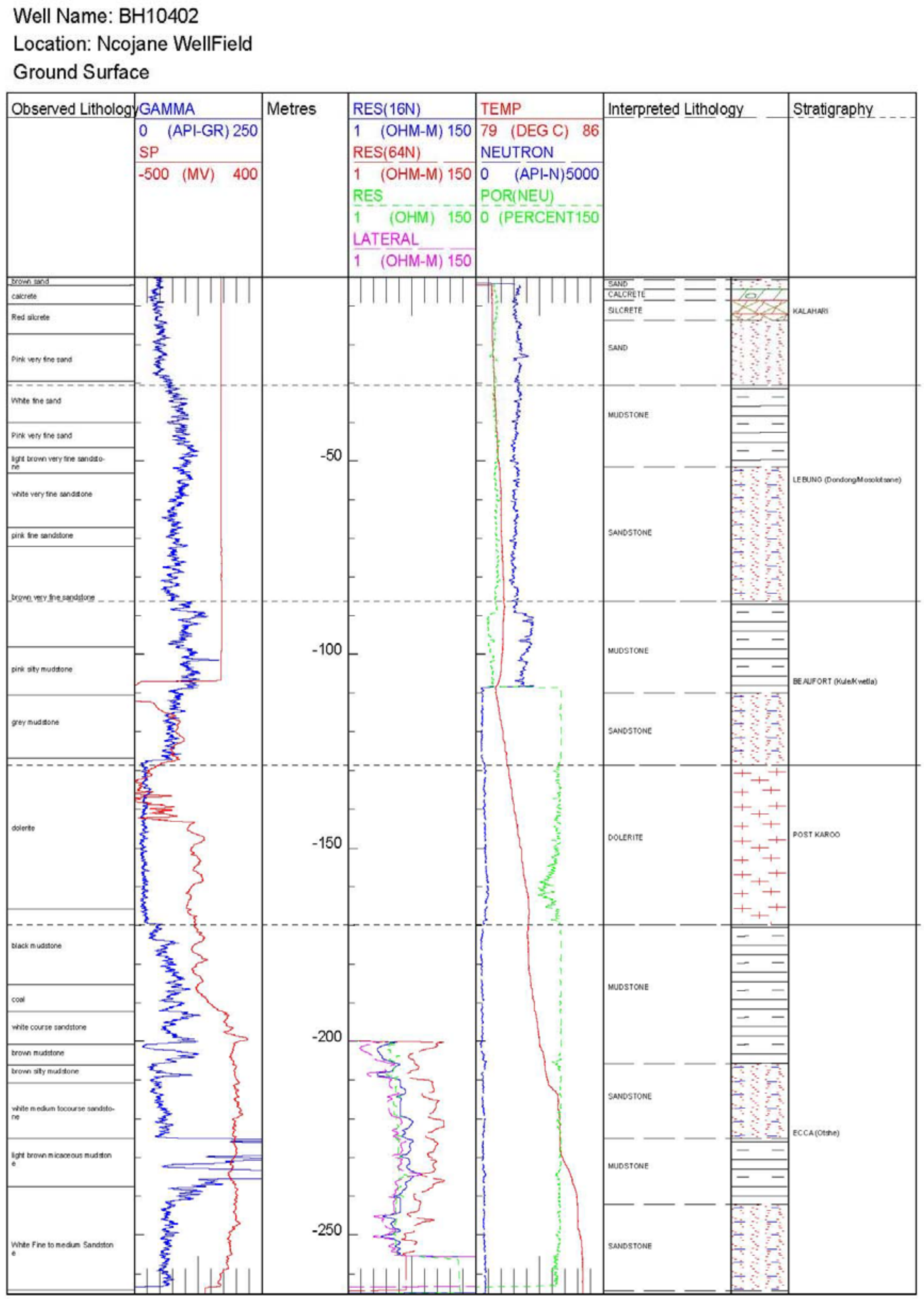

Figure 7.6 Temperature Logs Identifying both Water Level & Water Inflow Zones

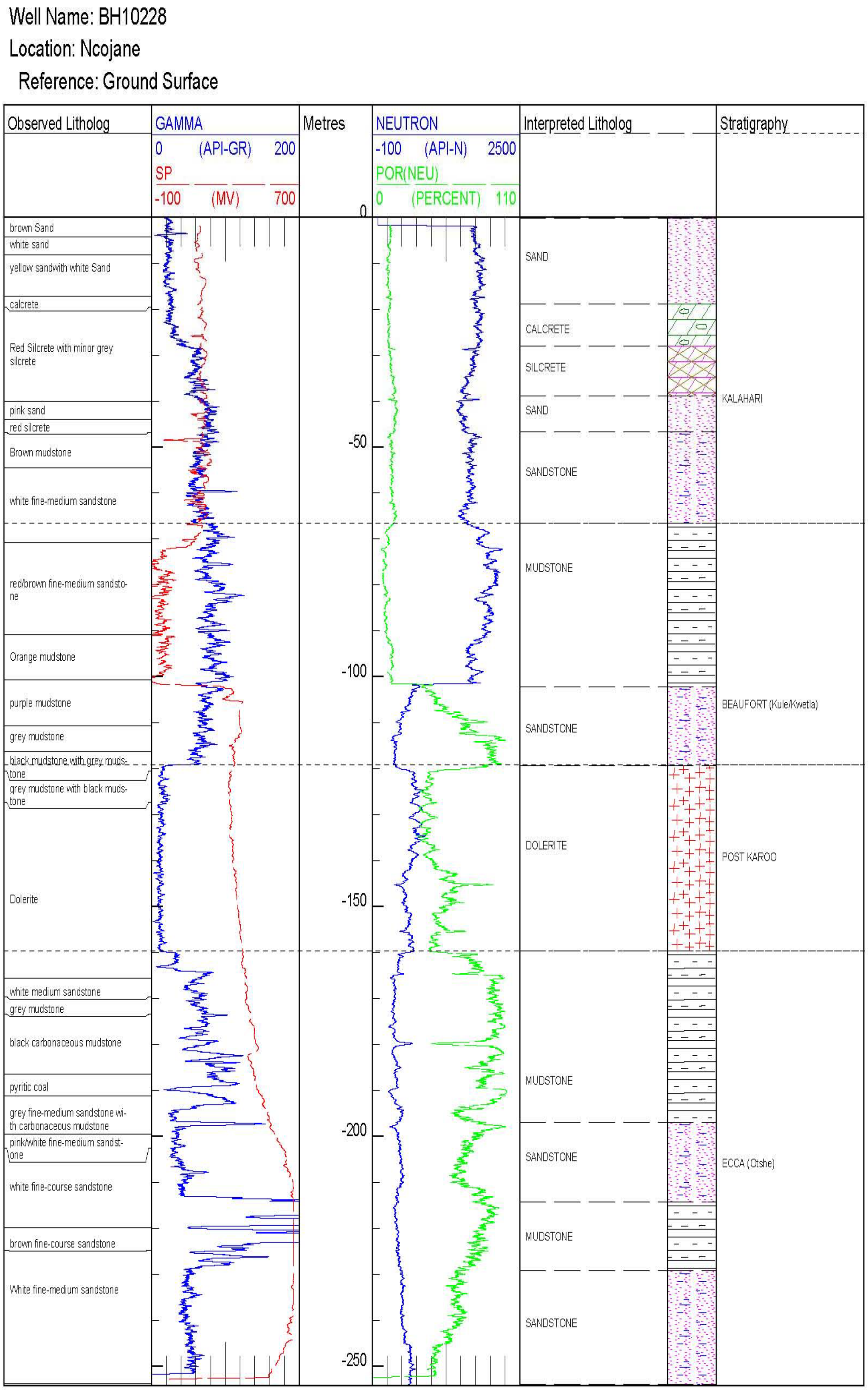

Figure 7.7 Neutron Counts Delineating Sandstone and Mudstone Contacts

8 DRILLING RESULTS AND HYDROGEOLOGICAL ASSESSMENT

8.1 OVERVIEW

The drilling programme of the Matsheng Groundwater Development Project was carried out in two phases, the Exploration and Production Drilling Phases. The exploration drilling programme was divided into two Drilling Contracts, Batch 1 and Batch 2 and the production phase was carried out under a single drilling contract.

Drilling Contractors for the Exploration Phase were Nhabe Drilling and Pula Groundwater Developers while Notwane Drilling Company carried out drilling during the Production Phase.

8.1.1 EXPLORATION PHASE BATCH 1 CONTRACT

Under the Batch 1 contract, which was originally awarded to Nhabe Drilling, 15 boreholes were planned (10 exploration and 5 monitoring boreholes) but only 12 (8 exploration and 4 monitoring boreholes) were drilled due to deeper drilling depths than originally anticipated. During this contract there were numerous organisational and logistical problems with the contractor which ultimately resulted in them pulling out of the contract without completing a single borehole. This resulted in a delay of about 4.5 months (from 19 May 2005 to end September 2005). Following Nhabe Drilling pullout, the Batch 1 Contract was re-awarded to Pula Groundwater Developers who started their activities on 14 October 2005 and completed on 10 March 2006. A total of 12 boreholes (4 monitoring and 8 exploration boreholes) were drilled. Three boreholes drilled under this contract were abandoned due to collapsing and loss of a drilling bit. One existing borehole (BH929) was cleaned and converted into two nested piezometers monitoring Sandstones 1 and 2 of the Ecca aquifer.

8.1.2 EXPLORATION PHASE BATCH 2 CONTRACT

The Batch 2 Drilling Contract was awarded to Pula Groundwater Developers and similar to the Batch 1 contract it was also planned to drill a total of 15 boreholes (10 exploration and 5 monitoring). Drilling under this contract was started on 23rd May 2005 and was completed on 10 February 2006 four months after the planned completion date. This was again due to the incompetence of the drilling contractor. Under this contract, 12 new boreholes (8 monitoring and 4 exploration) were drilled using two drilling rigs. In addition to the 12 drilled boreholes, 5 existing boreholes were cleaned and one was deepened from a depth of 167 to 284 m.

8.1.3 PRODUCTION PHASE

Notwane Drilling Company who were awarded the Production Phase drilling contract, started their drilling operations on 27 January 2007 and completed their operations on 07 September 2007 after completing only 6 of the 10 planned production boreholes. The reason for drilling only 6 boreholes was both as result of poor performance of the contractor (mainly) and because the yield from the 6 completed boreholes was assessed to be sufficient to meet the projected year 2023 water demand for the Matsheng Villages as well as for the secondary demand centres.

8.1.4 DRILLING OBJECTIVES

Four types of boreholes, monitoring, exploration, test production and production boreholes were drilled during the Matsheng Groundwater Development Project. These boreholes were sited using ground geophysical techniques, remote sensing studies as well as aeromagnetic data interpretation. Borehole sites were selected in different geological and hydrogeological environments of the project area bearing in mind the principal objectives of the exploration and production drilling phases which included;

- Delineation of structural features such as faults, lineaments and dolerite intrusions and evaluation of their hydrogeological significance as hydraulic barriers or areas with increased groundwater potential

- Evaluation of groundwater quality variation with depth as well as spatially
- Determination of borehole yields
- Determination of aquifer hydraulic parameters (e.g. transmissivity, storativity)
- Determination of influence of faults and lineaments on aquifer geometry, aquifer yields and ground water quality
- Generation of water level monitoring data for purposes of understanding the groundwater flow dynamics as well as for input into the numerical groundwater flow model and monitoring seasonal water level fluctuations as well as long term water level trends
- Understanding the influence of dolerite sills in water quality
- Selection of optimal locations for the production wellfields

To evaluate the groundwater potential of the different geological environments identified from remote sensing studies, aeromagnetic data interpretation and ground geophysical surveys, drilling sites were selected on different features such as:

- Structurally undisturbed areas characterised by uniform magnetic and or HLEM responses (where applicable) together with uniform resistivity layering on TEM sections
- Structurally disturbed (fractured) areas which are characterised by magnetic and HLEM (where applicable) anomalies as well as discontinuities in the TEM resistivity sections coinciding with remote sensing and aeromagnetic data interpreted structures
- Areas with dolerite sill intrusions characterised by short wavelength magnetic anomalies and high resistivities based on TEM sections

Production boreholes were drilled in areas which were evaluated to have the best groundwater potential both in terms of yields, groundwater quality as well as their potential for future wellfield expansion.

8.2 DRILLING PROGRAMME AND RESULTS

A total of 36 boreholes were completed during the Matsheng Groundwater Development Project amounting to total meterage of 9456 m. Borehole depths ranged from 201 to 444 m for exploration/test production and monitoring boreholes and from 244 to 263 m for production boreholes. These included 12 exploration boreholes, 2 test production boreholes, 6 production boreholes, 11 monitoring boreholes as well as 5 existing boreholes which were cleaned. In addition to the successfully completed boreholes, 7 boreholes were abandoned at different depths for various reasons.

In general, airlift yields measured over 90° V-notch weirs for monitoring boreholes ranged from 9 to 101 m^3/hr, for the exploration/test production boreholes the airlift yields ranged from 2 to 127 m^3/hr. For production boreholes airlift yields ranged from 44 to 78 m^3/hr. **Tables 8.1** and **8.2** summarises details of the project's exploration, test production, monitoring and production boreholes respectively.

8.2.1 DRILLING METHODS EMPLOYED

The drilling and construction methods used for project boreholes are discussed below for each borehole type.

8.2.1.1 MONITORING BOREHOLES

Monitoring boreholes were drilled using an 8 inch diameter drilling bit with the down hole hammer (DTH) method to a depths of approximately 80 m after which 6.5 inch plain casings were installed and cement grouted. Drilling was then carried out using a 6.5 inch bit to the terminal depth. When drilling deep monitoring boreholes (more than 300m), a 10 inch drilling bit was used to drill through the Kalahari Beds (80m) which were then cased and cement grouted using 8 inch plain casings. Further drilling to the top of Ecca (~200) was achieved using an 8 inch bit and 6.5 inch casings were installed and cement grouted. A 6.5 inch bit was then used to drill to the terminal depth. However, in some boreholes a 6.25 inch tri-cone bit was used instead of 6.5 inch DTH bit to overcome back pressure problems associated with high yielding water strikes particularly in the Ecca aquifer (Otshe Formation).

After completion of drilling, shallow (less than 300 m) monitoring boreholes were constructed with a 2 inch (50mm) PVC casing and screen assembly and deep monitoring boreholes were constructed with 2.4 inch (60mm) reinforced PVC casings and screens. Gravel pack consisting of 1.2 to 2.4 mm sub-rounded quartz grains was then tremied from the bottom of the hole to various depths above the top of the highest screened interval. The top 3m above the gravel pack was sealed off using bentonite and the remaining annulus was cement grouted to the surface. Monitoring boreholes were developed by blowing compressed air through a 1” airline using the PVC casing as an eductor pipe.

8.2.1.2 EXPLORATION AND TEST PRODUCTION BOREHOLES

Drilling of exploration boreholes was carried out with a 15 inch bit using the DTH drilling technique to depths of up to 80 m below ground level after which 12 inch plain casings were installed and cement grouted. A 12 inch DTH drilling bit was then used to continue drilling to depths of approximately 200 m after which 10 inch plain casings were installed and cement grouted. Drilling to the terminal depths was through a combination of 10 inch DTH bits and $9^{7/8}$ tricone bits. The tricone bits were used to overcome back pressure problems associated with high yielding water strikes in the Ecca aquifer (Otshe Formation). The exploration boreholes were completed with an assembly of 8 inch plain casing and factory slotted casings without gravel packing. However one borehole (BH10214) was left as an open hole because of low airlift yield (<4 m^3/hr).

For test production boreholes, drilling was carried out using a 17.5 inch DTH bit to depths of about 10m after 15 inch casings were installed. Further drilling was through a 15 inch DTH bit to depths of about 140m after which a string of 12 inch casing was installed and cement grouted. Further drilling to the terminal depths were achieved by a 12 inch drilling bit using the DTH method. Tri-cone bits were used to overcome the back pressure problems. Test production boreholes were constructed with 6.5 inch steel casings and 6 inch Louvered screens or wire wrap screens (20 slot). Similar to monitoring boreholes, gravel pack was tremied from the bottom of the borehole to various depths above the highest screen interval for test production boreholes. The remaining annulus was cement grouted.

Borehole development was through airlift pumping for exploration boreholes while the test production boreholes were developed by both airlifting and air jetting techniques. Verticality and alignment tests were carried out in all exploration and test production boreholes.

It was initially planned that the exploration boreholes would be left as 10 inch open holes in the main aquifer zone (approximately below 200 m) but this design was changed in the early stages of the exploration drilling programme due to collapsing problems. It was also realised that a completion diameter of 6.5 inch casings and screens limited the size of pumps during test pumping and 8 inch completion had to be utilised to cater for bigger pumps.

8.2.1.3 PRODUCTION BOREHOLES

Drilling of production boreholes was started with a 17 inch drilling bit down to depths of about 70 m (Kalahari) after which 15 inch plain casings were installed and cement grouted. Drilling was then continued with a 15 inch bit to the top of the first sandstone unit of the Ecca (~190 to 200m) after which 12 inch plain casings were installed and cement grouted. Drilling to the to the terminal depth (244 to 263 m) of the borehole was through a combination of 12 inch bits as well as 12 inch tricone bits. The boreholes were constructed with 8 inch epoxy coated casings and screens and borehole development was through air lift pumping. Verticality and alignment tests were carried out to the top of the first screen in all production boreholes.

8.2.2 SUMMARY OF DRILLING RESULTS

A map showing borehole locations in the project area is given in Figure **8.1** while summary details for project boreholes is given in **Tables 8.1** and **8.2**. Detailed descriptions of all project drilled boreholes including borehole logs, construction, water chemistry data and interpretation of pump testing data are given in ***Volume 2, Hydrogeological Report***.

8.2.2.1 NCOJANE BLOCK

A total of 24 boreholes were drilled in the Ncojane Block, of which 5 were monitoring boreholes, 11 were exploration boreholes, 2 were test production boreholes and 6 were production boreholes. Seven other boreholes (one monitoring, two exploration and four production) were drilled to different depths but were abandoned and cement grouted before completion. Replacement boreholes were drilled at the same location except at one production borehole site. In addition to the 24 drilled boreholes, one existing borehole BH9295 was also cleaned for retesting.

The main aquifer encountered during drilling in the Ncojane Block was in the two sandstone units of the Ecca Group (Otshe Formation) which are separated from each other by variably thick argillaceous units comprising of mudstone, shale siltstone and carbonaceous mudstone. Water strike depths ranged from 154 m to 289 m with an average water strike depth of 209 m. Airlift yields in the two sandstone aquifers ranged from 22 to 127 m^3/hr with TDS values of mostly between 168 mg/L to 1300 mg/L. Rest water levels for the Otshe sandstone aquifers in the Ncojane Block range from 85.40 m to 133.4 m below ground level.

In addition to the predominantly fresh water aquifers found in the Otshe Formation sandstone units, saline aquifers were encountered in sandstone units of the underlying Kobe Formation particularly in the southern part of the Ncojane Block (**Figure 8.1**). At one site (BH10218 and BH10217) two monitoring boreholes, one screened in the Otshe Sandstone units and one in the saline Kobe sandstone indicates that the head of the shallow aquifer at 1146.44 m above mean sea level (BH10218), is higher than that of the underlying saline aquifer 1137.59 m amsl (BH10217). A detailed analysis of the Ecca aquifer including aquifer geometry, spatial variation of salinity (TDS) and groundwater flow directions is given in **Chapter 11** of this report.

Table 8.1 Summary of Project Boreholes

Table 8.2 Summary of Production Boreholes

Several boreholes intercepted aquifers in the basal sandstone units of the overlying Mosolotsane and Kule (Kwetla) Formations in the Ncojane Block (**Table 8.3**). These relatively shallow aquifers often contain groundwater with highly variable quality with TDS values ranging from 1807 mg/L to 12,350 mg/L and have the potential to contaminate the underlying aquifers of the Otshe sandstone if they are not properly sealed off. These water strikes were grouted before continuing drilling into the underlying Otshe Sandstone aquifers.

Table 8.3 Water Strikes, EC, TDS for Mosolotsane and Kule (Kwetla) Formation

BH No	Water Strike (m)	Aquifer	EC (μS/cm)	TDS (mg/L)
BH10212	144	Kule Basal Sandstone	5940	3861
BH10212	155	Kule Basal Sandstone	6950	4518
BH10222	150	Kule Basal Sandstone	2900	1885
BH10314	105	Mosolotsane	14230	9250
BH10314	116	Mosolotsane	18700	12155
BH10314	155	Kule Basal Sandstone	19000	12350
BH10315	156	Kule Mudstone	2780	1807
BH10315	177	Kule Basal Sandstone	3310	2152
BH10315	210	Kule Basal Sandstone	4330	2815

8.2.2.2 MATLHO-A-PHUDUHUDU BLOCK

A lot of exploration work was carried out in the Matlho-a-Phuduhudu Block during the Hunhukwe / Lokalane project and consequently only five monitoring boreholes were drilled in this block during the Matsheng Project. These boreholes were drilled at the location of existing exploration boreholes to provide observation boreholes for estimation of the storativity values of the Ntane Sandstone during pump testing as well as providing water level head measurements (BH10225 and BH10317) for comparison with the underling Ecca Group aquifer (Otshe Formation). As well as drilling new monitoring (observation) boreholes, five existing boreholes were cleaned during the project. One of these five boreholes was converted into a nested piezometer cluster (BH9297 and BH10320) monitoring different levels of the Ecca aquifer while the rest of the boreholes were cleaned to allow pump testing with observation boreholes for calculation of the Ntane aquifer storativity values. A summary of the project boreholes in the Matlho-a-Phuduhudu Block is given in **Table 8.1**.

One, existing borehole BH9293 terminated in the Kule Formation was deepened from 167 to 284m because the existing TEM interpretation (WCS 2001) indicated that drilling was stopped before intercepting the Ecca aquifer. However a dolerite sill was intercepted from 239 m during drilling instead of the interpreted Ecca formation and the borehole was terminated 284 m in the dolerite.

As expected, the main aquifers in the Matlho-a-Phuduhudu Block are developed in the Ntane and Otshe Formations. Water strikes in the Ntane sandstone range from 143 to 244 m with TDS values ranging from 341 mg/L to 1829 mg/L. The rest water levels in the Ntane aquifer vary 135.305 to 148.048 m below ground level. A comparative analysis of the groundwater head of the two main aquifers i.e. the Ntane and Ecca (Otshe) at BH10225 and BH10317 indicates the head of the Ntane aquifer is higher than that of the Ecca. A detailed analysis of the Ntane sandstone aquifer incorporating existing borehole data is given in **Chapter 11**. This analysis includes among others aquifer geometry, spatial variation of TDS and groundwater flow.

8.3 DISCUSSION OF DRILLING RESULTS

As indicated earlier boreholes were sited and drilled in different geological/hydrogeological environments for a full evaluation of the potential of the aquifers in the project area particularly the Ecca in terms of borehole yields and groundwater quality. These environments included the following;

- Structurally undisturbed areas
- Structurally disturbed (fractured) areas
- Areas with dolerite sill intrusions

The drilling results are discussed below for each these environments.

8.3.1 STRUCTURALLY UNDISTURBED AREAS

Boreholes which were sited in structurally undisturbed areas include, BH10211, BH10215, BH10222, BH10228, BH10229, BH10314 and BH10316. Results from these boreholes (**Table 8.4, Figure 8.1**) indicate that the yield of the Ecca aquifer in these areas tends to be high with the majority of these tested, at rates of between 40 to 95 m^3/hr with the exception of BH10229 and BH10222 which were tested at rates of 12 and 20 m^3/hr respectively, indicating that the Ecca aquifer occurs as a primary aquifer. TDS values for these boreholes range from 179 mg/L to 1210 mg/L. All boreholes with higher TDS values (BH10222, BH10229 and BH10314) had water strikes in the basal sandstones of the Kule (Kwetla) Formation in addition to water strikes in the main Otshe Sandstone aquifers. Elevated fluoride and sodium concentrations in the range 2.3 to 2.5 mg/L and 317 to 471 mg/L respectively (**Table 8.4**) were also obtained in these boreholes. Some boreholes, which were expected to intercept a thick sequence of coarse grained sandstone actually intercepted dolerite intrusions between the Ecca Group and the overlying Kule Formation (e.g. BH10228 and BH10211) but these dolerites did not seem to have any effect on the groundwater quality and yield (**Table 8.4**). Boreholes with higher fluoride, TDS and sodium values are mostly located southeast of aeromagnetic data interpreted fault F6 (**Figure 8.1**).

8.3.2 STRUCTURALLY DISTURBED AREAS

Two exploration boreholes, BH10214 and BH10216 were drilled close to or within fault zones to evaluate the role of faulting on groundwater quality, lithology and borehole yields. These boreholes encountered multiple dolerite sill intrusions at different levels and contain groundwater with relatively high TDS with values of 1760 and 2016 mg/L. Fluoride and sodium contents for these two boreholes were also high with values of 3.5 to 2.3 mg/L and 746 to 648 mg/L respectively for these constituents. The Ecca lithology encountered in these boreholes was predominantly silty to fine grained sandstones, with minor medium to coarse grained sandstones. The tested yields of these two boreholes were 10 and 45 m^3/hr.

8.3.3 AREAS WITH DOLERITE INTRUSIONS

Some exploration boreholes were purposely sited in areas with interpreted dolerite sill intrusions for purposes of evaluating the role of these sills on groundwater quality while others intercepted dolerite sills in areas which were expected to be dolerite free. The reason for not always being able to distinguish dolerite free areas from areas with thick sandstones was that weathered dolerite has the same resistivity range as coarse sandstones and these flat lying sills were not picked by ground magnetic profiling. Boreholes which were sited purposely in areas with dolerite intrusions were BH10214, BH10219, BH10212 and BH10216. Boreholes which were not expected to intercept dolerite sills were BH10228 and BH10211. Drilling results from this type of environment indicates that boreholes with multiple dolerite intrusions and saturated basal sandstone units of the Kule Formation tend to have groundwater with elevated fluoride and sodium levels (**Table 8.4**). These boreholes include BH10212, BH10214 and BH10216. If the dolerite intrusion is below the Kule basal sandstones it appears that the dolerite isolates the basal sandstone units from the underlying Otshe aquifer. If dolerite intrusions are in areas where the Kule basal sandstone unit is unsaturated, the water quality is not affected probably indicating that the source of elevated constituents is basal Kule sandstone (BH10228 and BH10211).

Table 8.4 Yields, TDS, F and Na Concentrations for Boreholes in Different Environments

BH No	Tested Yield (m^3/hr)	Na (mg/L)	F (mg/L)	TDS (mg/L)	Environment	Remarks
BH 10212	12	315	1.8	845	Disturbed, Dolerite Expected	Multiple Dolerite intercepted, Kule Sandstone Saturated
BH 10214	10	746	3.5	2016	Disturbed, Dolerite Expected	Multiple Dolerite intercepted, Kule Sandstone Saturated
BH 10216	45	648	2.3	1760	Disturbed, Dolerite Expected	Multiple Dolerites intercepted, Kule Sandstone Saturated
BH 10219	95	326	1.8	794	Disturbed, Dolerite Expected	Single Dolerite Intercepted
BH 10228	93	81	0.59	397	Undisturbed	Unexpected dolerite intercepted below unsaturated Kule Formation
BH 10316	95	30	0.4	179	Undisturbed	Kule Unsaturated
BH10211	70	126	0.69	474	Undisturbed	Thin Dolerite intercepted/ Kule Unsaturated
BH10215	32	149	0.7	538	Undisturbed	Kule Unsaturated
BH10221	30	250	1.1	698	Disturbed	Unexpected dolerite intercepted. Kule Formation Unsaturated
BH10222	12	317	2.3	890	Undisturbed	Saturated Kule Sandstone above main aquifer
BH10229	20	317	2.3	870	Undisturbed	Some water Strikes in interlayered mudstones in Ecca aquifer
BH10314	40	471	2.5	1210	Undisturbed	Saturated Kule Sandstone above main aquifer

From the drilling results, it was concluded that areas with the best potential for wellfield development in terms of water quality and yield are areas underlain by undisturbed thick Ecca (Otshe Formation) aquifers with thin and unsaturated units of the overlying Mosolotsane and Kule formation or areas with dolerite intrusions between the Ecca and the overlying Kule basal sandstones. These areas are located to the northwest of fault F6 (Figure 8.1) and the Ncojane wellfield is located in such an area.

A detailed description of the structural control on aquifer geometry and spatial variation of groundwater quality is provided in **Chapter 11** of this report.

8.3.4 VARIATION OF WATER QUALITY WITH DEPTH

Drilling results have shown that in some boreholes the conductivity decreases with depth. This occurs mostly in boreholes with water strikes in the basal sandstones of Mosolotsane and Kule (Kwetla) Formations and a few boreholes with water strikes in the upper mudstone units of Otshe Formation. This trend clearly shows that these brackish or saline aquifers have to be properly sealed off to avoid contaminating the lower Ecca aquifers. Drilling water quality results of some boreholes with this trend are given **Table 8.5.** This trend was also noted during the Hunhukwe / Lokalane Project (WCS 2001).

Table 8.5 Variation of Drilling Water Quality with Depth

BH No	Water Strike (m)	Water Strike in	EC (μS/cm)	TDS (mg/L)
BH10229	183	(Otshe Mudstone 1)	5510	3,416
BH10229	198	Inter layered Mudstone in Sandstone 1	5970	3,701
BH10229	253	Otshe Mudstone 2	2080	1,290
BH10229	266	Otshe Mudstone 2	1775	1,101
BH10229	282	Otshe Sandstone 2	1503	932
BH10314	105	Mosolotsane Basal Sandstone	14230	8,823
BH10314	116	Mosolotsane Basal Sandstone	18700	11,594
BH10314	155	Kule Basal Sandstone	19000	11,780
BH10314	232	Otshe Mudstone 2	5040	3,125
BH10314	258	Otshe Mudstone 2	3700	2,294
BH10314	276	Otshe Sandstone 1	2800	1,736
BH10315	156	Kule Mudstone	2780	1,724
BH10315	177	Kule Basal Sandstone	3310	2,052
BH10315	210	Kule Basal Sandstone	4330	2,685
BH10315	250	Otshe Sandstone 1	890	552
BH9243	179	Mosolotsane Basal Sandstone	1486	921
BH9243	236	Otshe Sandstone 2	570	353
BH9243	248	Otshe Sandstone 2	420	260

Figure 8.1 Borehole Location Map

9 PUMPING TESTS OF PROJECT BOREHOLES

9.1 OVERVIEW

Pump testing of the exploration boreholes was carried out by Boreholes and Wells (Pty) Ltd Contractor with operations being carried between 12th October 2006 and 11th March 2007. A total of 17 boreholes were tested out of which 14 boreholes are located in Ncojane Block and 3 are located in the Matlho-a-Phuduhudu Block. Four of the 14 tested boreholes in the Ncojane Block had observation boreholes while all the three tested boreholes in the Matlho-a-Phuduhudu Block had observation boreholes. All tests in the Matlho-a-Phuduhudu Block were on boreholes which were previously tested during the Hunhukwe/Lokalane project and a repeat test was also carried out in one borehole in the Ncojane Block. These repeat tests were to allow for estimation of aquifer storativity values utilising data from observation boreholes which were not available during the Hunhukwe/Lokalane Project.

For the production phase, Geo-Civil Pty, Ltd was the appointed Contractor. Production phase pump testing activities commenced on 18th July 2007 and completed on 18th October 2007 with a total of 6 boreholes tested out which two had observation boreholes.

The location of the tested boreholes is given in **Figure 9.1**

9.2 OBJECTIVES OF PUMPING TESTS

Pumping tests were carried out to determine the yield potential, aquifer parameters, and performance characteristics of the completed boreholes. Groundwater samples were also collected for chemical and some isotope analysis during these tests for evaluation of compliance to drinking water quality standards (BOS32:2000), evaluation of groundwater types and recharge evaluation. The tests consisted of an initial calibration test, a step drawdown test (SDT), a constant rate test (CRT) and a recovery test.

9.3 METHODOLOGY

Water level data were collected manually from a fixed measuring point at the wellhead using an electric dipper. Measurements in the pumping borehole were taken through a PVC dipper access tube installed in the borehole and in monitoring (observation) boreholes measurements were also taken manually using an electric dipper. The discharge rate was measured using three methods: recording of the time required to fill a container of a known volume, a manometer and an orifice plate, and a flow meter. Water level, discharge measurements and well head water chemistry analysis (temperature, electrical conductivity, pH and dissolved oxygen) were recorded on boreholes at specific times during the pumping tests. In observation boreholes only water level measurements were recorded.

Two boreholes tested in the Matlho-a-Phuduhudu Block had observation boreholes while for the Ncojane Block six boreholes had observation boreholes. The data from observation boreholes was used to calculate the aquifer storativity values in addition to transmissivity values obtained from the rest of the boreholes.

9.3.1 TEST FORMAT

Calibration tests (15 minutes duration steps) were carried out to set up the pump testing equipment and to plan the pumping rates for the step drawdown tests. Step drawdown tests were conducted to evaluate the performance of the borehole in terms of the components of drawdown due to aquifer losses and well losses, and to select an optimal pumping rate for the constant rate test. Step drawdown tests normally consisted of 4 to 6 pumping steps with the discharge rates increased at the beginning of each step. The duration of each complete step of the step drawdown test was 100 minutes.

The duration of the CRT was usually 72 hours but in low yielding boreholes the durations were either 24 or 48 hours. In two boreholes, the duration of the tests were 51 and 60 hours due to mechanical breakdown of the pump testing unit. Four long duration tests were carried out with durations of 115, 120, 168 and 212 hours. The CRTs were immediately followed by recovery tests of 24 hours duration.

9.4 PUMPING TEST RESULTS

9.4.1 STEP DRAWDOWN TEST DATA ANALYSIS

Drawdown in a pumped borehole comprises of aquifer losses and well losses. The well losses are divided into linear and non-linear head losses. Step tests were carried out to determine the coefficients of aquifer and well losses, transmissivity as well as to decide the optimal discharge rates for the constant rate test.

Step drawdown pumping test data were analysed by preparing semi-logarithmic plots of time versus drawdown and determining the incremental drawdown for each pumping step using the Hantush-Bierschenk Method in the computer programme StepMaster™. The Hantush-Bierschenk method was used to determine aquifer loss and well loss coefficients (B and C) and to predict the drawdown in a well at a specified pumping rate after a specified period of time (Δt). This method is suitable for confined, leaky, and unconfined aquifers pumped step-wise at increasing rates. The coefficients B (aquifer loss) and C (non-linear well loss) were derived graphically from an arithmetic plot of specific drawdown (s_w/Q) versus Q.

An initial estimate of the transmissivity was also made from the step drawdown test data using the Eden-Hazel (1973) analytical method using the computer programme StepMaster™. In order to provide additional insights into the drawdown characteristics of the tested boreholes, specific capacities values at the end of each pumping step were also determined for each borehole.

9.4.2 STEP DRAWDOWN TEST RESULTS

The results of step drawdown test analysis for each borehole are summarised in **Tables 9.1** and **9.2** for the Ntane and Ecca Aquifers (Otshe) respectively. The results indicate that the specific capacities are generally inversely proportional to the pumping rate. However in some boreholes, an increasing trend in specific capacity values was observed, probably indicating that some degree of borehole development occurred during the step drawdown test. However, borehole leaky aquifers will have the same trend.

Step drawdown tests were carried out in three boreholes tapping the Ntane sandstone aquifer at discharge rates of between 10 to 62 m^3/hr (**Table 9.1**). Aquifer loss (B) values ranging between $5.82x10^{-3}$ to $8.62x10^{-3}$ (d/m^2) were obtained for the Ntane Aquifer while the well loss coefficient (C) values ranged between $-8.97x10^{-7}$ to $9.92x10^{-6}$ (d^2/m^5). The transmissivity values calculated from the step drawdown data for the Ntane Sandstone aquifer ranges between 43 and 64 m^2/d.

Step drawdown tests were carried out in 20 boreholes completed in the Otshe sandstone aquifer (**Table 9.2**) at discharge rates of between 4 and 102 m^3/hr. For the Ecca aquifer, the B value ranges from $4.10x10^{-7}$ to $9.09x10^{-2}$ (d/m^2) and the C values range from $-2.82x10^{-7}$ to $1.1x10^{-2}$ (d^2/m^5). Transmissivity values estimated from step drawdown test data for the Ecca (Otshe) aquifer range between 4 to 427 m^2/d.

The negative C value obtained in some boreholes may be attributed to some degree of borehole development, though leakage from overlying aquifers is also known to have the same effect. Example plots of step test data interpretations are presented in **Figure 9.2** to **9.4** while the rest of the interpreted data is given in ***Volume 2, Hydrogeology Report***.

Table 9.1 Step Test Results for the Ntane Aquifer

BH	Location	B (d/m^2)	C (d^2/m^5)	T (m^2/d)	Q (m^3/hr)	ΔS (m)	s_w (m)	Q/s_w ($m^3/hr/m$)
9237	Matlho-a-Phuduhudu	8.62E-03	9.92E-06	64.8	20.0	6.30	6.30	3.17
					30.0	5.20	11.50	2.61
					40.0	6.26	17.76	2.25
					50.0	6.52	24.28	2.06
9240	Matlho-a-Phuduhudu	8.35E-03	1.50E-06	43.4	20.0	4.12	4.12	4.85
					30.1	2.96	7.08	4.25
					41.4	3.10	10.18	4.07
					50.1	2.05	12.23	4.10
					62.21	3.06	15.29	4.07
9239	Matlho-a-Phuduhudu	5.82E-03	-8.97E-07	56.4	10.2	1.36	1.36	7.50
					20.3	1.47	2.83	7.17
					30.2	0.54	3.37	8.97
					40.3	1.36	4.73	8.53
					50.2	1.24	5.97	8.41

Table 9.2 Step test Results for the Ecca Aquifer

BH	Location	B (d/m^2)	C (d^2/m^5)	T (m^2/d)	Q (m^3/hr)	ΔS (m)	s_w (m)	Q/s_w ($m^3/hr/m$)
9295	Metsimantsho	3.82E-03	-2.82E-07	427.0	43.0	3.65	3.65	11.78
					65.0	1.66	5.31	12.24
					80.0	0.87	6.18	12.95
					102.0	1.56	7.74	13.18
10221	Ncojane Ranches	8.67E-02	6.63E-06	35.1	10.0	19.50	19.50	0.51
					15.0	15.00	34.50	0.43
					20.0	10.90	45.40	0.44
					30.0	17.70	63.10	0.48
		5.82E-02	6.57E-06	28.6	10.0	13.80	13.80	0.72
					15.0	8.55	22.35	0.67
					20.0	8.67	31.02	0.64
					25.0	6.01	37.03	0.68
					30.0	7.25	44.28	0.68
10211	Ncojane	1.99E-02	-1.07E-06	48.1	31.7	14.80	14.80	2.14
					42.9	3.51	18.31	2.34
					50.7	4.52	22.83	2.22
					60.4	4.22	27.05	2.23
					70.1	3.24	30.29	2.31
					80.1	3.87	34.16	2.34
10222	Ncojane	8.73E-02	1.10E-04	3.8	4.0	11.30	11.30	0.35
					7.0	2.96	14.26	0.49
					10.0	9.24	23.50	0.43
					13.0	17.90	41.40	0.31
					16.0	9.94	51.34	0.31
10228	Ncojane	1.37E-02	-7.79E-07	111.0	30.2	8.76	8.76	3.45
					45.5	7.09	15.85	2.87
					60.2	1.13	16.98	3.55
					75.3	6.11	23.09	3.26
					92.5	2.49	25.58	3.62
10229	Metsimantsho	9.09E-02	-3.19E-05	19.7	10.1	19.70	19.70	0.51
					14.1	8.74	28.44	0.50
					18.2	3.70	32.14	0.57
					22.2	7.60	39.74	0.56

Table 9.2 Continues

BH	Location	B (d/m^2)	C (d^2/m^5)	T (m^2/d)	Q (m^3/hr)	ΔS (m)	s_w (m)	Q/s_w ($m^3/hr/m$)
10314	Metsimantsho	4.61E-02	-1.93E-06	25	10	11.5	11.5	0.87
					20	8.69	20.19	0.99
					30	12.7	32.89	0.91
					40	8.18	41.07	0.97
					50	13.2	54.27	0.92
10215	Metsimantle	4.08E-02	4.78E-06	31	15.2	15.7	15.7	0.97
					21.3	6.48	22.18	0.96
					25.9	4.75	26.93	0.96
					30.2	3.91	30.84	0.98
					35.2	8.24	39.08	0.9
10315	Metsimantsho	9.10E-03	-6.20E-07	64	32.5	6.73	6.73	4.83
					45.3	2.38	9.11	4.97
					60.3	2.87	11.98	5.03
					70	1.41	13.39	5.23
10212	Metsimantsho	4.53E-02	6.47E-05	4	8	10.8	10.8	0.74
					12.1	7.83	18.63	0.65
					16.1	8.92	27.55	0.58
					20.1	11.7	39.25	0.51
					24.1	5.04	44.29	0.54
10216	Ukwi	2.10E-02	4.36E-06	15	20	11.5	11.5	1.74
					30	5.27	16.77	1.79
					40	7.4	24.17	1.65
					50	5.59	29.76	1.68
					61	12	41.76	1.46
10316	Metsimantle	1.49E-03	7.46E-08	300	25	0.943	0.943	26.51
					55	1.11	2.053	26.79
					75	0.732	2.785	26.93
					95	1.14	3.925	24.2
10219	Ukwi	1.98E-03	5.98E-08	48	31.3	14.8	14.8	2.11
					50.6	9.75	24.55	2.06
					72	8.76	33.31	2.16
					93	11.7	45.01	2.07
10402	Ncojane	1.30E-02	1.07E-06	75	25	7.68	7.68	3.26
					40	3.79	11.47	3.49
					55	2.66	14.13	3.89
					70	3.12	17.25	4.06
					77	5.39	22.64	3.4

Table 9.2 Continues

BH	Location	B (d/m^2)	C (d^2/m^5)	T (m^2/d)	Q (m^3/hr)	ΔS (m)	s_w (m)	Q/s_w (m^3/hr/m)
10404	Ncojane	1.54E-06	1.16E-02	82	30	9.23	9.23	3.25
					40	3.05	12.28	3.25
					50	4.45	16.73	2.98
					60	2.76	19.49	3.07
10405	Ncojane	4.10E-07	4.50E-03	194	30	3.3	3.3	9.09
					45	2.05	5.35	8.41
					60	2.56	7.91	7.58
					77	1.26	10.71	7.19
10407	Ncojane	2.97E-03	2.80E-06	73	30	3.01	3.01	9.97
					40	2.67	5.68	7.04
					50	3.56	9.24	5.41
					65	1.23	10.47	6.21
					77	4.32	14.79	5.21
10410	Ncojane	1.19E-02	4.40E-07	68	25	8.36	8.36	2.99
					40	2.15	10.51	3.81
					55	3.69	14.2	3.87
					70	5.39	19.59	3.57
					77	7.9	27.49	2.8
10411	Ncojane	1.06E-02	8.84E-07	61	20	6.86	6.86	2.92
					35	3	9.86	3.55
					50	3.66	13.52	3.7
					65	4.77	18.29	3.55
					78	5.36	23.65	3.3

9.4.3 CONSTANT RATE AND RECOVERY TEST DATA ANALYSIS

The CRT data were interpreted by the Theis, Cooper-Jacob, Hantush leaky (with storage in the confining layer) and Neuman unconfined analytical solutions using the computer programme "Aqtesolv". In pumping boreholes, these methods allowed for the calculation of transmissivity and in observation boreholes both storativity and transmissivity values were determined. The recovery data for all the boreholes were interpreted by the Theis recovery method and transmissivity was the only parameter calculated by this method.

In an ideal confined aquifer, the drawdown should form a straight line on a semi-log plot, however the early time is always distorted due to casing storage and skin effects and the early data was not interpreted. The results of the constant rate and recovery tests for all the boreholes in the project area are summarised in **Tables 9.3** and **9.4** for the Ntane and Ecca (Otshe) aquifers respectively.

Aquifer responses obtained from interpretation of pumping test data in conjunction with borehole lithological details ranged from unconfined with delayed yield, confined, confined leaky and confined with barrier boundary. Example plots of these typical aquifer responses are given in **Figures 9.5** to **9.9** while the rest of the interpreted data can be found in ***Volume 2, Hydrogeology Report***. For the majority of boreholes, completed in the Ecca aquifer the aquifer response was confined while the Ntane aquifer displayed mostly unconfined with delayed yield and leaky confined behaviour. In boreholes which displayed barrier boundaries, the latter slope of the drawdown curve was not interpreted, however for production boreholes the transmissivity obtained from the latter stages of the drawdown curve was utilised in order to obtain the most conservative estimate of the long term abstraction rate.

9.4.4 NTANE SANDSTONE AQUIFER

Three observation boreholes were completed next to existing boreholes drilled during the Hunhukwe/Lokalane Project. Although step tests were carried out in all the three existing boreholes, constant rate tests were only completed in two of these. The third borehole (BH9239) could not be tested due to excessive sand pumping despite attempts to develop the borehole using a drilling rig. The discharge rates for the two boreholes, BH9240 and BH9237 were 56 and 48 m^3/hr respectively with durations of 48 and 120 hours (**Table 9.3**). Transmissivity values obtained from interpretation of project test pumping data range from 37 to 88 m^2/d while the storativity values ranged from $6.7x10^{-4}$ to $2.2x10^{-3}$.

For the two re-tested boreholes tapping the Ntane aquifer, one has a confined aquifer response and the other is unconfined with delayed yield. The majority of the boreholes tapping the Ntane were interpreted to be unconfined during the Hunhukwe / Lokalane Project, but re-interpretation of the data during the inception phase showed that most of the aquifer responses were semi-confined. It has to be pointed out that although the pumping durations during the Hunhukwe/Lokalane Project were very long, the drawdowns were small because of low pumping rates, which might result in unreliable results.

Table 9.3 Summary of Constant Rate and Recover Tests, Ntane aquifer

BH No.	Total Drawdown (m)	Tested Dates	CRT Duration (hours)	Q (m^3/hr)	Pumping borehole		Obs. BH No	Observation boreholes		Aquifer type/ Response	
					T (m^2/d)			Pumping phase		Recovery phase	
					Pumping	Recovery		T (m^2/d)	S	T (m^2/d)	
9237	31.35	16/10/05 - 28/10/05	120	48	37	98	10223	62	6.7E-4	88	Semi Confined
9240	17.79	1/11/05 - 6/11/05	48	56	44	51	10225	51	2.2E-3	55	Unconfined with delayed yield

9.4.5 ECCA AQUIFER

Constant rate tests were completed in a total of 20 boreholes tapping the Ecca (Otshe) aquifer during the Matsheng Project including a previously tested borehole (BH9295). The discharge rates for these tests ranged from 10 to 95 m^3/hr and the test durations were mostly 72 hours. However, for one relatively low yielding borehole the test duration was 24 hrs and three boreholes had durations of 115, 212 and 168 hrs (**Table 9.4**). The pump intakes were between 150 and 180 m.

The transmissivity values obtained for the Ecca (Otshe) aquifer from project boreholes ranged from 3 to 474 m^2/d (different interpretation methods) while the storativity values ranged from $1.00x10^{-4}$ to $4.05x10^{-6}$. The aquifer type interpreted from test pumping data is mostly confined with some boreholes showing confined leaky and confined with barrier responses.

Table 9.4 Summary of Constant Rate and Recover Tests, Ecca aquifer

BH No.	Total Drawdown (m)	CRT Duration (hours)	Q (m^3/hr)	Pumping borehole		Obs. BH No	Observation boreholes			Aquifer Type
				Pumping Phase	Recovery Phase		Pumping T (m^2/d)	S	Rec T (m^2/d)	
9295	8.62	212	91	408	440	10220	420	7.70E-04	398	Confined
10211	35.11	72	70	97	82	10210	66	3.25E-04	82	Confined-Leaky
10222	57.28	72	12	7	7	NA				Confined
10228	27.78	115	93	418	474	10227	537	4.05E-06	431	Confined
10229	44.23	72	20	21	15	NA				Confined
10314	51.52	72	40	35	33	NA				Confined
10215	42.01	72	32	40	40	NA				Confined
10221	58.49	72	30	23	23	NA				Confined
10315	12.1	72	55	127	151	NA				Confined
10212	57.51	48	12	5	3	NA				Confined with barrier
10216	41.3	75	45	30	27	NA				Confined
10316	5.47	72	95	404	372	NA				Confined
10219	52.81	51	95	51	44	10218	51	6.73E-04	40	Confined Leaky with storage
10214	57.62	24	10	3	3	NA				Confined
10402	20.64	72	70	150	111	10227	266	1.31E-04	259	Confined leaky with barrier boundary
						10228	251	1.31E-04	243	
10404	26.40	168	65	95	95	10210	75	1.00E-04	82	Confined leaky with storage
10405	12.55	72	75	162	172	NA				Confined leaky with barrier boundary
10407	21.55	60	65	147.5	143	NA				Confined leaky
10410	25.75	72	70	87	85	NA				Confined leaky with barrier boundary
10411	22.36	72	70	163	189	NA				Confined leaky with barrier boundary

A comparative analysis of all testing pumping data for boreholes completed in Ntane and Ecca (Otshe) aquifers indicates that the average transmissivity value for the Ntane aquifer is 43 m^2/d while the average value for the Ecca aquifer is 142 m^2/d. The average tested yield for the Ecca aquifer is also higher than of the Ntane aquifer at 59 m^3/hr and 44 m^3/hr respectively (**Table 9.5**).

Table 9.5 Aquifer Properties of Representative Boreholes Completed in the Two Main Aquifers of the Project Area

Ntane Sandstone Aquifer

BH No	Tested Yield (m^3/hr)	CRT Duration (days)	S	Average T (m^2/d)
9236	28	3		25
9237*	48	5	6.70E-04	68
9239	25	3		62
9238	8	4		6
9240	30	4		59
9240*	56	2	2.23E-04	48
9241	16	7		4
9297	52	9		68
Average	**44**			**43**

Ecca (Otshe) Aquifer

BH No	Tested Yield (m^3/hr)	CRT Duration (days)	S	Average T (m^2/d)
8469	33	3		20
8470	35	3		41
8346	48	3		122
8363	53	3		128
8364	45	3		116
9184	30	5		95
9243	31	1		32
9294	45	2		62
9295	53	7		654
9295*	91	9	7.70E-04	424
9298	20	7		18
10211	70	3	3.25E-04	90
10215	30	3		40
10216	45	3		29
10219	95	2	6.73E-04	47
10221	30	3		23
10228	93	5	4.05E-06	446
10229	20	3		18
10314	40	3		34
10315	55	3		139
10316	95	3		388
10402	70	3	1.31E-04	213
10404	65	7	1.00E-04	87
10405	75	3		167
10407	65	3		145
10410	70	3		86
10411	70	3		176
Average	**59**			**142**

9295* Existing Borehole Re-tested during Matsheng project

9.5 RECOMMENDED ABSTRACTION RATES FOR THE PRODUCTION BOREHOLES

The recommended daily abstraction rates for the production boreholes were calculated based on the Cooper-Jacob approximation of the Theis Equation. This equation can be expressed as a follows;

$$Q = 4\pi\ Ts/[2.3Log(2.25Tt/r^2S)]$$

where:
Q = sustainable yield (m^3/day)
T= transmissivity (m^2/day)
s = available drawdown (m) {recommended pump intake-SWL}
t = pumping time (days)
r = radius of the borehole in (m)
S= storativity

It has to be noted that the yield calculated from the above equation is not very sensitive to the Log variables in the equation. However it is sensitive to transmissivity and available drawdown, therefore an accurate determination of these parameters is critical. The transmissivity was obtained from late time pumping testing data for each production borehole since most of these had negative boundaries and the storativity value was obtained from pumping boreholes with which had observation boreholes.

The recommended pump settings for all the production boreholes was set at 180 m which maximises the available drawdown, taken as the recommended pump intake minus the rest water level measured prior to pumping test.

A 20 year duration of continuous pumping was used in the calculation of the abstraction rates. By using long pumping durations it is believed (Kirchener and Van Tonder, 1995) that the influence of negative boundary conditions will be minimised. As it is not possible to predict what boundaries will be encountered beyond the duration of a pump test it is recommended that the pumping durations should be equal or longer than the anticipated period of no recharge.

The total daily abstraction from the 6 production boreholes of the Ncojane Wellfield is calculated as 9600 m^3/d which is more than the combined daily water demand of the Matsheng Villages and the Secondary Centres of 1655 m^3/d.

The daily abstraction rates obtained analytically were used in the numerical model to simulate wellfield abstraction. Numerical modelling results indicate that the wellfields should sustain the recommended yields, under a continuous pumping design for over 30 years.

It has to be noted that the daily abstraction rates are based on pumping test data which can not predict the pumping effects beyond the test duration and numerical modelling. It is therefore necessary that once the boreholes are brought into operation, regular water level and water quality monitoring is carried out to establish the maximum sustainable yield of each borehole. Long term sustainable abstraction rates can be ascertained through systematic monitoring and analysis of the data. It is also paramount to monitor groundwater quality for compliance to the Botswana drinking water standards, (BOS 32:2000) during operation of the wellfield The recommended daily abstraction rates for the production boreholes are presented in **Table 9.6**

Table 9.6 Recommended Abstraction Rates Ncojane Wellfield

BH Number	Easting	Northing	Screened intervals (m)	Recommended Pump Intake (m)	Pre-CRT SWL (m)	Available drawdown (m)	Recommended drawdown (m)	*T (m^2/d)	S	Calculated yield (m^3/hr)	Tested yield (m^3/hr)	Recommended yield (m^3/hr)	Daily Abstraction 24 hrs pumping (m^3/d)
BH10402	441130	7435358	189 to 248	180	106.4	74	74	45	1.31E-04	64	70	64	1 542
BH10404	445760	7438700	205 to 226 & 236 to 245	180	108.33	72	72	94	1.31E-04	127	65	65	1 560
BH10405	442666	7436299	190 to 195 & 200 to 250	180	106.25	74	74	55	1.31E-04	78	75	75	1 800
BH10407	440170	7432108	198 to 243	180	103.65	76	76	46	1.31E-04	68	65	65	1 560
BH10410	442253	7428629	213 to 258	180	101.52	78	78	43	1.31E-04	66	70	66	1 574
BH10411	438645	7431005	211 to 261	180	103.6	76	76	45	1.31E-04	67	70	67	1 601
											Total	**402**	**9 637**

*T Later time transmissivity to allow for negative boundary effects

Figure 9.1 Location of Tested Boreholes

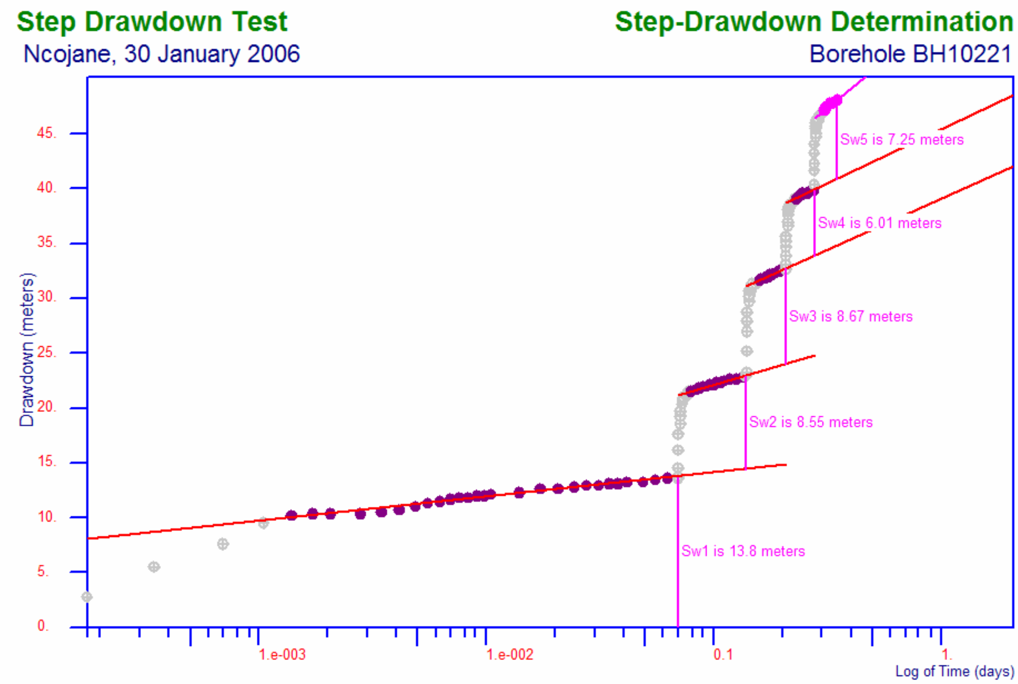

Figure 9.2 Calculating Incremental Drawdown per Step, BH10221 – Hantush-Bierschenk (semi-log)

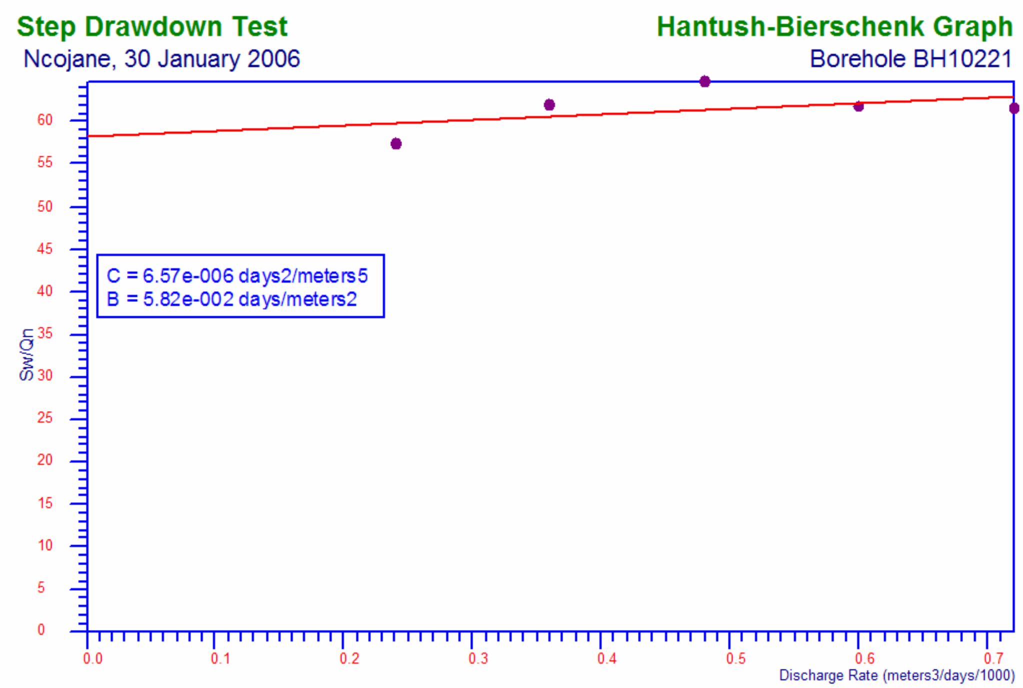

Figure 9.3 Calculation of C and B from Step Drawdown Test – Hantush-Bierschenk, BH10221

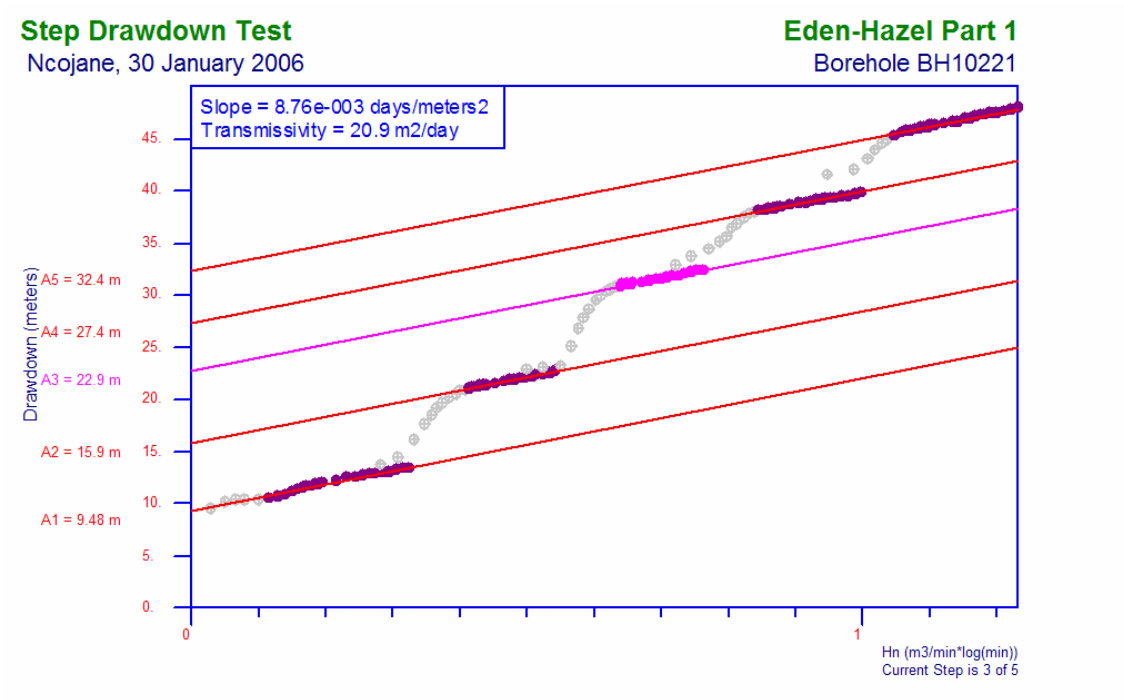

Figure 9.4 Transmissivity Estimation: Step Drawdown Test–Eden-Hazel (Part 1), BH10221

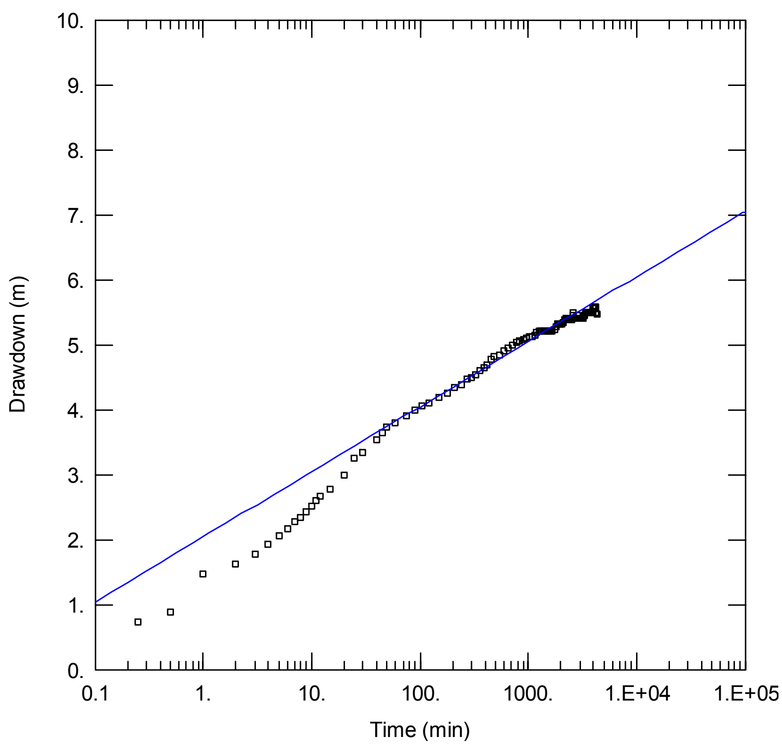

Figure 9.5 Typical Confined Aquifer Response, BH10316, Semi-Log Plot (Cooper-Jacob)

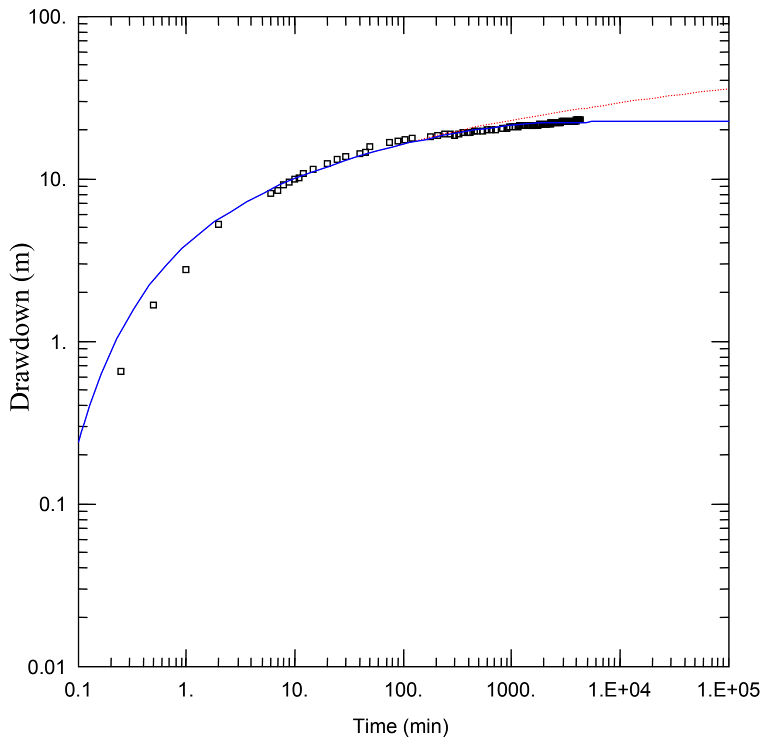

Figure 9.6 Typical Confined Leaky Response, BH10210, Hantush-Leaky

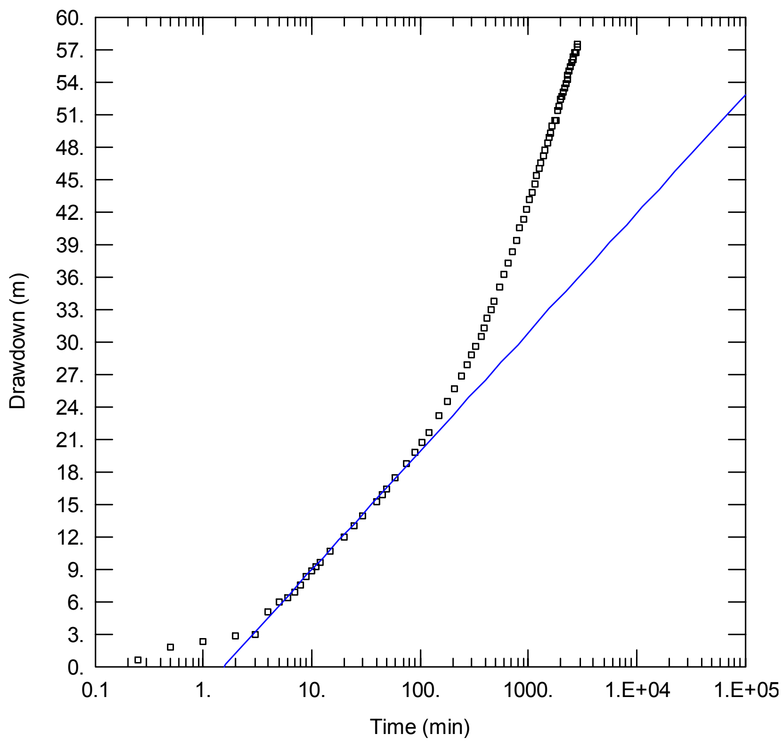

Figure 9.7 Typical Confined Aquifer Response with Barrier Boundary, BH10212, Cooper-Jacob

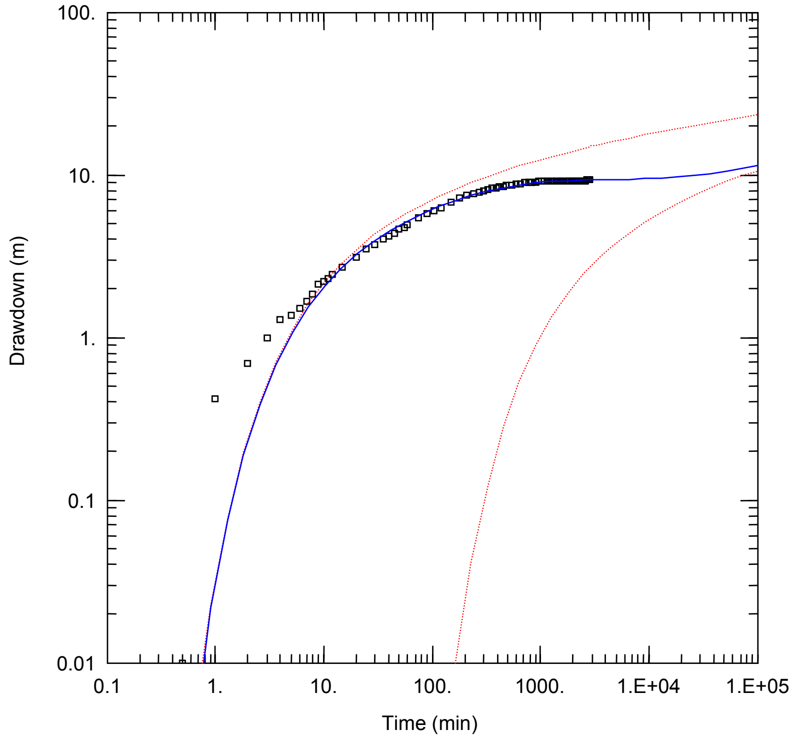

Figure 9.8 Typical Unconfined Aquifer Response with Delayed Yield, BH10225, Neuman

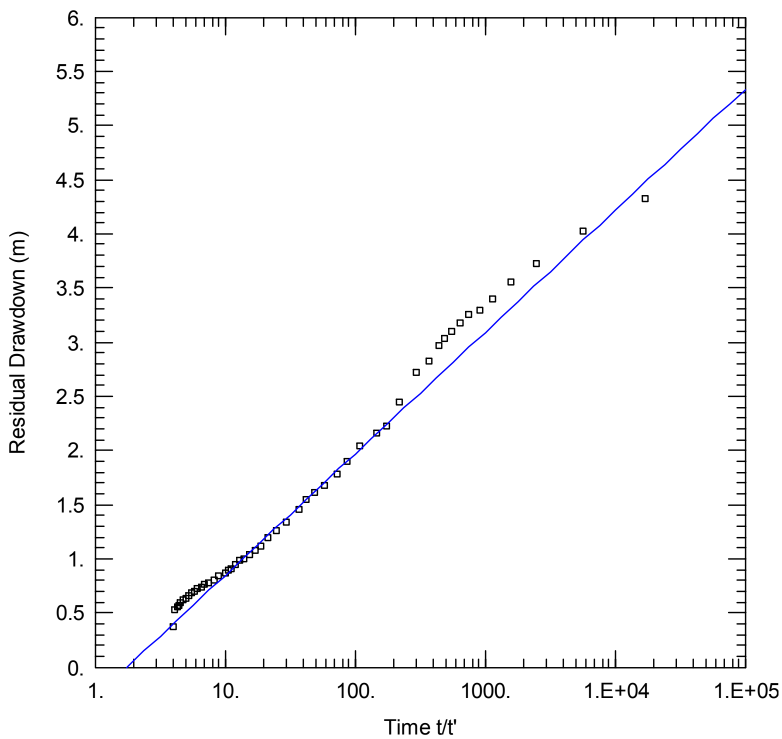

Figure 9.9 Typical Confined Recovery Test Response, BH10316, Theis, Recovery

10 GPS SURVEYS

During the project, high precision GPS surveys were carried out on monitoring, exploration, test production and production boreholes as well as on selected existing boreholes used for water level monitoring. A total of 35 boreholes were surveyed and results of the survey including ground elevation and casing elevations (measuring point) are given **Table 10.1** and locations of the surveyed boreholes are given in **Figure 10.1**.

10.1 OBJECTIVES

The GPS surveys were carried out to locate and level project boreholes and selected existing boreholes to an accuracy of +/- 1 m in x, y and +/- 10 cm in z. The surveys included the elevation of the top of casing (measuring point) and ground level. Apart from providing accurate borehole positional data, these surveys also provided measuring point elevation control for the construction of piezometric maps and numerical groundwater models.

10.2 EQUIPMENT AND SURVEY METHODOLOGY USED

A Lieca SR530 dual frequency Real Time GPS system was used for the survey. This GPS system is a radio enabled differential GPS system which allows for both real time (RTK) and post-processing (PPK) surveys. The current survey was carried out in post processing mode due to distances between the survey points. In Post Processing (PPK) mode, data is collected independently by the base and rover receivers, and position calculations are performed later in the office. Since there is no communication between the rover and base receivers during data collection, adequacy of data cannot be checked and significantly more data has to be collected (thus longer occupation time) in order to ensure the desired quality of the survey.

During this survey, two sets of data were collected for most of the observation points using two different modes: one by using PPK “topo point” mode and another by PPK “Observed control point” mode. The data with smallest ratios and RMS values was then selected for each survey point for final processing.

The survey data were projected onto the UTM co-ordinate system using the following parameters:

Co-ordinate system: UTM, Zone 34 K (18^o E to 24^o E)
Ellipsoid: Clarke 1880
Datum: Cape (South African)
Geoid model: EGM96

10.3 DATA AND ACCURACY

During the survey, the only existing benchmark in project area, (Matlho-a-Phuduhudu Block) of the Department of Surveying and Mapping (DSM) was used as a control point to tie in the surveyed points to the national grid of the DSM. Temporary control points were established where the baseline length (i.e. the distance between the rover and base station) was more than 10 km. The temporary control points were surveyed using the static method with an occupation time of one hour or more, depending on the baseline length. This survey was conducted by interchanging the position of the rover and base station with each other to check the configuration of the survey for any errors and whether the difference between the measured and actual (from DSM) position of the benchmark was within acceptable limits.

The quality of the GPS data survey was assessed through "internal" (i.e. derived only from GPS data) accuracy indices such as RMS (root mean square), vertical and horizontal precision, ratio or reference value. RMS provides a measure of confidence in GPS-derived positions (RMS is a radius of the error circle within which approximately 70% of position fixes are be found). The nominal accuracy of the GPS point position determination is as follows:

Horizontal
±10 mm + 2 ppm (parts per million) of baseline length, i.e. 1 mm per 1 km of distance between the base and the rover stations.

Vertical
±20 mm + 2 ppm (parts per million) of baseline length, i.e. 1 mm per 1 km of distance between the base and the rover.

For a baseline length of 10 km, the nominal accuracy of the GPS point position would be:
20 mm + (1x10) mm= 30 mm.

During the survey in the project area, the baseline length was always maintained below 10 km. Survey precision was randomly checked by occupying the same point during different phases of the survey.

Table 10.1 High Precision GPS Survey Results

BH No	Block	Easting	Northing	Ground Level Elevation (m amsl	Casing Elevation (m amsl)
BH10223	MAP	586358	7460350	1177.45	1178.4
BH10224	MAP	586902	7436518	1189.93	1190.91
BH10225	MAP	608914	7449809	1170.97	1171.81
BH10226	MAP	570319	7444055	1205.55	1206.44
BH9237	MAP	586367	7460348	1177.34	1177.77
BH9293	MAP	532473	7440719	1231.79	1232.27
BH10210	Ncojane	445827	7439007	1267.96	1268.92
BH10211	Ncojane	445818	7439004	1267.81	1268.8
BH10212	Ncojane	471357	7413720	1240.99	1242.08
BH10214	Ncojane	474333	7397979	1224.5	1225.41
BH10215	Ncojane	423550	7424116	1262.23	1262.68
BH10216	Ncojane	445843	7400347	1240.32	1241.04
BH10217	Ncojane	462926	7396725	1231.32	1232.14
BH10218	Ncojane	462941	7396727	1231.44	1232.09
BH10220	Ncojane	503298	7439428	1241.75	1242.74
BH10221	Ncojane	465933	7427586	1253.42	1254.04
BH10222	Ncojane	475982	7427299	1243.55	1244.47
BH10227	Ncojane	441140	7435377	1266.86	1267.63
BH10228	Ncojane	441134	7435388	1266.87	1267.56
BH10229	Ncojane	477486	7424731	1240.26	1240.99
BH10314	Ncojane	490310	7429080	1221.93	1222.66
BH10315	Ncojane	507682	7433985	1237.7	1238.59
BH6326	Ncojane	453660	7394892	1226.44	1226.9
BH8346	Ncojane	427452	7442568	1268.29	1268.5
BH8646	Ncojane	462708	7436128	1255.64	1255.85
BH9217	Ncojane	504418	7379165	1186.25	1186.72
BH9218	Ncojane	504513	7378617	1183.74	1184.27
BH9295	Ncojane	503305	7439434	1241.59	1242.15
BH10402	Ncojane	441127	7435359	1269.293	1270.601
BH10316	Ncojane	400854	7427984	1260.519	1261.413
BH10404	Ncojane	445806	7438994	1268.815	1270.062
BH10405	Ncojane	442715	7436590	1267.892	1269.014
BH10407	Ncojane	440212	7432266	1263.095	1264.401
BH10410	Ncojane	442582	7428919	1259.065	1259.826
BH10411	Ncojane	438640	7431015	1264.025	1265.041

Figure 10.1 Location of Surveyed Boreholes

11 HYDROGEOLOGICAL FRAMEWORK OF THE MAIN AQUIFERS

A conceptual hydrogeologic model for the groundwater basin including the two project area blocks was developed following the conclusion of the groundwater exploration programme. A conceptual model is essential for gaining an understanding of the critical components of the hydrogeological system(s) and their interplay. The aim of this chapter is to present the hydrogeological framework of the project area based on interpretation and integration all of data available in the project area including aeromagnetic data, ground geophysical data, ASTER satellite imagery, drilling, pump testing and groundwater quality. The hydrogeological framework is discussed aquifer wise with the focus on the two main aquifers found in the area which are namely the Ntane Sandstone and Otshe (Ecca) aquifer.

11.1 HYDROGEOLOGIC FRAMEWORK OF NTANE SANDSTONE AQUIFER

The upper most formation of the Lebung Group, the Ntane Sandstone Formation, was established as one of the main aquifers during the Hunhukwe/Lokalane Project (WCS, 2001). However, this sandstone only occurs in the eastern part the project area in the Matlho-a-Phuduhudu Block while to the west, including the Ncojane Block, the Ntane has been removed through pre-Kalahari erosion. Lithologically, the Ntane Sandstone consists primarily of red or pink, fine to medium grained friable sandstone. In the area where the Ntane Sandstone aquifer occurs (Matlho-a-Phuduhudu Block), no water strikes were recorded in the Kalahari Beds while only minor water strikes were recorded in the overlying Stormberg Lava where present. Water strike depths range from 140 to 230 meters, while water levels range from 113 to 156 meters. Groundwater TDS values for the Ntane Sandstone aquifer ranges between 305 mg/L to 1918 mg/L. A hydrogeological summary of boreholes completed in the Ntane aquifer is presented in **Table 11.1**. In general water level trends in this aquifer are flat to declining with very little evidence for active recharge. Currently there is very limited large scale groundwater abstraction from this aquifer. The potential for the Ntane aquifer to sustain large scale wellfield abstraction has been evaluated as limited and it is not considered as viable long term solution for sustainable water supply to the major demand centres of the project area. However it is a viable source for local (village scale) water supply.

Table 11.1 Hydrogeological Summary of Boreholes Completed in Ntane Sandstone

BH No.	Location	BH Depth (m)	WS**** (m bgl)	Screened Zones (m bgl)	RWL (m bgl)	Water Level Height above 1st WS (m)	Date	Airlift yield (m^3/h)	Tested Yield (m^3/h)	T (m^2/d)	TDS (mg/L)
9237	Near Bere	244	141	Open	129.628	11	26/01/06	8	48	57	616
9238	MAP	180	158	Open	136.39	22	11/10/05	3	8	7	546
9239*	MAP	276	152 & 220	149.37-167.46	135.99	16	26/01/06	12.5	25	56	1154
9240*	MAP	232	167	Open	134.78	32	27/01/06	7.5	30	35	316
9241	MAP	221	151	155-158	136.205	15	29/11/06	4.5	16	8	679
9297**	MAP	287	197	-	147.2	50	08/09/2004	30	50	46	305
7210	Lonetree	241	140 & 167	157-163	128	12	05/03/93	25	-	-	-
9044	MAP	210	171 & 182	184-196	134	37	06/09/99	5	-	-	700
9134	Bere	286	140,187 & 196	141.3-146.8	113	27	13/11/99	13	18	-	828
9236	MAP	295	167 & 201	174-177	156.191	11	12/02/06	7	28	25	326
10223***	Near Bere	215	143, 170, & 188	139.16 -210.16	129.61	13	27/10/05	9	NA	88	859
10224***	MAP	240	182, 206 & 230	159-173.24 & 178.92 & 232.88	135.185	47	26/01/06	14	NA		1918
10225***	MAP	209	168 & 182	161.88-201.64	133.97	34	27/01/06	9	NA	55	358
10226***	MAP	201	162 & 174	173.34-193.12	147.16	15	12/02/06	8	NA	NA	333

Notes:
** borehole retested* — *** Project Observation Borehole*
*** borehole was later deepened to 444 m* — *****Water Strike*

11.1.1 AQUIFER GEOMETRY

The occurrence of the Ntane Sandstone forms a roughly triangular pattern, thinning laterally to a point just east of the Ncojane Block in the west and widening eastward towards the Central Kalahari Karoo Basin. Its depth (top) increases from ~40 meters in the west to over 150 m in the east (**Figure 11.1**), whilst the depth to the bottom increases from ~50 m in the west part of the Matlho-a-Phuduhudu Block to over 220 m in the east (**Figure 11.2**). The thickness of the Ntane Sandstone in the project area is in order of 5 m (BH9292) to 113 m (BH7210). It attains its maximum thickness in the southeastern part of the Matlho-a-Phuduhudu Block (**Figure 11.3**) in what has been termed the Lebung –Sub-basin (WCS, 2001). It thins towards the western, northern, and southern margins of this basin. The thickness of the Ntane Sandstone in the central part of the basin (BH10226, BH9044, and BH10225) ranges between 50 to 95 meters.

Saturated thickness of the Ntane Sandstone aquifer is less than 30 m in the west (BH9236) and increases to over 80 m in the east (**Figure 11.4**), attaining a maximum thickness in the central parts of the basin around BH10224, BH9044, BH10226, BH10225 and BH10223 where the saturated thickness is about 70 to 90 m.

In the north, the limit of the Ntane Sandstone aquifer coincides with a thin cover of basalt whilst its southern boundary occurs to the south of Hunhukwe Village where only the lower argillaceous Mosolotsane Formation is present (**Figure 2.4**). In the western most areas, the sandstone is very thin is eventually truncated by pre-Kalahari unconformity just west of the Ncojane ranches. The eastern boundary of the aquifer extends beyond the project area.

The Ntane Sandstone aquifer is largely overlain by Kalahari Beds except in the northern parts of the Matlho-a-Phuduhudu Block where it is overlain by preserved Stormberg Basalts. It is underlain by primarily argillaceous units of the Mosolotsane and Kule Formations. Hydraulic head data for both the Ntane and Ecca Aquifer suggests that these two aquifers are hydraulically not connected (BH10226/BH9297 and BH10225/BH10317) with head being vertically downwards. There was no change in water levels in the Ecca at BH9297 during pump testing of BH10226 at the same location.

11.1.2 AQUIFER HYDRAULIC CHARACTERISTICS

Rest water levels in the Ntane Sandstone aquifer range between 113 to 156 meters and water strikes are between 140 and 230 meters. The Ntane Sandstone aquifer was previously interpreted to be fully unconfined (WCS, 2001), however, borehole logs suggest that it probably occurs as both an unconfined and semi-confined aquifer in the central portions of the basin, with many boreholes having rest water levels between 11 and 50 meters above the first water strikes, indicating some degree of confinement in some areas (**Table 11.1**). The likelihood of at least the central/ (BH9044) portions of the Ntane aquifer being semi-confined is also indicated in hydrogeological cross section (**Figure 11.5**).

The interpreted Ntane aquifer response in existing pumping test data and existing boreholes re-tested during the current project is semi-confined to unconfined with delayed yield. However, for purposes of groundwater resources evaluation and exploitation, the Ntane aquifer was treated as an unconfined aquifer. Based on the assumption that for unconfined aquifers, only the bottom third of the saturated thickness can be screened, the exploitable saturated thickness of the Ntane aquifer as presented in **Figure 11.6** indicates that only a small portion of the Ntane aquifer in the central part of the Ntane basin has potential for wellfield abstraction.

Transmissivity values for the Ntane sandstone aquifer obtained from interpretation of existing data as well as data obtained during the current project ranges from 7 to 88 m^2/d with an average value of 43 m^2/d. Storativity values obtained from two observation boreholes, BH10223 and BH10225 are 6.70×10^{-4} and 2.20×10^{-3} respectively. Tested borehole yields range from 8 to 56 m^3/hr with average an value of 42 m^3/hr.

11.1.3 GROUNDWATER FLOW

Piezometric head in the Ntane aquifer (**Figure 11.7**) indicate that the general direction of ground flow is predominantly from west to east, with a north-easterly component in the central portion of the Matlho-a-Phuduhudu Block. Local flow variations occur in the southern part of this block with the flow patterns tending to a south-easterly direction. The general direction of groundwater flow follows the alignment of the Group 5 (W-E), Group 1 (NW-SE) and Group 3 (NE-SW) lineament directions obtained from Aster Imagery interpretation (**see chapter 5**). In terms of seasonal groundwater level fluctuations, the water levels in this aquifer are very flat to declining indicating that there is probably very negligible recharge to this aquifer.

11.2 HYDROGEOLOGIC FRAMEWORK OF THE ECCA (OTSHE) AQUIFER

A large part of the project area is underlain by the Otshe Formation which constitutes the main aquifer unit within the Ecca Group. Aquifers are primarily developed in two sandstone units, (Sandstone 1 and Sandstone 2) separated from each other by varying thickness of mudstones, coals, carbonaceous mudstones, shales and siltstones. Within the main sandstone units are interbedded thin argillaceous units. A typical litho-stratigraphic sequence through Otshe Formation is given in **Figure 11.8**.

In the Ncojane Block and the northern parts of the Matlho-a-Phuduhudu Block, water strike depths range from 154 to 277 m in Otshe Sandstone 1 with an average and median value of 198 m. In the Ncojane Block, TDS values in Sandstone 1 mostly range between 174 mg/L and 986 mg/L. However, three boreholes BH10214, BH10222 and BH10229 encountered groundwater with higher TDS values in Sandstone 1 with values of between 2319 to 3701 mg/L. These water strikes were encountered in either the mudstone units interlayered within this sandstone or silty sandstones as well as close to the contact with the overlying mudstone (**Table 11.2**). In the central, eastern and southern parts of the Matlho-a-Phuduhudu Block water strikes are much deeper, ranging between 307 m and 328 m in Otshe Sandstone 1. As well as the deeper water strikes, the TDS values are also slightly elevated ranging between 1544 and 1761 mg/L (**Table 11.2**).

Water strikes in Otshe Sandstone 2 range between 203 and 289 m with average and median values of 237 and 229 m respectively. TDS values range between 260 and 1767 mg/L. However the majority of water strikes in Sandstone 2 have TDS values of less than a 1000 mg/L (**Table 11.2**).

In addition to the two main sandstone aquifers, water strikes are also encountered in the two mudstone units of the Otshe Formation i.e. mudstone 1 and mudstone 2. Groundwater quality in these mudstone units which are interlayered with thin sandstones is variable, but slightly elevated to high TDS values ranging between 1065 to 6045 mg/L were obtained (**Table 11.3**). In Ngwatle and Masetlheng areas, water strikes have been recorded at depths of more than 440 meters with TDS values ranging between 922 and 2156mg/l (**Table 11.5**).

Water levels in boreholes monitoring Ecca (Otshe) aquifer show a range of responses from stable, continuously rising and receding trends throughout the monitoring period indicating that this is very dynamic aquifer. Of the two aquifers assessed in project area, the Ecca aquifer was found to have the best potential for sustainable long term water supply to the Matsheng Villages as well as the Secondary centres both in terms of volumes and groundwater quality. The Ncojane Wellfield, which was assessed through numerical modelling to be capable of supplying 9600 m^3/d (~3.5 MCM/annum) for the next 30 years was developed in this aquifer.

Table 11.2 Water Strikes, Yield, and TDS Values for Ecca (Otshe) Aquifer

Block	BH No	Water Strike (m)	Aquifer	Airlift Yield (m^3/hr)	Field TDS (mg/L)
Ncojane	BH10211	199	SST 1	5	428
Ncojane	**BH10214	174	SST 1	4	2,319
Ncojane	BH10215	173	SST 1	4	986
Ncojane	BH10217	182	SST 1	16	808
Ncojane	BH10217	188	SST 1	17	767
Ncojane	BH10217	229	SST 1	23	817
Ncojane	BH10219	180	SST 1	30	866
Ncojane	BH10219	188	SST 1	13	818
Ncojane	BH10220	154	SST 1	16	713
Ncojane	BH10221	277	SST 1	46	620
Ncojane	BH10222	188	SST 1	27	2,604
Ncojane	BH10227	199	SST 1	93	403
Ncojane	BH10228	199	SST 1	93	403
Ncojane	BH10229	183	SST 1	7	3,416
Ncojane	*BH10229	198	SST 1	14	3,701
Ncojane	BH10315	250	SST 1	127	552
Ncojane	BH10316	162	SST 1	6	174
Ncojane	BH10316	174	SST 1	37	186
Ncojane	BH10402	198	SST 1	72	410
Ncojane	BH10404	198	SST 1	72	475
Ncojane	BH10404	225	SST 1	85	506
Ncojane	BH10405	193	SST 1	77	357
Ncojane	BH10405	206	SST 1	92	345
Ncojane	BH10410	201	SST 1	51	650
Ncojane	BH10411	202	SST 1	63	357
Ncojane	BH10211	224	SST 2	26	484
Ncojane	BH10212	223	SST 2	4	1,767
Ncojane	BH10212	249	SST 2	26	825
Ncojane	BH10215	203	SST 2	6	837
Ncojane	BH10215	215	SST 2	11	515
Ncojane	BH10217	275	SST 2	9	854
Ncojane	BH10220	210	SST 2	25	1,085
Ncojane	BH10222	289	SST 2	12	1,240
Ncojane	BH10229	282	SST 2	20	932
Ncojane	BH10407	205	SST 2	70	345
Ncojane	BH10407	232	SST 2	117	338
Ncojane	BH10410	226	SST 2	114	507
MAP	BH10317	307	SST 1	13	1,544
MAP	BH10317	328	SST 1	31	1,761
MAP	BH9294	208	SST 1	20	248
MAP	BH9298	200	SST 1	2	1,519
MAP	BH9298	215	SST 1	9	1,494
MAP	BH9243	236	SST 2	7	353
MAP	BH9243	248	SST 2	32	260

Notes

***BH10214 Silty Sandstone*

**BH10229 Water Strike in Interlayered Mudstone in Sandstone 1*

Water Strike Close to the Contact with Overlying Mudstone 1

SST 1 Otshe Sandstone 1(Ecca Group)

SST 1 Otshe Sandstone 2 (Ecca Group)

MAP Matlho-a-Phuduhudu

Table 11.3 Water Strikes, EC and TDS Values for Otshe Mudstone 1 and 2

Block	BH No	Water Strike (m)	Aquifer	Field TDS (mg/L)
Ncojane	BH10216	134	Mud 1	2021
Ncojane	BH10216	168	Mud 1	2034
Ncojane	BH10216	173	Mud 1	1668
Ncojane	BH10216	191	Mud 2	1829
Ncojane	BH10217	169	Mud 1	1600
Ncojane	BH10229	253	Mud 2	1290
Ncojane	BH10229	266	Mud 2	1101
Ncojane	BH10314	232	Mud 2	3125
Ncojane	BH10314	258	Mud 2	2294
MAP	BH9297	389	Mud 1	6014
MAP	BH9297	393	Mud 1	4458
MAP	BH9298	174	Mud 1	1065

Notes:

1. *Mud 1 Otshe Mudstone 1 (Ecca Group)*
2. *Mud 2 Otshe Mudstone 2 (Ecca Group)*
3. *MAP Matlho-a-Phuduhudu*

11.2.1 AQUIFER GEOMETRY

A west-southwest –east-northeast hydrogeological cross section and contour map to the top of the Ecca (Otshe Formation) Group based on borehole information from both existing and project boreholes are presented in **Figures 11.5** and **11.9**. From the contour map (**Figure 11.9**), it is observed that the top of the Ecca Group (Otshe Formation), defined by a sequence of argillaceous units including mudstones, shales, carbonaceous mudstones and siltstone occurs at depths ranging from less than 100 meters in the northwestern part of the project area to over 370 m in the southeastern part.

In the Ncojane Block, the Otshe Formation is found at depths of less than 100 to 160 meters (around Kule, Ncojane and Ukwi areas) and between 120 and 200 meters in the western and northern parts of the Matlho-a-Phuduhudu Block. The depth to the top of the Otshe Formation increases significantly towards the southeast, with depths in excess of 350 meters (B9297, BH7927 and BH8545) and appears to be related to down faulting across faults **F6**, and **F7** (**Figures 11.9**).

As indicated earlier, the main aquifers in Ecca Group are developed in two sandstone units of Otshe Formation which have been designated as Sandstone 1 (Aquifer 1) and Sandstone 2 (Aquifer 2). Both aquifers of the Otshe Formation (Aquifer 1 and 2) are comprised of fine, medium and coarse grained sandstones. These sandstones, particularly Sandstone 1 are often micaceous. **Table 11.4** summarises the depth and thickness of the Otshe Formation in the project area as interpreted from borehole geophysical logging data and lithological logs.

Sandstone 1 (Aquifer 1) generally occurs at depths ranging from 147 to 192 m in the Ncojane block, the western and northern parts of the Matlho-a-Phuduhudu Block with the exception BH10221 and BH10315 where the sandstone was intercepted at 289 m and 245 m respectively. To the east of the project area, the depth to top of this aquifer increases significantly to over 391 m due to faulting across faults **F6** and **F7** . Sandstone 1 has a thickness ranging from 17 m to 50 m with an average thickness of 29 m, with the exception of BH10216 where only 3 m of this sandstone was intercepted.

Table 11.4 Depth of Different Lithological Units, Ecca Group

		Ecca Group														Post Karoo Dolerites								
		Otshe Formation												Kobe Form										
Block	BH No	Mud 1 Top	Mud 1 Bot	Mud 1 Thick	SST 1 Top	SST 1 Bot	SST1 Thick	Mud 2 Top	Mud 2 Bot	MUD 2 Thick	SST 2 Top	SST 2 Bot	SST 2 Thick	Mud 3 Top		Dol 1 Top	Dol 1 Bot	Dol 1 Thick	Dol 2 Top	Dol 2 Bot	Dol 2 Thick	Dol 3 Top	Dol 3 Bot	Dol 3 Thick
Ncojane	10220	129	147	18	147	180	33	180	206	26	206	>253		>253										
Ncojane	10221	235	289	54	289	>327	>38 m									122	176	54						
Ncojane	10222	166	181	15	181	215	34	215	253	38	253	>290		>290										
Ncojane	10227	163	192	29	192	210	18	210	226	16	226	298	72	298	>400	116	159	43						
Ncojane	10215	106	153	47	153	187	34	187	209	22	209	226	17	226										
Ncojane	10228	163	192	29	192	210	18	210	226	16	226	>256												
Ncojane	10211	134	192	58	192	209	17	209	220	11	220	>256				160	165	5						
Ncojane	10216	126	137	11	173	176	3	176	190	14	190	212	22	212		57	70	13	76	96	20	137	164	27
		164	173	9																				
Ncojane	10213	171	192	21	192	209	17	209	220	11	220	300	80	300	>350									
Ncojane	10229	160	179	19	179	225	46	225	276	51	276	306	30	306										
Ncojane	10314	157	176	19	176	196	20	196	269	73	269	292	23	292										
Ncojane	10217	145	181	36	181	231	50	231	257	26	257	290	33	290	>400	71	145	74						
Ncojane	10212	158	170	12	170	186	16	196	222	26	222	254	32			27	68	41	122	135	13			
Ncojane	10315	209	245	36	245	280	35	280	>300							37	71	34						
Ncojane	10214	143	163	20	163	200	37	200	230	30	230	246	16	246	313	55	143	88	313	>319				
Ncojane	10316	90	112	22	112	127	15	127	170	43	170	220	50	220	>250									
Ncojane	10219	148	181	33	181	231	50	231	257	26	257	290	33	290	>290	71	145	74						
Ncojane	8346			0																				
Ncojane	10402	169	192	23	192	226	34	226	243	17	243	>264				127	169	42						
Ncojane	10404	144	192	48	192	226	34	226	235	9	235	>250				154	157	3						
Ncojane	10405	169	193	24	193	218	25	218	224	6	224	>255				127	155	28						
Ncojane	10407	170	171	1	176	191	15	191	205	14	205	246	41	246	>249	118	170	52	171	176	5			
Ncojane	10410	183	196	13	196	202	6	202	225	23	225	>263				135	183	48						
Ncojane	10411	169	200	31	200	228	28	228	238	10	238	>260				119	169	50						
MAP	10317	289	301	12	301	329	28	329	347							347	>349							
MAP	9243	190	210	20	210	240	30	240	250	10	250	262	12	262	275									
MAP	9297	383	393	10	393	418	25	418	433	15	433	>444												
MAP	9298	177	197	20	197	220	23	220	240	20	240	270	30	270	290									
MAP	8545	368	391	23	391	420	29	420	451	31	451	468	17	468	480									
MAP	9294	200	207	7	207	>207																		
MAP	9244	290																						

Sandstone 1 is overlain by a sequence of argillaceous units comprising of mudstones, shales, siltstones and carbonaceous mudstones with thickness ranging from 10 m to 72 m with an average thickness of ~ 30 m (Mudstone 1**, Table 11.4**). Interlayered with these argillaceous units, are relatively thin sandstone units which are occasionally water bearing and usually contain groundwater with slightly elevated TDS values.

Underlying Otshe Sandstone 1 is another argillaceous unit (Mudstone 2) comprising predominantly of grey mudstone, black carbonaceous mudstone with occasional thin coal beds. The depth to the top of this unit varies between 176 m to 280 m (average 210 m) in the Ncojane and the western part of the Matlho-a-Phuduhudu Block. In the south east and eastern parts of the Matlho-a-Phuduhudu Block, the depth to the top of this unit is over 360 m due to faulting (**Figure 11.9**).

Mudstone 2 is in turn underlain by Sandstone 2 (Otshe Aquifer 2) which forms the second main aquifer unit within the Otshe Formation. This sandstone occurs at depths ranging from 192 m to 276 m in the Ncojane Block and the northern and western parts of the Matlho-a-Phuduhudu Block. East of faults **F6** and **F7**, this sandstone occurs at depths in excess of 430 m. The thickness of Sandstone 2 ranges from 12 to 80 m and is very similar to that of Sandstone 1 (**Table 11.4**). Its average thickness is 34 m.

The majority of boreholes in the project area have not penetrated the full thickness of the Ecca Formation, therefore the thickness of the Otshe aquifer is not well constrained. However, several boreholes have penetrated to the top of the overlying Kobe Formation and data from these boreholes indicate that the thickness of the Otshe Formation ranges from 48 m to 146 m with an average thickness of about 105 m.

Several boreholes in the project area intercepted mudstone, shales coal, siltstones, a sandstones underlying Sandstone unit 2 belonging to the Kobe Formation (**Table 11.4**). These units were intercepted at depths ranging from 212 m to 468 m. Aquifers within the Kobe Formation contain groundwater with variable quality ranging from fresh to saline. The saline Kobe aquifer was encountered in boreholes located southeast of fault **F6.** Water level data from a cluster of piezometers at the site of BH10217 (Kobe) and BH10218 (Otshe, Sandstone 1) indicates that the head of the Otshe is higher than that of the Kobe i.e. groundwater head in vertically downwards.

The northern limit of the Ecca Aquifer (Otshe) aquifer in the project is defined by its truncation along the Ghanzi Ridge. To the south and east, it appears to be laterally continuous and extends beyond the project area, although it occurs at greater depths and is generally brackish. In the west, it forms an important aquifer in Namibia throughout its extent.

11.2.2 Aquifer Hydraulic Characteristics

Groundwater occurrence in the Otshe aquifer is under confined conditions with rest water levels rising between 27 and 318 m above the first water strikes (**Tables 11.5 and 11.6**). Rest water levels in the Otshe Sandstone aquifer range from 77 m to 153 m. In the majority of cases, the interpreted aquifer response from test pumping data is confined. However, some boreholes also had semi-confined leaky responses and barrier boundary effects. Average transmissivity values obtained for this aquifer throughout the project area range from 4 to 431 m^2/d and storativity values obtained from test pumping data analysis ranged from 1.00×10^{-4} to 4.05×10^{-6} which are values typical of confined aquifers. Tested borehole yields ranged from 10 to 95 m^3/hr.

Table 11.5 Hydrogeological Summary Details of Ecca Aquifer (Existing Boreholes)

BH No.	Location	Borehole Depth (m)	Water Strike (m bgl)	Screened Zones (m bgl)	Rest Water Level (m bgl)	Water Level Rise above 1st Water Strike (Ecca)	Airlift Yield (m^3/h)	Tested Yield (m^3/h)	T (m^2/d)	TDS (mg/L)
8469	Kule	193	172	171-187.5	96.17	76	15	33	20	762
8470	Kule	211	150 & 201	149.5-155	93.84	56	20	35	41	973
9243	MAP Block	298	236 & 248	235-238	111.3	125	32	31	14	232
9244	MAP Block	298	298	-	153	145	43	18	18	2877
9294	MAP Block	284	168, 191 & 208	-	129.8	38	20	50	19	234
9297	MAP Block	444	380 & 393 (Mudstone)	-	149.2	231	36	25	23	4042
8545	MAP Block	500	393	-	134.8	258	51			5272
6342	Masetlheng	414	408-410	-	89.8	318	-	-	-	-
6161	Ncaang	336	275,306	-	100	175	25	-	-	-
8346	Ncojane	169	144-145	144-160.5	98.7	45	25	48	122	448
8363	Ncojane	181	159	158.5-175	111.02	48	25	53	128	538
8364	Ncojane	181	154	153-175	115.5	39	18	45	116	341
9217	Ngwatle	455	167, 193, 283 & 439	No screens	76.6	90	60	25	7	2066
9218	Ngwatle	449	157, 212, 250, 279, 356, 396, 435 & 440	437.9-449	83	74	70	30	9	2156
7755	Okwa Valley	319	187	187.5-204	123.5	64	8	-	-	-
7760	Okwa Valley	284	164	-	123	41	3	-	-	-
7763	Okwa Valley	244	236	-	99	137	25	-	-	-
7764	Okwa Valley	236	230	-	99	131	25	-	-	-
7826	Okwa Valley	210	190	-	122	88	5	-		-
9183	Ukwi	208	189	185.02-202.72	82.25	107	95	30	92	922
9184	Ukwi	203	137 & 183	182.32-199.32	83.7	43	66	30	100	936

Table 11.6 Hydrogeological Summary Details of Ecca Aquifer (Project Boreholes)

BH No	Location	Borehole Depth (m)	Ecca Water Strikes (m)	Screened Zones (m bgl)	Rest Water Level (m bgl)	Water Level Rise above 1st Water Strike (Ecca)	Airlift Yield (m^3/h)	Tested Yield (m^3/hr)	Average T (m^2/d)	TDS
**BH9295	Ncojane Block	232	160 & 215	160 -195 & 211- 223	132.63	27.37	50	91	424	676
BH10221	Ncojane Block	327	277	276 - 299.2	98.72	178.28	12	30	23	698
BH10222	Ncojane Block	290	188 & 289	274.6-286	97.855	90.15	12	12	7	890
BH10227	Ncojane Block	300	199	190-250.9	106.50	92.50	101	Observation	431	
BH10210	Ncojane Block	250	195 & 218	192.83-244.07	109.45	85.55	25	Observation	398	
BH10215	Ncojane Block	250	173, 203 & 233	211.68-247.76	97.906	75.09	37	32	40	538
BH10228	Ncojane Block	256	199	211.68-247.76	106.60	58.40	74	93	446	397
BH10211	Ncojane Block	250	195 & 218	188.89-244	108.26	86.74	43	70	90	474
BH10216	Ncojane Block e	251	173, & 191	173.15-185.40	86.63	86.37	37	45	29	1760
BH10229	Ncojane Block	320	183, 198, 253, 266, 282 & 289	268.02-317	95.49	87.51	44	20	18	870
BH10314	Ncojane Block	300	232, 258, & 276	299.5-235.62 & 241.75-254	88.26	143.74	43	40	34	1210
BH10212	Ncojane Block	268	223, & 249	275.48-281.61 & 284.74-297	88.26	134.74	25	12	4	845
BH10315	Ncojane Block	287	250	248.31- 279	131.30	118.70	127	55	139	448
BH10218	Ncojane Block	290	172, 183, 189, & 213	175.80-246.67	85.65	97.35	59	Observation	40	
BH10214	Ncojane Block	324	170 & 300	Open	96.15	73.85	3	10	3	2016
BH10316	Ncojane Block	250	162 & 174	173.09 - 215.99	114.60	47.40	47	95	388	179
BH10317	MAP	348		371.642-374.487	144.37	162.63	44	NA		
BH10219	Ncojane Block	297	183,188, & 212	172.94 - 246.43	85.40	97.60	64	95	48	794
BH10402	Ncojane Block	257	198	189-248	106.9	91.1	72	70	213	358
BH10404	Ncojane Block	250	198 & 225	205-226 & 236-245	107.15	90.85	64	65	87	517
BH10405	Ncojane Block	255	193 & 206	190-195 & 200-250	109.20	83.8	78	75	167	351
BH10407	Ncojane Block	249	205 & 232	198 -243	104.37	100.64	70	65	145	351
BH10410	Ncojane Block	263	185, 201 & 226	213 -258	101.00	84	74	70	86	410
BH10411	Ncojane Block	263	202	211-261	103.6	98.4	44	70	176	364

Note Average T is from Recovery and Pumping Phase Data

11.2.3 GROUNDWATER FLOW

Groundwater flow for the Ecca (Otshe) aquifer as depicted on Piezometric head contour map (**Figure 11.13**), shows that groundwater flow is primarily from the west to east (Group 5 lineament direction) with a northwest to southeast component (Group 1 lineament direction) in the southern part of the of the Ncojane Block. Several faults and lineaments were inferred from aeromagnetic and remote sensing data interpretation during the study, Faults F4, F5, F6, & F7. Faults **F6** and **F7**, although having a significant impact on the depth to the top of the Otshe Formation (dip slip faults), seem to have very limited impact if any on the groundwater flow direction. On the other hand faults, **F4** and **F5** seem to have little impact on the depth to the top of Ecca (strike slip faults), but significant impact on the direction of groundwater flow with the groundwater flow direction running parallel to their orientation (**Figure 11.10**). Regionally, the Ecca aquifer system is laterally continuous and groundwater inflow is from Namibia, where reported sub-cropping conditions and saturated Kalahari Beds result in enhanced recharge potential.

11.3 GROUNDWATER QUALITY

In groundwater development, the available resource does not only depend on quantity and yield, but also on the groundwater quality of the aquifers to be exploited. In large parts of the project area, water quality is the main constrain limiting the exploitation of groundwater resources much more than the available quantity of water since most of the project area aquifers have relatively good yields but contain groundwater which is saline and is not suitable for human consumption.

Information on the groundwater chemistry for the project area was collated from existing reports and DWA data, as well as chemical analysis from groundwater samples collected during the drilling and test pumping activities of the current project. The project samples were analysed at both the DWA laboratory in Gaborone as well as the CSIR laboratory in Stellenbosch. Data from a total of 61 boreholes, 15 from the Ntane aquifer and 46 from Otshe Sandstone aquifer is available.

In this chapter an analysis of the available groundwater quality data is presented with the following objectives;

- Interpret the hydrochemistry in terms of the conceptual hydrogeology
- Evaluate the groundwater quality in the exploration and wellfield areas
- Determine the potability of the water and identify the treatment needs for compliance with drinking water quality specifications if any

The evaluation of the hydrochemistry was carried out in the framework of the conceptual hydrogeological model of the exploration areas and the Botswana Drinking Water Specifications (BOS 32: 2000). A detailed evaluation of the hydrochemistry is provided in **Volume 4- Hydrochemistry and Environmental Isotopes Report.**

11.3.1 HYDROCHEMICAL EVALUATION

As discussed in previous chapters, the main aquifers in the project area occur in the Ntane and the Otshe sandstones. The hydrochemistry of these two main aquifers is discussed in detail although minor aquifers also occur in the Mosolotsane, Kule/Kwetla and Kalahari Formations. Groundwater chemistry data for the Ntane sandstone is limited to the eastern part of the Matlho-a-Phuduhudu block where it forms a aquifer while most of the data for the Otshe pertains to western part of the Ncojane block where it is the main aquifer.

11.3.1.1 NTANE AQUIFER

Hydrochemical data for the Ntane aquifer is relatively sparse, with only 15 boreholes having reliable analytical data. However the available data was used to determine whether any noteworthy trends could be observed in the Ntane aquifers as well as for comparative hydrochemical analysis with other project area aquifers.

The salinity distribution trend for this aquifer is illustrated in **Figure 11.11** in the form of a TDS contour map. From this figure it is observed that groundwater in the central and western parts the Ntane Sub-basin is fresh with TDS values of between 200 and 650 mg/L with the lowest TDS found in the west associated with thin Kalahari cover (near BH9045). Towards the margins of the basin, particularly in the basalt sub-crop area in the north and the southern part of the Matlho-a-Phuduhudu Block, groundwater with relatively elevated TDS values (650 to 1000 mg/L) occurs (**Figure 11.11**). This trend is also observed in the sodium (Na) and chloride (Cl) distribution patterns (**Figure 11.12** and **11.13**), suggesting that recharge to the Ntane aquifer if any occurs mainly in the west in areas with thinner Kalahari cover. The distribution patterns of TDS and Na indicates that in terms of groundwater development only the central portion of the Ntane Sub-basin has the potential for long term abstraction as the areas towards the basin margins already have water quality which is close to and above the Class II limits for drinking water for TDS (1000 mg/L) and sodium (200 mg/L) respectively. Significant exploitable saturated thickness for this aquifer is also limited to a small area in the central portion of the basin. Groundwater quality analysis results also supports the findings from groundwater flow data, that the aquifer may be compartmentalised into at least two flow systems, one in the north and one in the central part of the basin (**Figures 11.11** to **11.13**)

The sodium percentage (total cations) is a useful parameter to follow hydrochemical evolution in an aquifer as it generally increases along the flow path due to various processes contributing sodium to the groundwater system particularly if the aquifer is confined. For the Ntane aquifer, the sodium percentage is at its highest in the central part of the Ntane basin, which may indicate that the groundwater is recharged in the western parts and eastern parts. However, this could also be related to water of different salinities being recharged in different parts of the aquifer, i.e. without any significant hydrochemical development taking place such as ion exchange (**Figure 11.14**).

The hydrochemical composition of the Ntane aquifer is given a Stiff diagram in **Figure 11.15**. This diagram shows the absolute concentrations of the various parameters and the size of the figures gives an indication of the salinity of the water. At the same time the three axes each for cations and anions give a clear indication of the relative compositions. It is evident from **Figure 11.15** that except for five boreholes, the salinity and composition of the groundwater at the various boreholes are fairly similar with some minor deviations. The five boreholes are BH5698, BH9134 and BH9135 in the north, BH9241 in the west and BH9239 in the south. The latter borehole has the highest salinity. Borehole BH9237, and to a lesser extent BH9044, seem to have some resemblance to the higher salinity water but could be influenced by low salinity water from the east and west. Low salinity boreholes BH7172, BH7170 and BH9240 located in the east show very similar composition, including a very low chloride concentration**.**

11.3.1.2 OTSHE AQUIFER

The Otshe aquifer is well represented with regard to boreholes with analytical data, particularly in the Ncojane Block, with a total of 40 exploration and 6 production boreholes in the study area. This means that hydrochemical trends in the Otshe aquifer can be identified with a high degree of confidence. Furthermore, as set out in the description of the hydrogeologic framework the Otshe is essentially a confined aquifer. Hence a consistent hydrochemical evolution is expected along the flow path in the aquifer from the recharge area to the discharge area except for faults that may affect the groundwater flow in the aquifer by connecting it with either overlying or underlying aquifers.

In general the groundwater flow is primarily from the west to east with a northwest to southeast component in the southern part of the of the Ncojane Block which means that the hydrochemical evolution in the aquifer should take place in an eastward or north-easterly direction.

Overall, the total dissolved solids (TDS) values for groundwater from the Ecca (Otshe Sandstones 1 and 2) aquifer are less than 1000 mg/L except in the extreme south of the Ncojane Block (Ngwatle and Masetlheng) and the eastern parts of the Matlho-a-Phuduhudu Block. Salinity in the overlying Mosolotsane/Kule basal aquifers, where present, is consistently high and these aquifers could act as sources of contamination for the underlying Otshe aquifers. It was found (**Chapter 8**) that most boreholes which had water strikes in the basal sandstone units of the Kule Formation had relatively elevated fluoride and sodium concentrations.

Regionally, the salinity increases from the west to east and northwest to the southeast following the regional flow directions interpreted from the piezometric head of the Ecca aquifer. A relatively sharp increase in salinity (TDS) southeast of faults **F6** and **F7** indicates that these structures play an important role in the salinity distribution of the Ecca (**Figure 11.16**), by either connecting it with overlying or underlying poor quality aquifers. Also noticeable in this figure, is the distinctively low salinity region in the west and northwestern portions of the area (TDS less 1000 mg/L), suggesting that these areas are actively recharging or receiving active inflow from recharge areas to the west. The possibility of active recharge to the Ecca in western parts is also indicated by water level monitoring data. In the project area, sodium and fluoride tend to exceed the Class II and Class III limits for drinking water. To evaluate the spatial distribution of these parameters, contour maps for these parameters are presented in **Figures 11.17** and **11.18**. **Figure 11.17** indicates that sodium is less than 400 mg/L (Class III limit) for a large part of the project area to the northwest of faults F6 and F7, again indicating that these structures play an important role in groundwater quality distribution of the of the Ecca (Otshe).

The same trend is observed in the fluoride distribution pattern (**Figure 11.18**) where concentrations of less than 1.5 mg/L are observed to the northwest of these faults. Of interest to note, is that the majority of boreholes which have low TDS, sodium and fluoride values did not have any water strikes in the overlying Kule basal sandstones and also occur to the northwest of faults F6 and F7. This probably indicates that the saturated Kule Formation acts as source of these ions in the groundwater.

The hydrochemical evolution of groundwater generally starts from a calcium magnesium bicarbonate water and ends as a sodium chloride water. Between these end members a whole series of possible combinations exists. During the hydrochemical evolution, the sodium concentration expressed as a percentage of the total cation concentration, increases from a low value of 20 per cent to nearly 100 per cent. The reasons for these changes are ion exchange on clays and other materials, the dissolution of salts from the rock matrix, precipitation of salts, oxidation-reduction reactions, and other processes. Not all of these processes operate in each aquifer but the general principle of evolution into a sodium-chloride type water, takes place in most aquifers. These processes are often illustrated by means of the trilinear (Piper) diagram or the Durov diagram which depict the changes in the relative composition of the groundwater. In the Otshe aquifer the groundwater in the presumed recharge areas (western and northwestern parts) has sodium percentage values ranging between 40 and 50 per cent but as hydrochemical evolution takes place down gradient of the flow direction it rapidly increases to 90 per cent and higher (**Figure 11.19**).

Stiff diagrams of the relative composition of groundwater are given in **Figures 11.20** and **Figure 11.21**. These Figures show a consistent pattern as expected down the flow gradient that is groundwater evolving towards sodium-chloride type water.

11.3.1.3 GROUNDWATER TYPES

Trilinear diagram for all the aquifers in the project is given **Figure 11.22**.

The groundwater type in the Ntane aquifer is predominantly Na-HCO_3 with only a few boreholes with Na-Ca-HCO_3 type groundwater mostly located in the in the central portion of the basin (**Figure 11.22**). One borehole (BH9239) located in the south has Na-Cl type groundwater, attributed to mixing with saline ground water from the underlying Mosolotsane Formation.

Groundwater types in the Otshe aquifer are distinctively different in the northwestern and southeastern parts of the project area, recharge zones vis vis discharge zones. In the northwest, the groundwater type is predominantly Ca-Na-HCO_3 (**Figure 11.22**). For the southeast, Na-Cl-HCO_3, and Na-Cl groundwater types predominate with boreholes in the extreme southeast having Na-Cl type water, again reinforcing the observation hydrochemical evolution takes place down gradient of the flow path.

11.3.2 COMPLIANCE TO DRINKING WATER SPECIFICATIONS

Drinking water specifications for Botswana, (BOS 32:2000 standards) were established on 13 September 2000 and were made mandatory by the government with effect from 3 April 2003. The specification lists three Classes for drinking water requirements:

1. Class I (Ideal)
2. Class II (Acceptable) and
3. Class III (maximum allowable)

These classes are for **Physica**l, **organoleptic** (aesthetic), **chemical** (inorganic macro, inorganic micro and organic determinants) and **microbiological** requirements for drinking water. According to BOS32:2000 "*waters that fall within Classes I and II can be consumed for a whole life time without adversely affecting human health, and any determinant that falls within Class III is a potential problem that poses a health risk to consumers*". Therefore water that falls within Class III requirements should be used for short term consumption only i.e. for periods not exceeding one year (BOS 32:2000). All Classes of water must comply with the microbiological requirements as per BOS 32:2000 specification (**Table 11.8**).

The results of chemical analysis of water samples from both project and existing boreholes are discussed as under in terms of compliance to drinking water standards. These samples were analysed at both the DWA (Gaborone) and CSIR (Stellenbosch, South Africa).

Table 11.7 BOS 32:2000 Physical, Organoleptic (aesthetic, Inorganic macro and Inorganic Micro Determinants requirements

Physical and organoleptic (aesthetic) requirements

Determinants	Units	Upper limit and ranges		
		Class I **(Ideal)**	Class II **(Acceptable)**	Class III **(Max. allowable)**
Colour	TCU	15	20	50
Conductivity at 25˚ C	µS/cm	700	1500	3100
Dissolved Solids	mg/l	450	1000	2000
Odour	n/a	Not objectionable	Not objectionable	Not objectionable
pH value at 25˚ C	pH	6.5-8.5	5.5-9.5	5.0-10.0
Taste	n/a	Not objectionable	Not objectionable	Not objectionable
Turbidity	NTU	0.5	5	10

Chemical requirements: Inorganic macro-determinants

Determinants	Upper limit and ranges		
	Class I Ideal mg/L	**Class II Acceptable mg/L**	**Class III mg/L**
Ammonia as N	0.2	1	2
Calcium as Ca	80	150	200
Chloride as Cl	100	200	600
Chlorine residual	0.3-0.6	0.6-1.0	1
Fluoride as F	0.7	1	1.5
Hardness as CaCO3	20	200	500
Magnesium as Mg	30	70	100
Nitrate as NO_3	45	45	45
Nitrite as NO_2	3	3	3
Potassium as K	25	50	100
Sodium as Na	100	200	400
Sulphate as SO_4	200	250	400
Zinc as Zn	3	5	10

Chemical requirements: Inorganic micro-determinants

Determinants	Upper limit and ranges		
	Class I µg/L	**Class II µg/L**	**Class III µg/L**
Aluminium as Al	100	200	200
Antimony as Sb	5	5	5
Arsenic as As	10	10	10
Cadmium as Cd	3	3	3
Chromium as Cr (total)	50	50	50
Cobalt as Co	250	500	1000
Copper as Cu	1000	1000	1000
Cyanide (free) as CN	70	70	70
Cyanide (recoverable) as CN	70	70	70
Iron as Fe	30	300	2000
Lead as Pb	10	10	10
Manganese as Mn	50	100	500
Mercury as Hg (total)	1	1	1
Nickel as Ni	20	20	20
Selenium as Se	10	10	10

Table 11.8 BOS 32:2000 Organic and Microbiological Requirements

Chemical requirements: Organic Determinants

Determinants	Upper limit and ranges		
	Class I	Class II	Class III
	(Ideal)	(Acceptable)	(Max. allowable)
	µg/L	µg/L	µg/L
Chemical requirements: Organic Determinants			
Total organic carbon	8000	8000	8000
Total trihalomethanes	1000	1000	1000
Phenols	10	10	10
Chloroform	30	30	30
Total pesticides	5	5	5
Pesticide	1	1	1
Poly-aromatic hydrocarbons	100	100	100
Toluene	700	700	700
Xylene	500	500	500
Ethyl benzene	300	300	300

Microbiological requirements

Determinants	Units	Allowable compliance contribution		
		95% min	4% max	1% max
		Upper limits		
Total coliform	Count/ 100 ml	Not detected	10	100
Faecal coliform	Count/ 100 ml	Not detected	1	10
Faecal streptococci	Count/ 100 ml	Not detected	10	100

NOTE 1 If any coliform bacteria are found in a sample, take a second sample immediately after the tests on the first sample have been completed. This shall be free from coliform bacteria; and,

NOTE 2 not more than 5 % of the total number of water samples (from anyone reticulation system) tested per year may contain coliform bacteria.

[1)] The allowable compliance contribution shall be at least 95 % to the limits indicated in column 3, with a maximum of 4 % and 1 % respectively, to the limits indicated in columns 4 and 5. The objective of disinfection should, nevertheless, be to attain 100 % compliance to the limits indicated in column 3.

11.3.2.1 NTANE SANDSTONE AQUIFER

Chemical analysis results from boreholes tapping the Ntane Sandstone aquifer are given **Table 11.9**. The results indicate that most of the measured parameters in the Ntane aquifer are within the limits of the BOS32:2000 standards with the exception of a few parameters. Parameters that exceed the limits are:

- TDS and EC in BH9239 with values 1154 mg/L and 2140 µS/cm respectively. These parameters exceed Class II limit but are within Class III limit.
- Sodium exceeds Class II standards in samples from three boreholes, (BH9239, BH9134 and BH9135) located in the south and northern margins of the Ntane Basin. In these boreholes, sodium ranges between 222 and 370 mg/L and is within the Class III standard of 400 mg/L
- BH9239 with a chloride concentration of 378 mg/L exceeds the Class II level but is within the Class III level of 600 mg/L.

Most of the existing boreholes which are completed in Ntane Aquifer (Lokalane Project) were analysed when the BOS32:2000 standards were not in place, with the result that most of the parameters listed in this standard were not analysed. However two boreholes (BH9240 and BH9237) in the central portion of the basin were re-sampled during the current project and most of the BOS 32:2000 parameters were analysed for. Results from these boreholes indicate that the groundwater in this aquifer is within the Class II BOS32:2000 limits for drinking water (**Table 11.9**).

Table 11.9 Water Quality of the Ntane Aquifer

Major Constituents

BH No	Date	K (mg/L)	Na (mg/L)	Ca (mg/L)	Mg (mg/L)	SO4 (mg/L)	Cl (mg/L)	HCO3 (mg/L)	NO3 (mg/L)	F (mg/L)	EC (μS/cm)	TDS (mg/L)
2211	09/08/04	7	58	67	11	15	35	340	1	0	660	422
5698	09/09/04	16	207	42	33	67	171	469	3	1	1380	883
7170	27-May-99	6	72	36	13	16	28	301	27	0	590	384
7172	30-May-00	11	68	37	12	14	23	267	26	0	570	371
9044	21-Jun-99	8	128	31	17	48	110	256	24	0	950	537
9134	09/09/04	17	224	34	27	83	171	456	1	1	1380	883
9135	09/09/04	17	222	35	27	67	175	390	3	1	1408	788
9237	02-Jun-00	16	157	40	21	68	105	343	5	0	1086	616
9238	30-May-00	13	125	45	21	76	38	404	8	<.05	915	546
9239	02-Jun-00	7	370	42	26	105	378	407	21	0	2140	1154
9240	18-Oct-00	6	60	24	20	5	16	281	27	<0.05	517	316
9241	11-May-00	10	200	50	11	56	93	438	16	1	1120	679
9297*	18-Sep-00	5	53	48	6	15	21	244	14	0	499	305
9237	26-Oct-05	25	163	39	29	64	103	416	0	0.17	1070	580
9240	11-May 05	20	39	46	20	7	15	297	27	0.09	1180	300
Class 2		60	200	150	70	250	200		45	1	1500	1000
Class 3		100	400	200	100	400	600		45	2	3100	2000

Minor Constituents

BH No	Date	Fe (mg/L)	Mn (mg/L)	CO_3 (mg/L)	As (mg/L)
2211	09/08/04	<0.05	<0.05		
5698	09/09/04	4.3	0.12		
7170	27-May-99				
7172	30-May-00			11.4	
9044	21-Jun-99	0.87	0.69	15	
9134	09/09/04	0.72	<0.05		
9135	09/09/04	0.5	0.02	35	
9237	02-Jun-00	0.08	<.1	0	
9238	30-May-00			0	
9239	02-Jun-00	0.32	<.1	0	
9240	18-Oct-00			0	
9241	11-May-00	0.32	<.1	0	
9297*	18-Sep-00	<0.1	<0.1	0	
9237	26-Oct-05	0.134	0	0	
9240	11-May 05	0.114	0	0	
Class 2		0.3	0.1		
Class 3		2	0.5		

Note, Constituent highlighted in grey exceeds the Class II limit (BOS32:2000)

11.3.2.2 ECCA (OTSHE) AQUIFER

Chemical analysis results from project boreholes tapping the Otshe aquifer are given **Tables 11.10** and **11.11** for exploration and production boreholes respectively**.** The results indicate that most of the measured parameters in the Ecca (Otshe) aquifer are within the limits of the BOS32:2000 standards with the exception of sodium, fluoride, TDS, and Chloride in a number of exploration boreholes.

- Sodium exceeds the Class II limits (200 mg/L) in virtually all exploration boreholes with the exception of BH10211, BH10228, BH10215, BH10316 and BH10315. All boreholes though are within the Class III (400 mg/L) limit with exception of BH10214, BH10314 and BH10216 which had values of 746 mg/L, 471 and 648 mg/L.
- Fluoride exceeds the Class II limit in the same boreholes which also exceed the Class II limit for sodium.
- TDS exceeds the Class II limit in only three boreholes BH10214, BH10314 and BH10216.
- Chloride values exceeding the Class II limits were obtained in two boreholes BH10214 and BH10216, however both of these boreholes have concentrations which fall within the Class III limit of 600 mg/L, are probably contaminated by the overlying aquifer as these boreholes were left open.

All boreholes with parameters exceeding the limits for drinking water standards are located to the southeast of fault F6 which is an area not targeted for wellfield development. It also has to be noted that for sodium, which has no adverse health effects (WHO, 2003) at concentrations of less than 400 mg/L, the Class III should be considered if no alternative is available. This is because sodium is a major constituent of groundwater in Botswana as a whole and strictly sticking to the Class II limit would exclude a lot of potentially useful groundwater.

For the six production boreholes in the Ncojane Wellfield, the groundwater is of very good quality with only the hardness exceeding BOS 32:2000 Class I limit in all boreholes (**Table 11.1**). However for three boreholes BH10404, BH10407 and BH10410 sodium and TDS (salinity) slightly exceeds the Class I specification while chloride marginally exceeds the Class I specification in BH10404 & BH10407. One borehole BH10402 has a fluoride value which is slightly above the Class I limit.

However, all parameters in the production boreholes are well within the Class II specification which is a very rare case for groundwater in Botswana.

Table 11.10 Groundwater Quality of Ecca Aquifer Project Exploration Boreholes

Major Constituents

BH No	Sample Date	K (mg/L)	Na (mg/L)	Ca (mg/L)	Mg (mg/L)	NH4 as N (mg/L)	SO4 (mg/L)	Cl (mg/L)	Alkalinity as CaCO3 mg/L	NO3 mg/L	F mg/L	EC (μS/cm)	TDS (mg/L)	Hardness as CaCO3 mg/L
10211	25-Nov-06	8.2	126	15	13	<0.1	20	59	262	4.7	0.69	740	474	90
10222	28-Nov-06	5	317	2.8	2.6	<0.1	44	103	550	<0.1	2.3	1390	890	18
10228	5-Dec-06	6	81	25	15	<0.1	13	41	211	4.4	0.59	620	397	126
10229	10-Dec-06	3	317	2.3	2.1	<0.1	43	88	547	<0.1	2.3	1360	870	14
10221	3-Feb-06	3.3	250	2.5	2.1	0.1	36	85	388	<0.1	1.1	1090	698	15
10215	28-Jan-06	10.1	149	17	13	<0.1	35	60	295	0.15	0.7	840	538	96
10314	26-Jan-06	2.7	471	1.1	0.6	<0.1	76	115	744	<0.1	2.5	1890	1210	5
10214	10-Mar-06	3.5	746	3.2	3.3	0.1	326	418	682	<0.1	3.5	3150	2016	21
10316	21-Feb-06	3.5	30	20	5.9	<0.1	8.3	13	87	0.85	0.4	280	179	74
10219	3-Mar-06	1.7	326	1.6	1.1	<0.1	86	102	455	<0.1	1.8	1240	794	8.6
10212	11-Feb-06	2.9	315	2.4	2.1	<0.1	72	98	487	<0.1	1.8	1320	845	15
10216	19-Feb-06	4.4	648	4.9	3.6	<0.1	195	464	527	<0.1	2.3	2750	1760	27
10315	9-Feb-06	4.7	168	1.1	1.2	<0.1	19	41	290	<0.1	1.1	700	448	8
Class 2		50	200	150	70	1	250	200		45	1	1500	1000	200
Class 3		100	400	200	100	2	400	600		45	1.5	3100	2000	500

Minor Constituents

BH No	Sample Date	Al (mg/L)	As (mg/L)	Cd (mg/L)	Cr (mg/L)	Co (mg/L)	Cu (mg/L)	Fe (mg/L)	Pb (mg/L)	Mn (mg/L)	Ni (mg/L)	Zn (mg/L)	Cyanide as CN mg/L	pH (Lab) (20°C)
10211	25-Nov 06	<0.1	<0.01	<0.005	<0.05	<0.05	<0.05	0.11	<0.05	<0.05	<0.05	<0.05	<0.05	8
10222	28-Nov-06	0.61	<0.01	<0.005	<0.05	<0.05	<0.05	0.47	<0.05	<0.05	<0.05	<0.05	<0.05	8.4
10228	5-Dec-06	<0.1	<0.01	<0.005	<0.05	<0.05	<0.05	0.41	<0.05	<0.05	<0.05	<0.05	<0.05	7.4
10229	10-Dec-06	<0.1	<0.01	<0.005	<0.05	<0.05	<0.05	0.18	<0.05	<0.05	<0.05	<0.05	<0.05	8
10221	3-Feb-06	<0.1	<0.01	<0.005	<0.05	<0.05	<0.05	0.2	<0.05	<0.05	<0.05	<0.05	<0.05	7.3
10215	28-Jan-06	<0.1	<0.01	<0.005	<0.05	<0.05	<0.05	0.23	<0.05	<0.05	<0.05	<0.05	<0.05	7.3
10314	26-Jan-06	0.15	<0.01	<0.005	<0.05	<0.05	<0.05	0.16	<0.05	<0.05	<0.05	<0.05	<0.05	7.5
10214	10-Mar-06	<0.10	0.01	<0.005	<0.05	<0.05	<0.05	0.27	<0.05	<0.05	<0.05	0.08	<0.05	8.5
10316	21-Feb-06	<0.11	<0.01	<0.005	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	6.5
10219	3-Mar-06	<0.12	<0.01	<0.005	<0.05	<0.05	<0.05	2	<0.05	<0.05	<0.05	<0.05	<0.05	7.7
10212	11-Feb-06	<0.13	<0.01	<0.005	<0.05	<0.05	<0.05	0.07	<0.05	<0.05	<0.05	<0.05	<0.05	7.7
10216	19-Feb-06	<0.14	<0.01	<0.005	<0.05	<0.05	<0.05	0.07	<0.05	<0.05	<0.05	<0.05	<0.05	8
10315	9-Feb-06	<0.15	<0.01	<0.005	<0.05	<0.05	<0.05	0.05	<0.05	<0.05	<0.05	<0.05	<0.05	7.7
Class 2		0.2	0.01	0.003	0.05	0.5	1	0.3	0.01	0.1	0.02	5	0.07	5.5 - 9.5
Class 3		0.2	0.01	0.003	0.05	1	1	2	0.01	0.5	0.02	10	0	5.0 - 10

Note, Constituent highlighted in grey exceeds the Class II limit (BOS32:2000)

Table 11.11 Chemical Analysis Results of Production Boreholes

Macro Constituents

BH No	Sample Date	K (mg/L)	Na (mg/L)	Ca (mg/L)	Mg (mg/L)	Nitrite as NO2 (mg/L)	SO4 (mg/L)	Cl (mg/L)	Alkalinity as CaCO3 (mg/L)	Nitrate as NO3 mg/L	F (mg/L)	EC (mS/cm)	TDS (mg/L)	Hardness as CaCO3 mg/L
BH10402	23/9/07	7.3	88.2	25.9	19.3	<0.2	18.8	67.9	204	17.1	0.72	690	442	144
BH 10404	05/8/07	7.8	135.5	21.4	19.0	<0.05	33.0	112.5	208	17.1	0.59	840	538	132
BH10405	24/8/07	6.5	85.8	26.5	16.9	2.90	17.2	67.9	188	13.9	0.64	650	416	136
BH10407	05/9/07	8.3	139.5	22.7	19.7	<0.2	31.3	116.1	219	17.7	0.64	860	550	138
BH10410	16/9/07	7.5	112.0	21.8	16.3	<0.2	21.1	77.8	235	<0.2	0.69	720	461	122
BH10411	17/10/07	7.5	90.9	26.7	19.9	<0.2	19.5	62.5	215	17.6	0.6	690	442	148
Class I		25	100	80	30	3	200	100		45	0.70	700	450	20
Class II		50	200	150	70	3	250	200		45	1.00	1500	1000	200
Class III		100	400	200	100	3	400	600		45	1.5	3100	2000	500

Note Parameters Highlighted in grey exceeds the Class I Limit

Micro Constituents

BH No	Sample Date	Al (mg/L)	As (mg/L)	Cd (mg/L)	Cr (mg/L)	Co (mg/L)	Cu (mg/L)	Fe (mg/L)	Pb (mg/L)	Mn (mg/L)	Ni (mg/L)	Zn (mg/L)	Cyanide as CN mg/L	pH (Lab) (20°C)
BH10402	23/09/2007	<0.1	<0.01	<0.01	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	6.80
BH10404	05/08/2007	<0.1	<0.01	<0.01	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	6.80
BH10405	24/08/2007	<0.1	<0.01	<0.01	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	6.60
BH10407	05/09/2007	<0.1	<0.01	<0.01	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	6.70
BH10410	16/09/2007	0.1	<0.01	<0.01	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	6.90
BH10411	17/10/2007	0.3	<0.01	<0.01	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	7.60
Class I		0.1	0.01	0.003	0.05	0.25	1	0.03	0.01	0.05	0.020	3	0.070	6.5-8.5
Class II		0.2	0.01	0.003	0.05	0.50	1	0.3	0.01	0.1	0.020	5	0.070	5.5 - 9.5
Class III		0.2	0.01	0.003	0.05	1	1	2	0.01	0.5	0.020	10	0.070	5.0 - 10

11.3.3 CONCLUSIONS FROM HYDROCHEMISTRY

11.3.3.1 GENERAL

From a hydrochemical perspective both the Ntane and the Otshe aquifer may yield water suitable for potable purposes. However, exploitable areas are geographically restricted. For the Ntane aquifer, it is only the area is in the eastern part of the Matsheng investigation area (Matlho-a-Phuduhudu Block) which has exploitable groundwater while for the Otshe aquifer only the Ncojane Block has potable groundwater.

For the Otshe sandstone aquifer hydrochemical data was available for a total of 40 existing and exploration boreholes providing a good coverage of the most important area. The 6 production boreholes are located relatively close to each other and provide detailed information on the consistency of the water quality over a short distance. Only a limited number (13) of boreholes were available for the study of the hydrochemistry in the Ntane and this should be taken into account when considering the aquifer water quality interpretation.

Not all characteristics of the Mosolotsane and Kwetla aquifers have been discussed in detail as the available data is very limited and the exploitation potential of these aquifers is limited due to water quality. However, there is a potential pollution risk from these aquifers to the main aquifers particularly through leakage from improperly constructed boreholes or leaky casings. Therefore boreholes drilled through these aquifers have to be properly sealed and constructed to isolate these from the underlying aquifers.

11.3.3.2 NTANE AQUIFER

The recharge area(s) of the Ntane sandstone aquifer are not clearly defined from the chemistry data as there is little indication of hydrochemical evolution in this aquifer. Although the groundwater gradient is eastwards, only calcium, potassium, and nitrate show any consistent gradient over the area with data. The presence of appreciable concentrations of calcium limits the occurrence of high fluoride. The Stiff chemical composition diagrams clearly illustrate the nearly erratic nature of the hydrochemistry in the aquifer.

Available data seem to confirm that recharge has to take place in several areas which may be expected due to the unconfined nature of the aquifer.

The occurrence of nitrate in the Ntane sandstone needs to be investigated e.g. by ^{15}N investigations in order to identify the likely sources and for developing a management plan as needed. The fact that potassium, not a pollutant itself but rather a potential pollution indicator, follows exactly the opposite trend would seems to indicate that the nitrate is possibly related to natural sources, e.g. soil nitrate.

In areas where the aquifer is unconfined, there is a risk of pollution and an aquifer protection needs and strategy might have to be developed.

11.3.3.3 OTSHE AQUIFER

According to the hydraulic gradient, groundwater flow in the Otshe Aquifer is mainly from west to east in the investigation area. Hydrochemical evolution in the Otshe sandstone aquifer mainly takes place in an easterly direction and recharge seems to take place in the west in an area where the Otshe sandstones are expected to sub-crop under thin Kalahari cover. Further sub-outcrops may occur in the northwest, as hydrochemistry hints at recharge in those areas. Recharge or seepage along faults from overlying aquifers may also take place in confined parts of the aquifer (**Faults F6 & F7**). These faults may introduce saline water from the overlying Mosolotsane/Kwetla Formations. To the east of these faults the Otshe aquifer is found at greater depths while hydrochemical evolution reaches the highly saline stage.

In the Otshe aquifer, nitrate generally occurs at very low levels except at Ncojane (BH8346) which points at the possibility of anthropogenic pollution. Pollution may be taking place via a faulty borehole construction. The confined nature of the Otshe aquifer should protect it against pollution except where leaky boreholes drilled through the confining layer pose a threat.

Water strike sampling during drilling served an important purpose as it clearly identified the higher salinity in the overlying and underlying formations. This was clearly demonstrated at BH10217 where the salinity in the overlying mudstone was double that in the aquifer while the underlying Kobe formation had salinity which was ten times higher than the Otshe aquifer. This phenomenon represents a serious risk for water quality in production boreholes. The high salinity presents a corrosion hazard and damage to the borehole casing or inadequate sealing during construction will lead to leakage and contamination of the good quality water in the Otshe aquifer.

Groundwater from the production boreholes completed in Otshe aquifer is of very good quality and comply with the BOS 32:2000 limits for Class II potable water.

11.3.3.4 Recommendations

Longer term monitoring of the groundwater quality and abstraction volumes is essential to protect the groundwater quality in the Otshe aquifer. The risk for pollution exists not only from faulty borehole construction, e.g. inadequate sealing in confining layers or incorrect placement of screens, but also from corrosion, and seepage from surface pollution points.

Adequate protection zones should be maintained around wellfields to prevent any pollution from surface to reach the aquifer.

The possibility of anthropogenic pollution at BH8346, Ncojane needs to be established. Re-sampling and analysis, as well as inspection of BH8346 by borehole camera and hydrochemical logging is recommended. It should be complemented by ^{15}N isotope investigations in order to identify the likely sources of nitrogen. This is essential for developing a protection plan to safeguard the aquifer against pollution.

For the unconfined Ntane sandstone aquifer an aquifer protection strategy is required.

Figure 11.1 Depth to Top of the Ntane Sandstone

Figure 11.2 Depth to Bottom of Ntane Sandstone

Figure 11.3 Thickness of the Ntane Sandstone

Figure 11.4 Saturated Thickness of Ntane Sandstone

Figure 11.5 West-Southwest-East-Northeast Hydrogeological Cross-Section

Figure 11.6 Exploitable Saturated Thickness Ntane Sandstone

Figure 11.7 Piezometric Head Ntane Sandstone

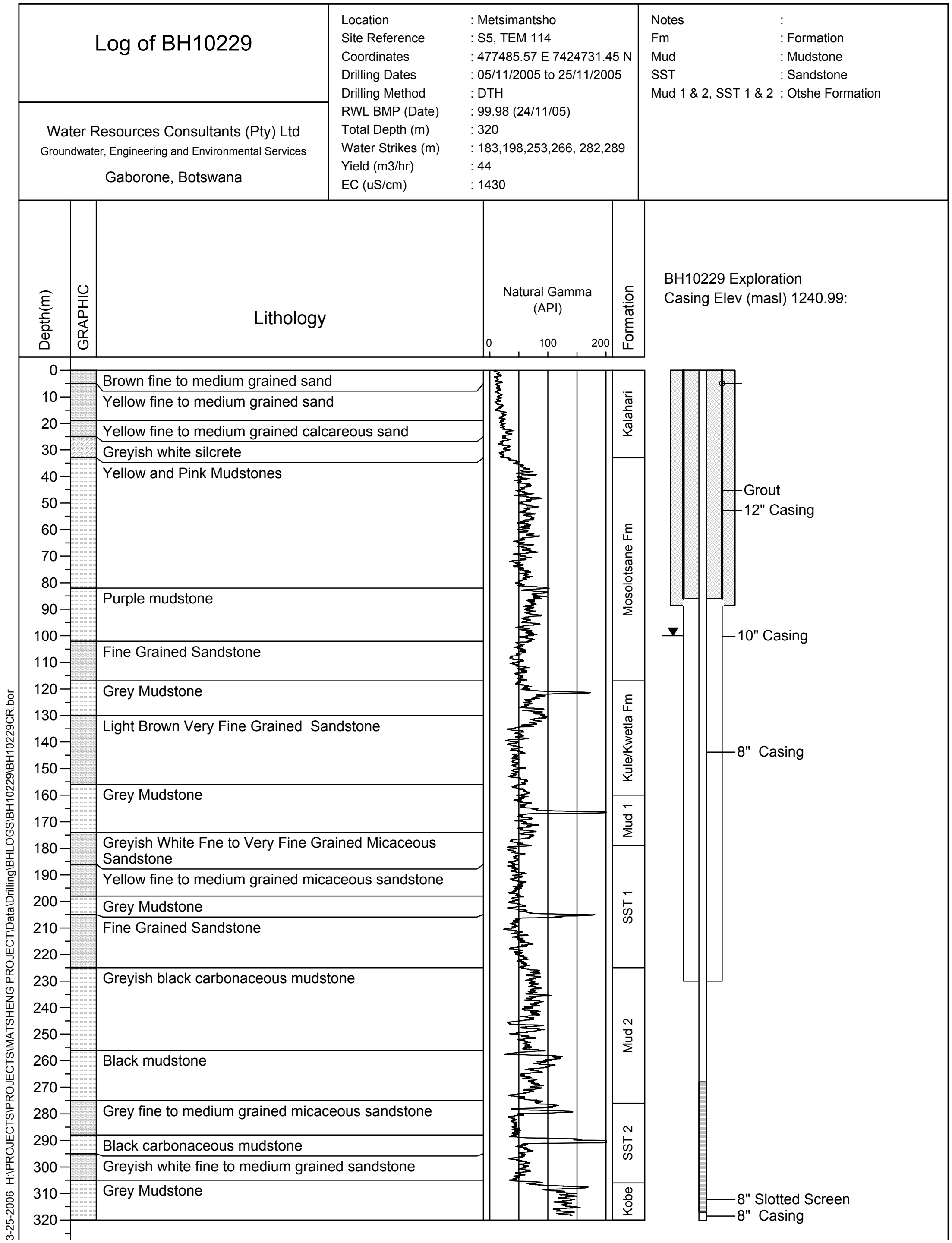

Figure 11.8 Typical Lithostratigraphic Column through the Otshe Formation

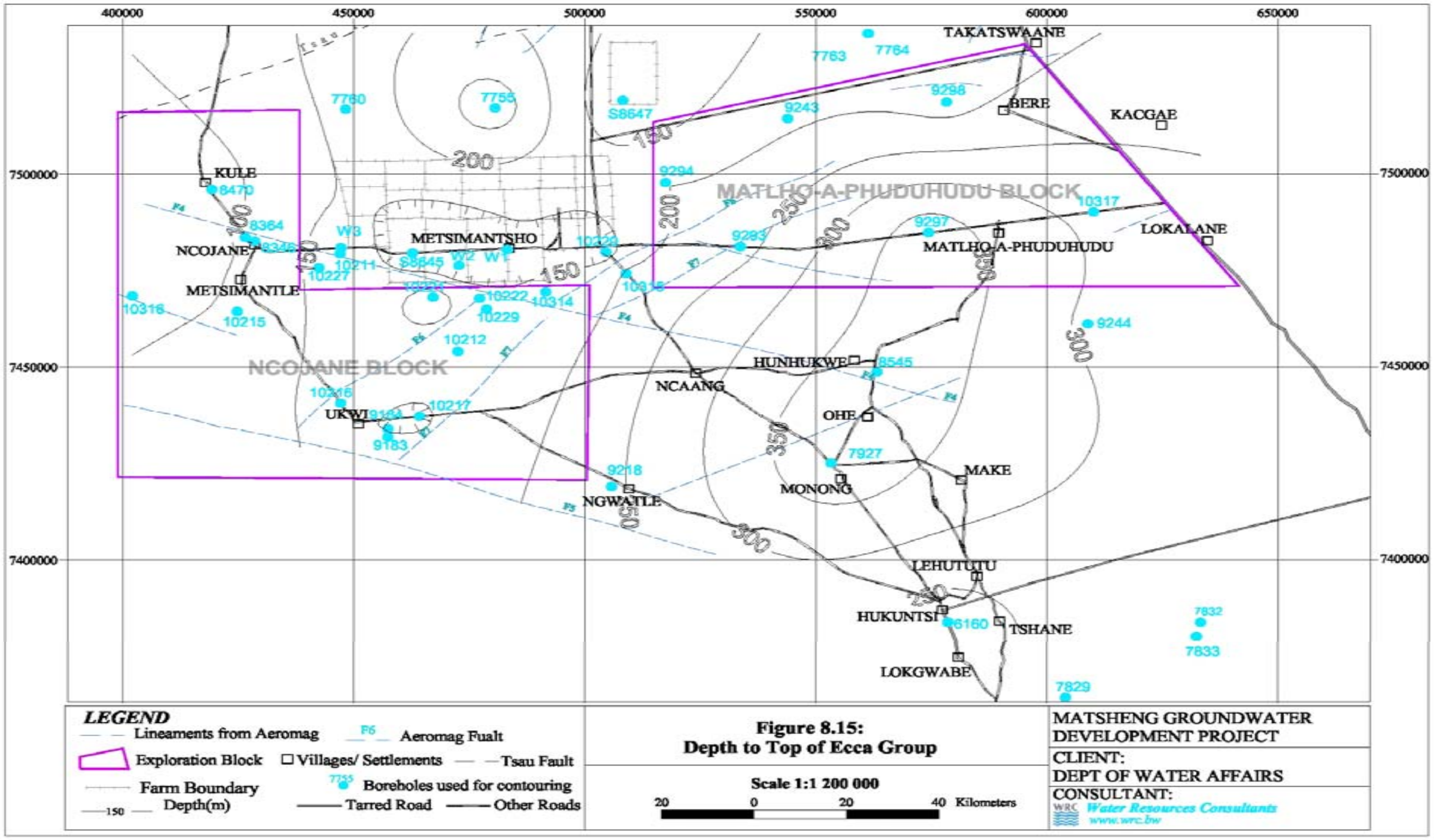

Figure 11.9 Depth to Top of Ecca

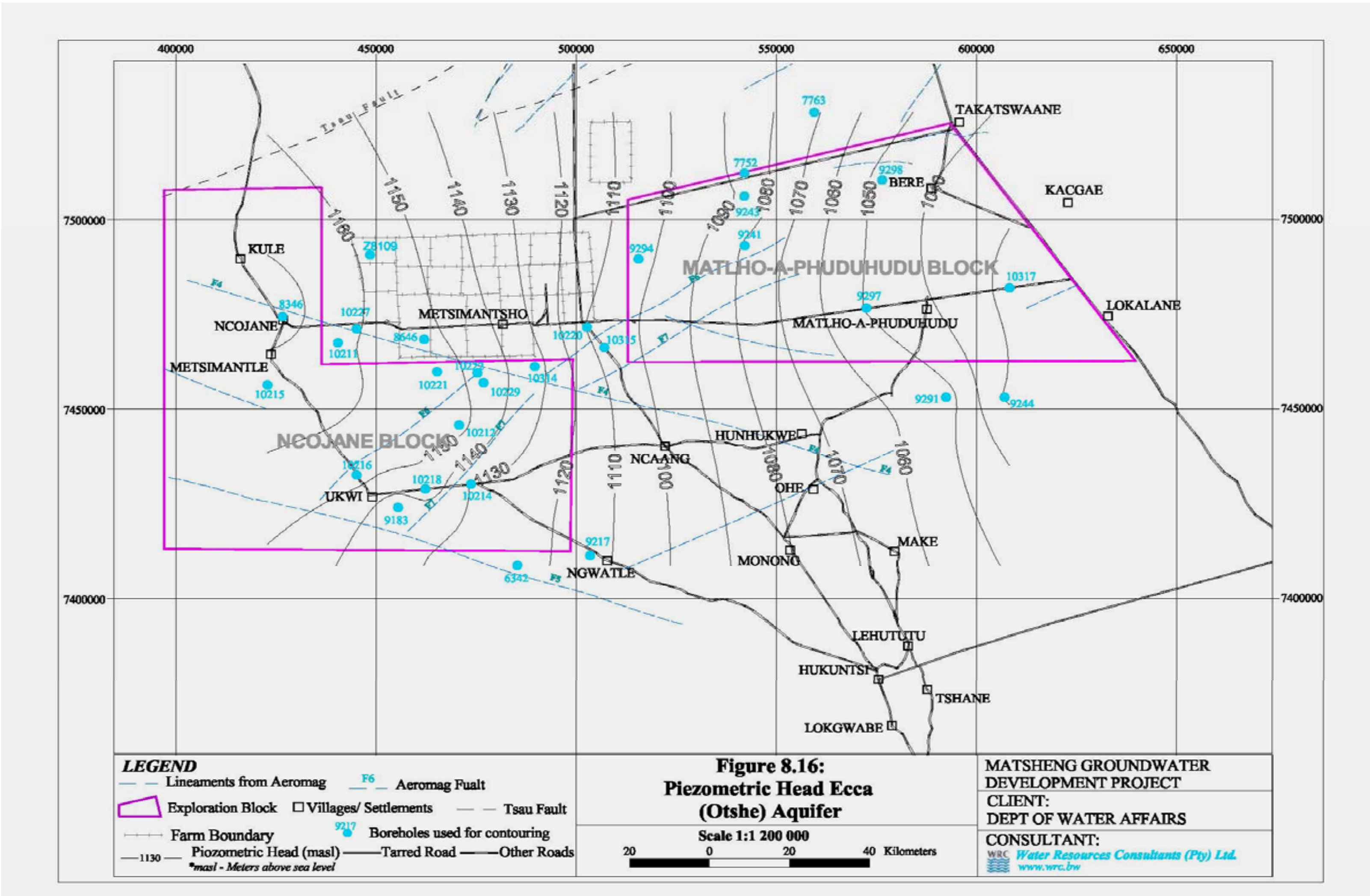

Figure 11.10 Piezometric Head Ecca Aquifer

Figure 11.11 TDS Distribution Ntane Aquifer

Figure 11.12 Sodium Distribution Ntane Aquifer

Figure 11.13 Chloride Distribution Ntane Aquifer

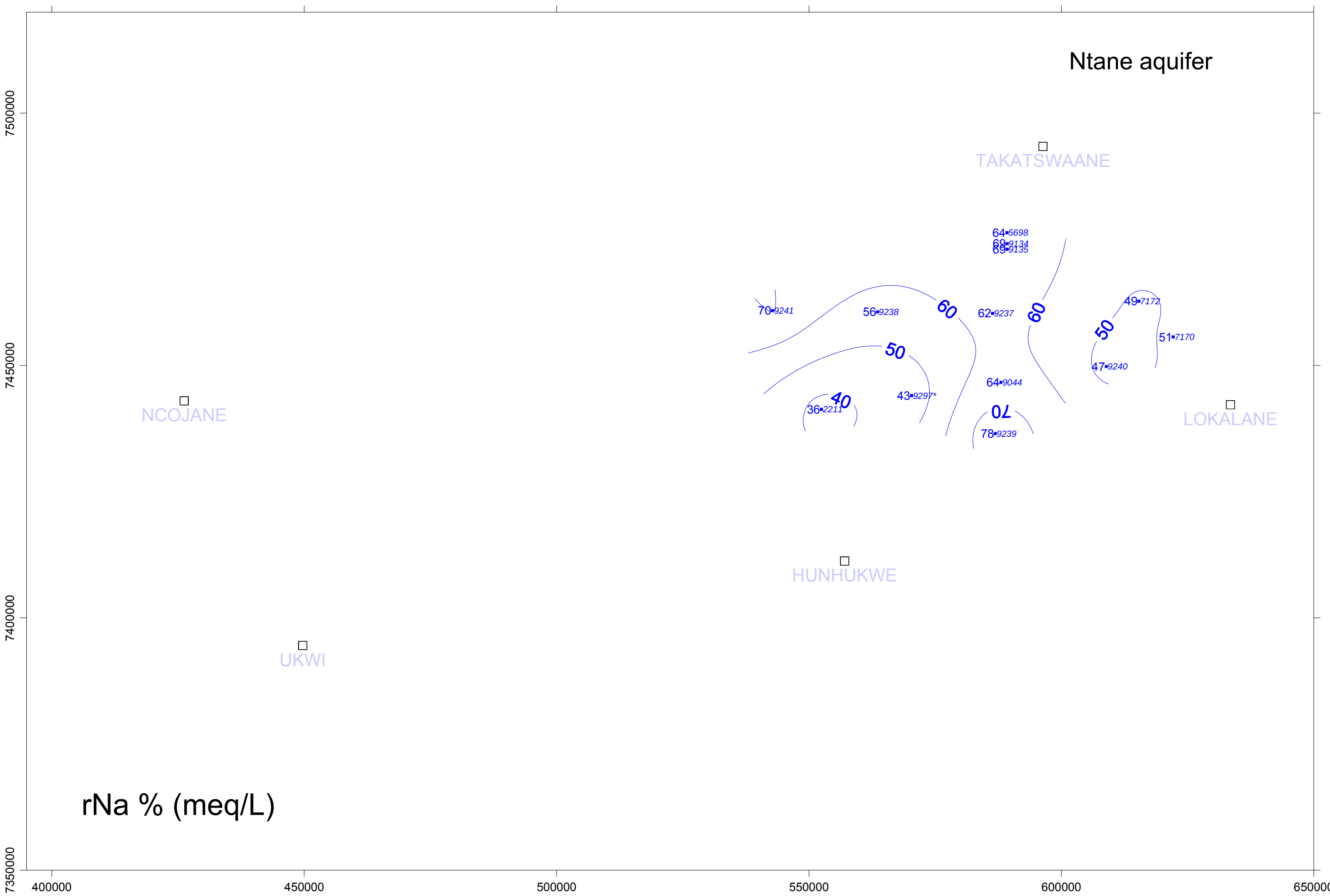

Figure 11.14 Sodium Percentage Distribution Ntane Aquifer

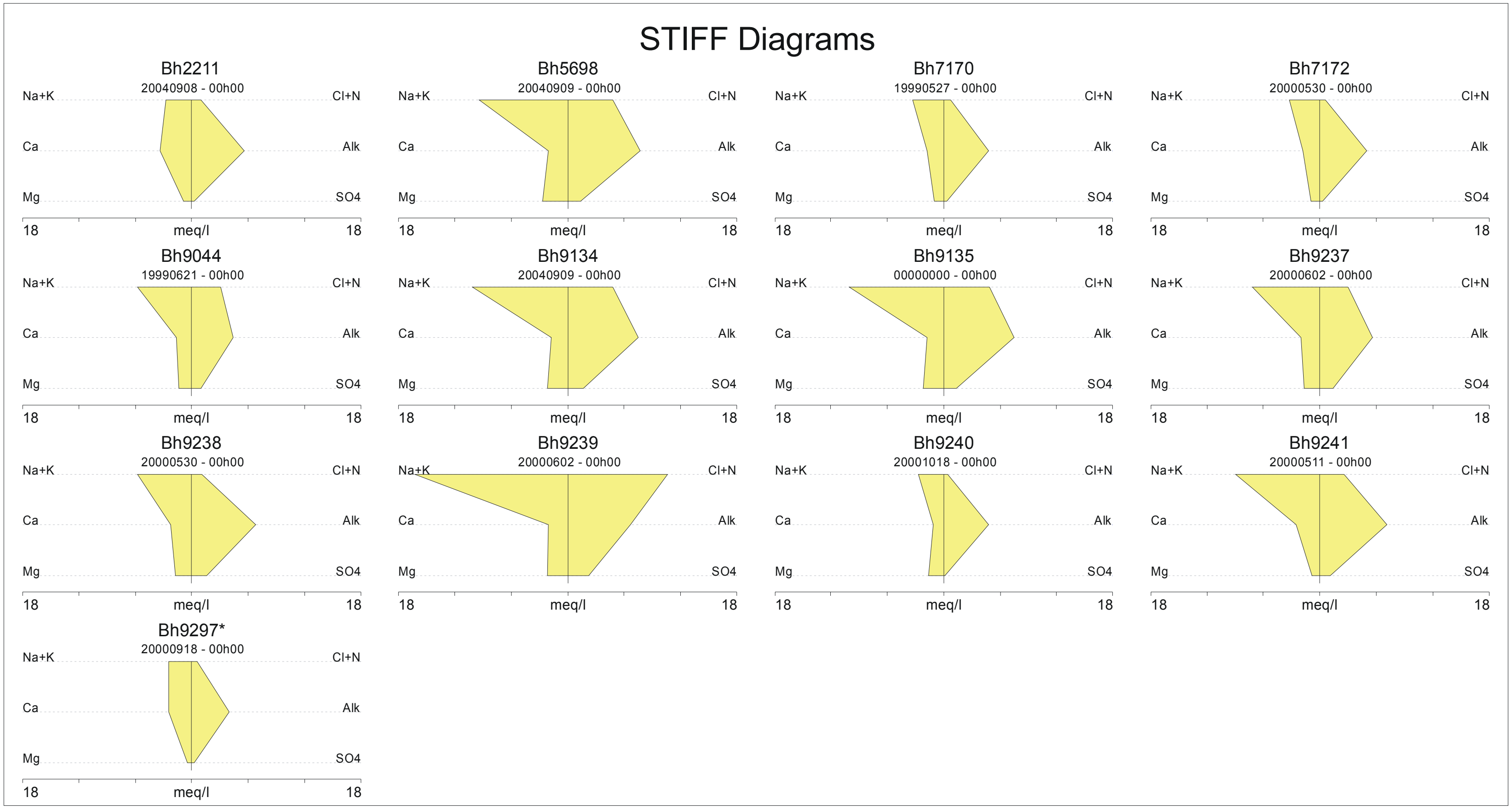

Figure 11.15 Stiff Chemical Composition Diagrams for Exploration Boreholes in the Ntane Aquifer

Figure 11.16 TDS Distribution Ecca Aquifer

Figure 11.17 Sodium Distribution Ecca Aquifer

Figure 11.18 Fluoride Distribution Ecca Aquifer

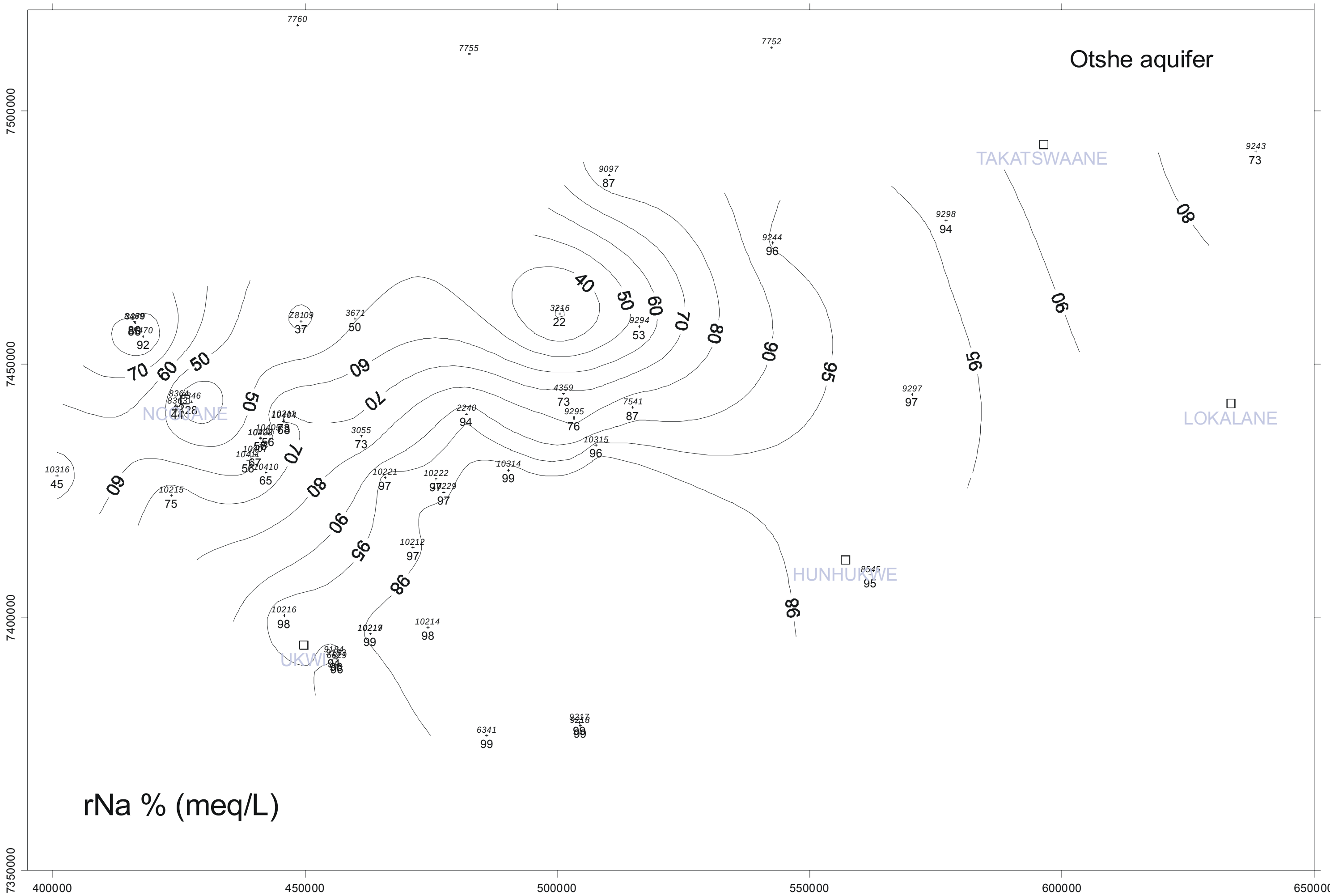

Figure 11.19 Sodium Percentage Distribution in the Otshe Aquifer

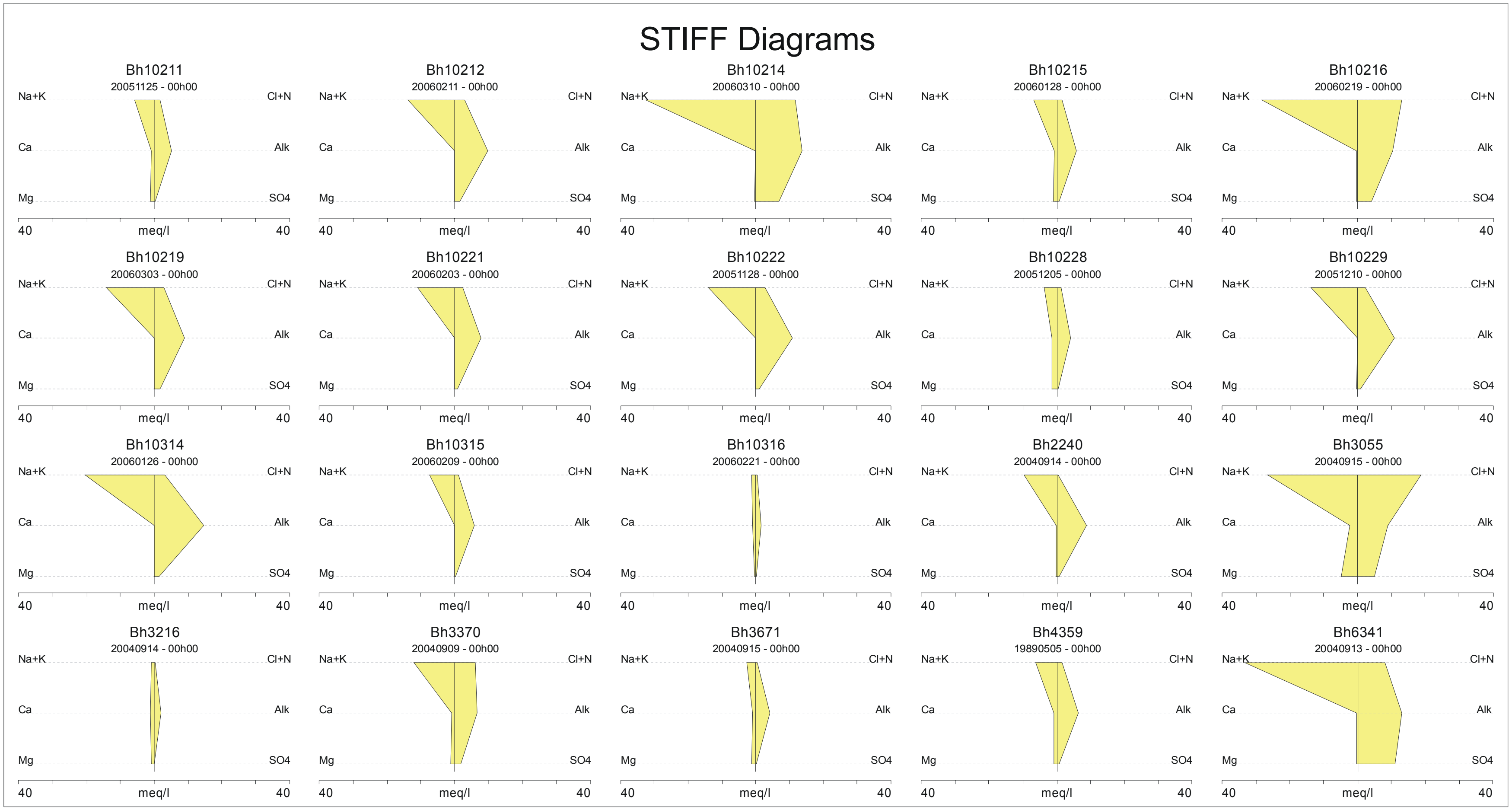

Figure 11.20 Stiff Chemical Composition Diagrams for the Exploration Boreholes in the Otshe Aquifer (Part 1)

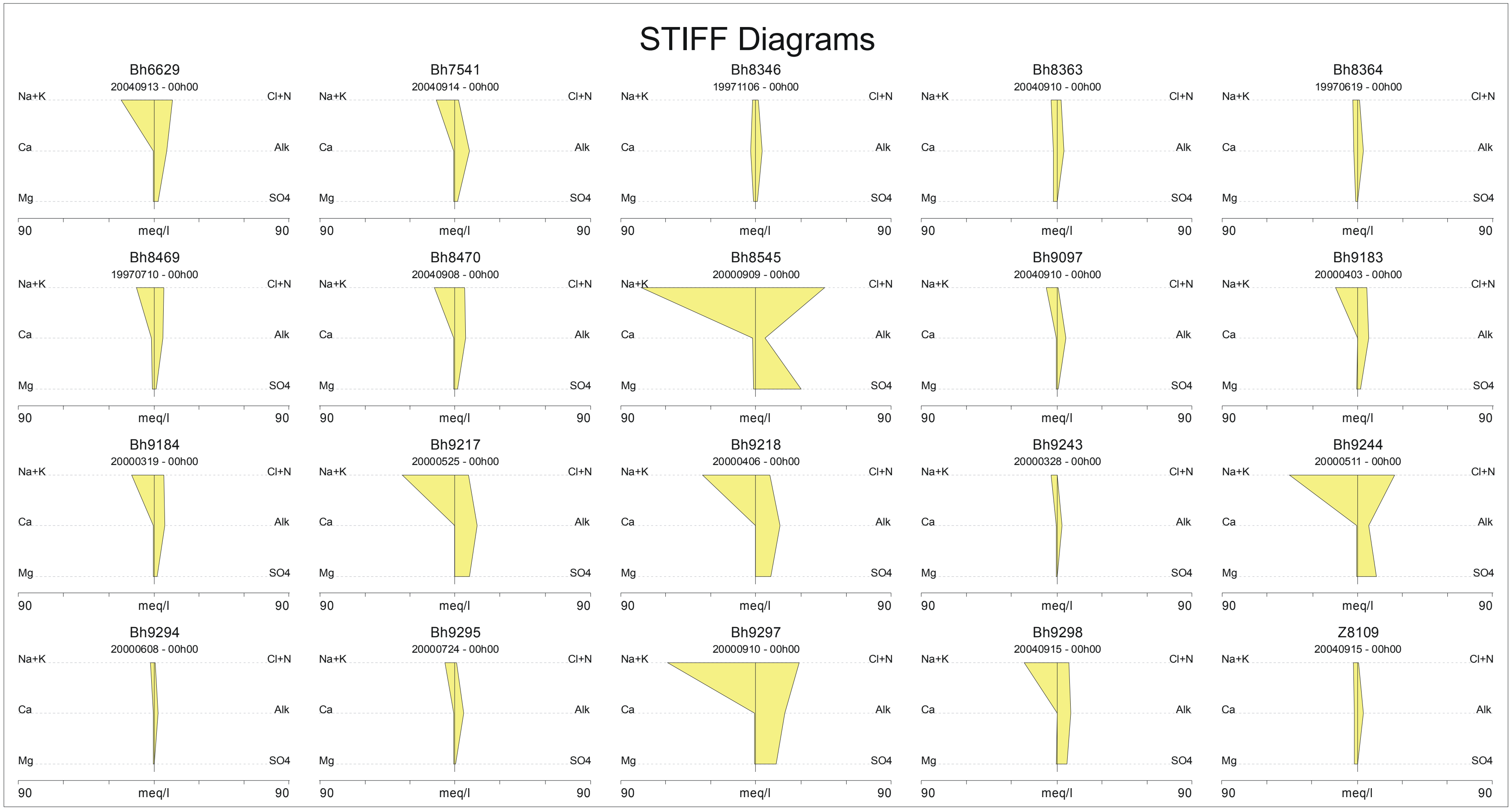

Figure 11.21 Stiff Chemical Composition Diagrams for the Exploration Boreholes in the Otshe Aquifer (Part 2)

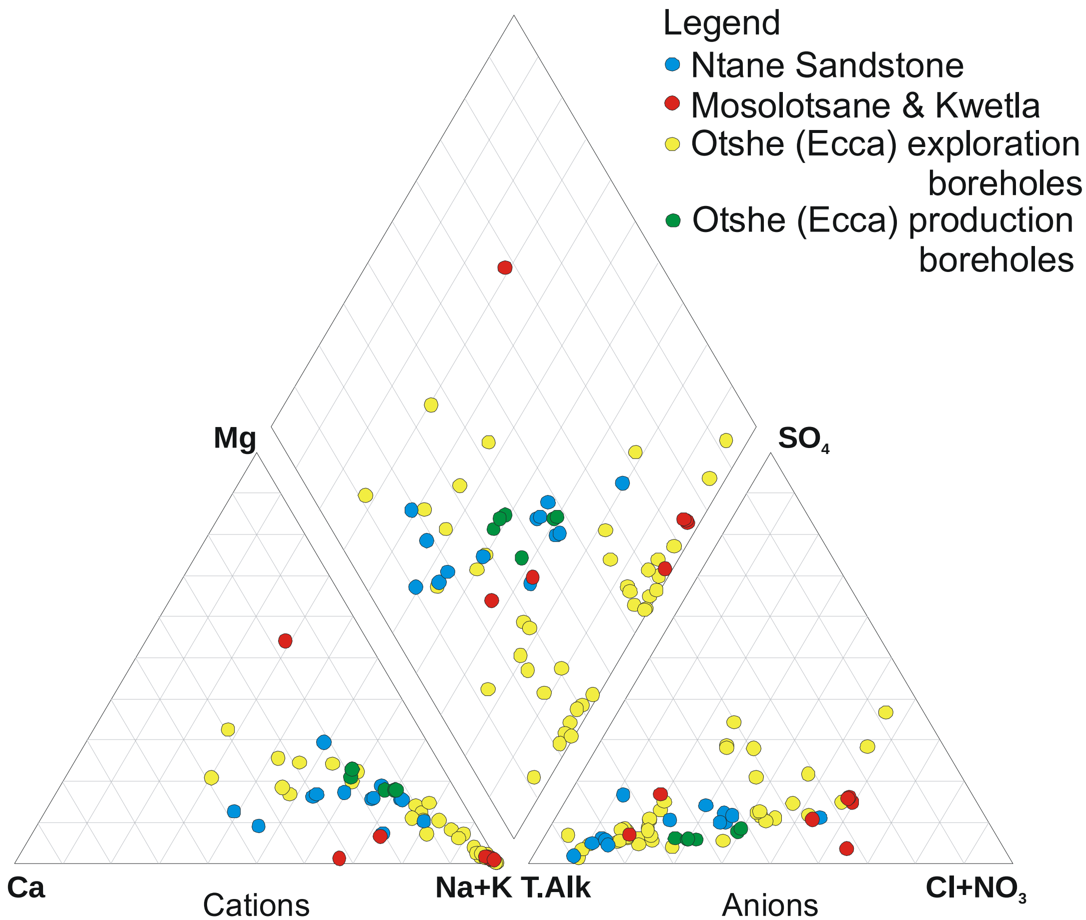

Figure 11.22 Trilinear Diagram All Aquifers

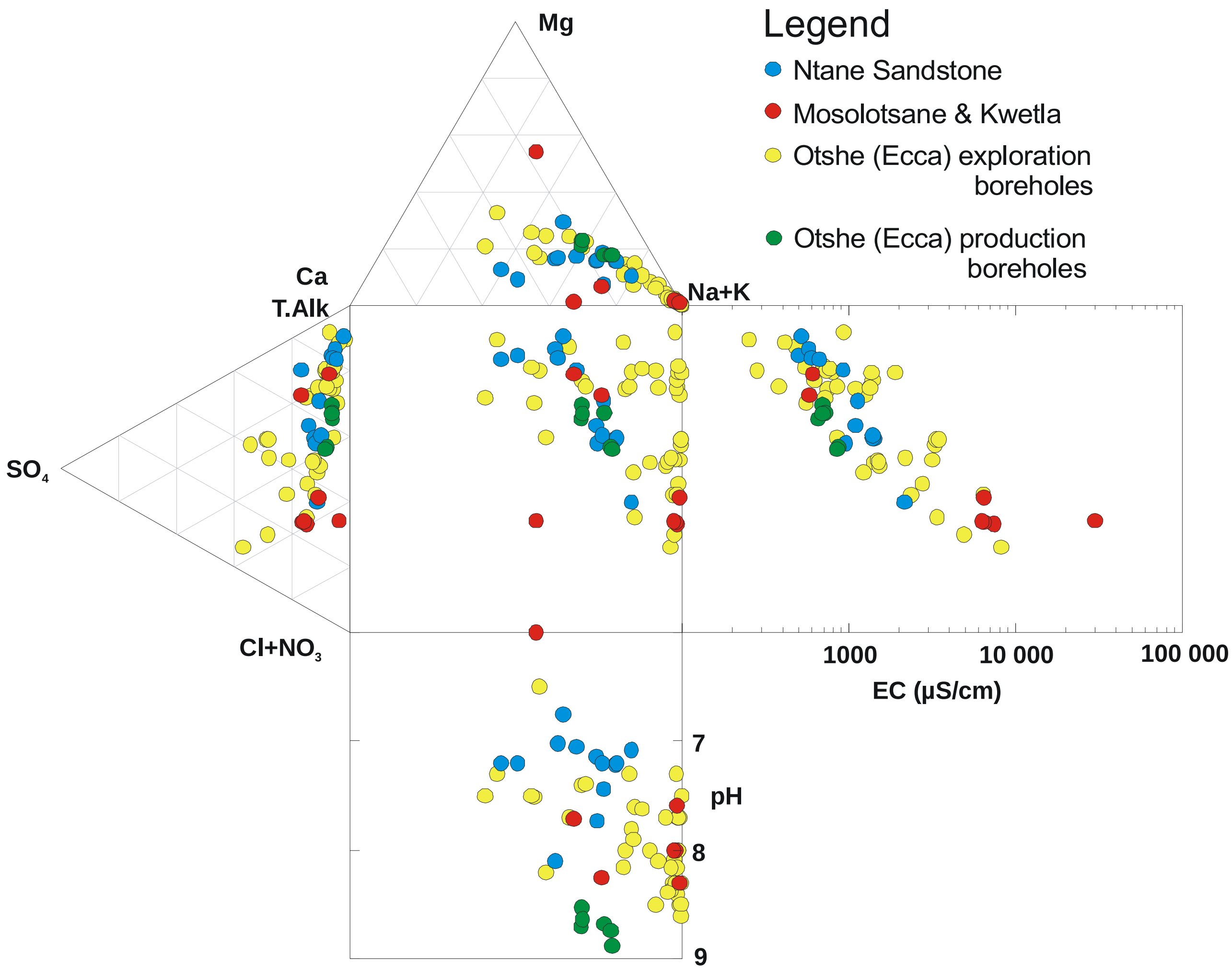

Figure 11.23 Durov Diagram All Boreholes

12 RECHARGE EVALUATION

Recharge in the project area (even if it occurs) is a difficult parameter to investigate, since it is highly variable both in time and space and is poorly quantified. This is largely due to limited data, particularly long term time series groundwater levels in this large, trans-boundary groundwater basin and to the lack of perception on the appropriate mechanism.

Previous recharge studies in the project area were confined to the Matlho-a-Phuduhudu Block, which includes the Hunhukwe/Lokalane Project (WCS, 2001), and the MSc theses of Chilume (2001) and Rahube (2003) who mainly used the data collected during the Hunhukwe/Lokalane. The methods used to estimate recharge in these studies included hydrograph analysis, radioactive and stable isotope studies, and the chloride mass balance together with numerical groundwater modelling. A common conclusion from all the recharge studies in and around the area is that, recharge is normally extremely low (0.01 to 0.4 mm/yr) with significant recharge occurring only during rare major rainfall events like the 2000 and the 2005 rainy season.

In Namibia, recharge rates for Ecca aquifers of 0 to 0.85 mm/yr were estimated for average rainfall years and up to 18 mm/yr during the high rainfall event in 2000 (JICA, 2002).

12.1 OVERVIEW OF RECHARGE ESTIMATES IN THE PROJECT AREA

12.1.1 CHLORIDE MASS BALANCE (CMB)

This method was first used by Erikson and Kunakasem (1969). Chloride concentrations in groundwater reflect the degree to which chloride in precipitation is concentrated by evaporation. The input of chloride from precipitation and from dry deposition can be equated to the mass of chloride in groundwater. This concept provides a recharge calculation method that is applicable in those cases where chloride is conservative in the hydrogeologic systems and the mass of chloride lost by surface runoff, adsorption or reaction with mineral phases is considered insignificant. Knowing the total amount of chloride deposited annually (from precipitation and dry deposition), it is possible to calculate the amount of annual recharge to an aquifer. Wood and Sanford (1995) calculate the groundwater recharge flux, R, from the equation:

$$R = T_D/Cl_{gw} = PCl_{wd}/Cl_{gw} \qquad \text{equation (A)}$$

where:

R = groundwater recharge flux (mm/a),
T_D = total annual chloride deposition rate (mg/m^2/a)
Cl_{gw} = chloride concentration in groundwater (mg/L),
P = precipitation (mm/a) and
Cl_{wd} = mean chloride content in precipitation (wet and dry deposition) (mg/L)

The chloride mass balance method was used extensively in Botswana during the GRES projects. Gieske (1992) and Selaolo (1998) produced chloride deposition maps of the country based on a limited number of rainfall collectors. It must be pointed out that the CMB method only provides an estimate of the micropore component of the total recharge. Macropore recharge, throughoutcrops and direct river recharge, will not be subject to evaporation losses and not show up by the CMB method. This is however hardly likely in the present project area due to the extensive Kalahari sand cover.

There are two ways of determining the parameter Cl_{wd} (chloride concentration of soil below the root zone or in groundwater). One method is to analyse the chloride content in soil moisture with depth. In general, chloride increases in soils with depth due to water removal by trees and by evaporation directly from the soil. From the depth at which the soil moisture is beyond the reach of trees, its chloride content will remain constant (Gieske 1992). In arid areas, the profile is frequently more complex, since many rainstorms do not penetrate deep into the soil cover (Gieske 1992, Wrabel 1999). The stable portion of chloride profile represents 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 groundwater can be assumed to be unaffected by leaching of aquifer material. Sampling at the water table is ideal. In many cases the chloride content of groundwater within a locality is quite variable and some average value needs to be estimated. One way is to calculate the harmonic mean of the chloride contents of all the boreholes in the suitable area to calculate an average Cl_{gw} to use in the calculation. The equivalent method is to calculate recharge separately for each borehole and use the arithmetical mean to estimate the average of the area.

In the Matlho-a-Phuduhudu Block, recharge estimates using the chloride mass balance method ranged between 0.2 and 15 mm per year (WCS, 2001) which was based on the variable chloride content of the groundwater samples selected for calculation. This was based on Cl_{wd} = 300mg/m^2/a. Later evaluations by Chilume (2001) and Rahube (2003) yielded recharge values in the same range In the Ncojane Block (Ncojane and Kule Villages), values of between 2.3 and 8.8 mm/yr were earlier derived (WRC, 1998), based on the presence of more low-level chloride abundances there.

The variable results from these studies highlight the problems inherent to this method. Firstly, in order to use this method, the chloride deposition rate (T_d in mg/m^2/yr), has to be known. The second problem with this method is the fundamental assumption that chloride is a conservative ion once it reaches the groundwater system. Chemistry data from the area indicate that this is not the case in some parts of the project area. Calculation of acceptable recharge rates based on the groundwater chloride content **does not prove** that recharge is actually occurring. The calculation merely indicates the micropore recharge rate if the vadose zone recharge were to be taking place over the presumed time scale.

12.1.2 Stable Isotopes (Deuterium and ^{18}O)

Allison *et al*. (1984) developed an empirical method of estimating groundwater recharge from precipitation in semi-arid to arid regions in Australia with rainfall varying from 100 to 710 mm/yr and recharge rates of 1 to 140 mm/yr, and where a uniform sandy, unsaturated cover is usually present.

Under these conditions, it was observed that ^{18}O-D (deuterium) analyses of groundwater plot below but parallel to the local meteoric water line. This is interpreted to be 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 water 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.

For a uniform soil, it has been shown empirically that the enrichment in ^{18}O and deuterium is related to the recharge by the following equation (Allison et al, 1984):

$$\Delta\delta D = \frac{C}{\sqrt{R}} \qquad \text{equation (B)}$$

where:

$\Delta\delta D$ is the displacement of δD
C is 22 (constant)
R is mean annual recharge mm/a

Recharge values estimated in this manner are generally more accurate in areas with low recharge, typically less than 10 mm/yr (Selaolo, 1998). The assumption of this method is that recharge occurs in un-vegetated (barren) soils. Nevertheless this method appears to give acceptable results in Botswana (Selaolo, 1998). This method also excludes macro-pore recharge and the effects of soil moisture withdrawal by trees and therefore provides a minimum recharge estimate for the appropriate timescale (decades to centuries).

The method requires that a local meteoric rainfall line (^{18}O-D relation) be available. In arid regions this requires quite a few years of samples in order to be certain that the data set is representative of the actual rainfall that is recharging. Groundwater samples that are to be used for this comparison need to be obtained from those parts of the aquifer that are likely to be recharge regions (up gradient of the flow path, low chloride, high ^{14}C, thin sand cover). In that respect the requirements are similar to that of the chloride method.

12.1.3 TRITIUM AND RADIOCARBON

The presence of tritium (^3H) and radiocarbon (^{14}C) above about 80 pmc, are both indicative of recent (post 1960AD) recharge. In a qualitative sense they are therefore recharge indicators and are frequently used as such. In low-flow situations where reliable samples can be obtained from well-defined depths, ^{14}C and tritium profiles can indicate vertical flow rates which can be equated with recharge rates. This is however not applicable in the present study area where the water table is quite deep and a large amount of the recent recharge, if such exists, is contained in the unsaturated zone.

In cases where the water flow pattern is understood, a simplified application of ^{14}C interpretation can be made. The mean residence time (MRT) of water in the aquifer can be calculated from (Gieske 1995):

$$MRT = 8267 * \ln(A_o/A) \qquad \text{equation (D)}$$

valid for a confined aquifer, or

$$MRT=8267/(A_o/A - 1) \qquad \text{equation(E)}$$

valid for an unconfined aquifer
where A_0 is the initial 14C content of the water, and
A is the measured 14C content of the water

MRT of the water can then be used to derive a long-term recharge quantity from:

$$R = pH/MRT \qquad \text{equation (F)}$$

where p = total porosity of the aquifer, and
H = depth of the saturated water column of the aquifer.

Rahube (2003) has used this method to calculate recharge values of water in the Lokalane/Ncojane basin and produced recharge values of 0.04 to 0.2 for the Ecca and 0.6 to 2.5 for the Ntane. It is however not clear what values for p and H were used and whether the water quantities in the unsaturated zone were taken into account. The advantage of the method is that it handles the long-term recharge and encompasses the total recharge over the time span of the MRT. The disadvantage is that it includes a number of assumptions which are difficult to test in these large study areas.

12.2 RECHARGE EVALUATION FROM PROJECT DATA

12.2.1 GROUNDWATER NUMERICAL MODELLING

In order to estimate recharge values from the numerical groundwater model, it was assumed that the aquifer transmissivity is better known than the recharge. Recharge values required to produce the observed water levels were then calibrated with the numerical model. Recharge values obtained for the Ecca aquifer based on modelling ranged between 0.15 mm/yr to 0.63 mm/.

The value of recharge obtained through numerical modelling is uncertain because it depends on aquifer transmissivities used. However the estimated recharge values are considered good as lower bound values. An estimate of was obtained can be obtained from the head variations after rainfall events. For example, water level rise of 150 mm to 250 mm was observed between November 2005 and February 2006 (Piezometers BH6342 and BH10220). With a storage coefficient of about 0.01 this would mean that there was a recharge of 1.5 to 2.5 mm over a time frame of about 4 months or a recharge for the whole year of 0.5 to 0.8 mm/yr if no further recharge occurred. The interval spanned by these values includes the calibrated estimate of recharge of 0.63 mm/yr obtained in zone 2 (where the two piezometers lie)

12.2.2 RAINWATER SAMPLING

The deuterium-offset and the CMB methods both require long-term chemistry and isotope data of rainfall from localities in or close to the study area. The earlier work did not provide much rainfall data that were thought to be of value for the present project. The sample network of rainfall collectors that were used in the GRES projects (Gieske 1992, Selaolo 1998) has a sparse coverage of the western part of the country: Only the two year (1988/90) data from Tshane can potentially be applicable to this project. Sampling of rainfall for ^{18}O, D and Cl determination was therefore included in the Matsheng project to fill this data gap.

Five pairs of cumulative rain collectors were set up. Cumulative rain collectors are fairly simple devices that can be set up unattended for a full rainy season and yield suitable representative rainfall samples. The samplers were deployed at five localities; at the same sites as the recording rain gauges that were deployed for the project (**Figure 12.1**). The samplers were supplied by the CSIR and consist of 1 metre long PVC tubes into which the rainfall is collected while it is covered with oil to prevent evaporation. The oil layer ensures that the samples that are retrieved in this way are a representation of the cumulative rainfall during the sampling period (Weaver & Talma 2004) suitable for chemical and isotope determination. When these samplers are set up for long enough periods, then the dry deposition ends up in the sample as well and the water sample therefore represents the total salt deposition for that period. Pairs of samplers were set up in order to identify contamination of the samples. Rainwater samples were collected for two periods that covered the period February 2005 to February 2006.

Table 12.1 Analysis Results for Rainwater samples

Locality	Rainfall amount	Chloride	Nitrate	Phosphate	Sulphate	$\delta^{18}O$	δD	Cl input
	mm	mg/l	mg/l (as NO3)	mg/l (as PO4)	mg/l (as SO4)	‰SMOW	‰SMOW	mg/m^2
Period: February to June 2005								
Ukwi primary school	155	1.12	<0.05	<0.05	2.64	-1.7	-1	173
Ukwi west rain gauge	232	0.38	<0.05	<0.05	1.14	-3.0	-10	88
Ncaang primary school	147	0.46	<0.05	0.16	1.44	-1.4	2	68
Ncojane ranches	221	0.73	3.52*	<0.05	2.01	-1.6	-1	163
Ncojane CJSS	126	0.87	<0.05	<0.05	2.06	-1.4	-2	110
Period: June 2005 to February 2006								
Ukwi primary school	298	0.45	0.95	0.23	1.02	-8.0	-51	135
Ukwi west rain gauge	512	1.70*	0.72	0.22	0.93	-6.5	-41	872*
Ncaang primary school	131**	0.32	0.82	0.21	1.03	-6.5	-37	42**
Ncojane ranches	741	0.25	0.70	0.24	1.06	-6.3	-39	199
Ncojane CJSS	502	0.21	1.11	0.15	0.76	-6.2	-38	105

** contaminated samples*

*** Recorder not working for period Dec 05 to Feb 2006, rainfall data shown is for October & November 05*

The (short) winter samples show a fairly clear consistent chemical content. The usual contamination indicators (P and N) are generally low and the chloride values of the pairs are consistent. The summer samples have lower Cl but are more contaminated. Contaminated analyses were ignored and data from the remaining data pairs averaged to obtain acceptable chemical contents for each period (**Table 12.1**). The resulting chloride levels of rainfall range between 0.21 and 1.12 mg/L with lower values during the rainy season (**Table 12.1**). The chloride contents from the five stations showed acceptable patterns for each season when compared with the rainfall (**Figure 12.2**). One can see the dilution effect of concentration by increased rainfall and the higher concentrations during the drier seasons. This relation was used to interpolate one contaminated Cl. These Cl values are consistent with other values obtained throughout Botswana (Gieske 1992) and Namibia (Wrabel 1999) but may vary from year to year (Selaolo 1998). Chloride contents <1 mg/L were found by Wrabel (1999) in Namibia generally in the later part of summer. On that basis the chloride values presented here are likely to be minimum values and acceptable for processing.

Table 12.2 Chloride deposition details for the period Feb 2005 - Feb 2006

Site	Rainfall amount mm	Total Cl deposition $mg/m^2/y$	Mean rainfall chloride mg/L	^{18}O input ‰SMOW	D input ‰SMOW
Ukwi primary school	453	308	0.68	-5.9	-34
Ukwi west rain gauge	744	237	0.32	-5.4	-31
Ncaang primary school	447*	164	0.37	-4.8	-25
Ncojane ranches	962	362	0.38	-5.2	-30
Ncojane CJSS	628	214	0.34	-5.2	-31
Average	**647**	**257 s,d. =87**	**0.42**	**-5.3**	**-30**

**447* estimated rainfall includes data gap between Dec 2005 and February 2006

The chloride depositions for the five stations represent a complete calendar year and the average annual chloride deposition rate calculated for the five stations of 257 $mg/m^2/yr$ (**Table 12.2**) is comparable with annual data obtained by from studies. A value of 300$mg/m^2/yr$ was earlier used for the Lokalane area (WCS 2001) based on contour maps by Selaolo (1998). The 1988/90 value obtained from Tshane (302 $mg/m^2/yr$) fits in with this pattern and compares quite favourably; given that it is known that such values can vary 20%-30% from year to year (Gieske 1992) and 33% within the present study area.

^{18}O and deuterium for the first low rainfall are high (more positive) (**Table 12.1**). Those from the wetter second period, in contrast, show significantly lower ^{18}O and deuterium content (**Figure 12.3**). The local meteoric water line (LMWL) for these two seasons was calculated from the regression through all the analyses and result in the general relation:

$$\delta D = 7.86 * \delta^{18}O + 11.7 \text{‰} \qquad \text{equation(C)}$$

The slope of this regression line (7.86) is quite close to the global meteoric water line (slope 8.0, Figure B) that was established for coastal stations worldwide (Gat 2005). These are all good samples, since they cluster close together and represent long-term (many months) average rainfall. To what extent this one year's data is representative of a long-term mean, remains open. The two samples that were analysed during the Lokalane project in 2000 (WCS 2001) are merely single storm samples and therefore less representative (**Figure 12.3**).

Selaolo (1998) has given a summary of the LMWL's analysed at various stations and years throughout Botswana and shown that most of the slope values for local rainfall data sets range between 5.6 and 7.5. This makes the present data set with its slope of nearly 8 quite exceptional. The reason must be sought in the exceptional conditions that prevailed during the months of 2005/2006 rainfall season when total rainfalls of triple the normal rainfall were observed (962 mm for Ncojane compared to the long-term mean of 250). It is known that exceptionally high rainfalls produce anomalous stable isotope patterns (Gat 2005, EI 1997) and it is a reasonable explanation to assume that the high rainfalls during the project period prevented the rain from evaporating during and just after rainfall thereby retaining the original slope 8 in the resulting infiltrating water.

It can be argued that if recharge in the arid zone is only produced by such exceptional rain events and not by the 'regular' annual rainfall, then the isotope characteristics of these exceptional ones should be used for recharge determination by the D-off-set method and not those produced from normal years.

12.2.3 Chloride Mass Balance

As is shown by the ^{14}C data (**Table 12.4**), the Ntane sandstone which is saturated only in the eastern part, has the youngest water and represents the best examples of recent recharge. However, no new boreholes were drilled in this area during the present project and no new chemical analyses of groundwater are therefore available. The data from the previous study around Lokalane (WCS 2001) can however be used. In this study CMB calculations were made on the basis of a chloride deposition rate of 300 mg/m^2/yr (data obtained during 2005/6 at the five rainfall stations of the present project averaged at 257). Chloride concentrations from 20 boreholes (20 to 1448 mg/L) in the Ntane were used (**Figure 12.4**) and produced a range of recharge estimates between 0.2 and 15 mm/yr, with an average of 6 mm/yr. Given the limited distribution of low chloride boreholes, it seems likely that recharge is localised and that it only occurs in some areas but then at rates greater than 5mm/yr.

Effective application of the CMB recharge method requires chloride values of groundwater in the soil moisture below the root zone, or in groundwater at the water table not too far below the root zone, in order to minimize the possibility that additional sources of chloride be intercepted. The new groundwater data obtained in the present project for the Ecca (Otshe) aquifer represent deep water of great age (>11 000years, see **Table 12.4**). CMB calculation of the project groundwater vis-à-vis the present rainfall in the project area is subject to considerable doubt since:

1. the present day chloride deposition rate is unlikely to be applicable to recharge events that occurred 10 000 to 30 000 years ago when conditions were certainly much different;
2. the chloride content at the first water strikes during drilling in the Ecca (134 + metre) could well have changed during its long passage down to these levels as is suggested by the chloride variation in groundwater (**Figure 12.8**) 20 in the hydrochemistry section).

Nevertheless, such a calculation can indicate some ball-park number of recharge: where it may occur. The chloride chemistry map of the Otshe (Figure 20 of the hydrochemistry section) indicates low Cl values in the west and north-western part of the project area. The minimum chloride value of 8 mg/L (BH 3016) represents a recharge rate of 38 mm/a. The harmonic mean of all the chloride values in the Ecca (**Figure 12.4**) of 58 mg/L indicates a recharge rate of 5 mm/a. The true value of recharge, in those areas where recharge has occurred in the past would then be somewhere between 5 and 38 mm/yr.

12.2.4 Stable Isotopes (^2H and ^{18}O)

Results of stable isotope analysis for the groundwater samples obtained during the present project are shown in **Table 12.3**. Overall the stable isotope ($\delta^{13}C$, $\delta^{18}O$ and δD) data are quite similar throughout the aquifer, suggesting that no separate water bodies are involved within the subdivisions of the Ecca. Vertically the water properties are quite uniform: $\delta^{18}O$ in those boreholes where multiple water strikes were encountered is constant within ± 0.2% with no evident vertical trend. The exception is the deepest sample from BH10217 (335 m deep) taken from the Kobe aquifer, below the Otshe sandstone.

The distribution of ^{18}O in the groundwater throughout the study area tends to show more negative values in the west (**Figure 12.5**). The combination of ^{18}O and deuterium (**Figure 12.6**) gives a different pattern for the samples from the present investigation (along an evaporated line with a slope of 3.8) than for those of the 2000 project in the east (along the GMWL).

Recharge calculation by the deuterium offset method described earlier was done using the local meteoric water line established by Selaolo (1998): $\delta D = 6.7*\delta^{18}O + 8.3$ ‰. This has been established over a longer time span and the annual averages established for 2005/6 in the present study area fit the curve quite well (**Figure 12.6**).

The four available δD, $\delta^{18}O$ pairs from the Ntane data of the 2000 project (**see Figure 12.6**) yield recharge rates of 8, 10, 14 and 16 (mean 12) mm/a. The data for the Ecca are more difficult to interpret. As was the case with the CMB approach, there is the problem of using present day rainfall data to apply to groundwater that was recharged many thousands of years ago (well within the Pleistocene). It is known that the stable isotope composition of Pleistocene groundwater (and its rainfall) was certainly different from the Holocene (Stute & Talma 1996, Kulongoski & Hilton 2004).

No reliable recharge values can therefore be obtained from these old samples.

Table 12.3 Isotope Results from the present Project

Borehole	Date	Water Strike Depth/ Screen Zone Aquifer	Aquifer	Detail	$\delta^{18}O$ ‰SMOW	δD ‰SMOW	Tritium TU	^{14}C pmc	^{13}C ‰PDB	Chloride mg/L
BH 10211	24-11-05	188.89-244	SST 1/2	CRT 48hrs	-7.3	-50				59
BH 10212	11-02-06	275 .48-281.61 & 284.74-297	SST2	CRT 48hrs	-7.5	-52		2.8 ± 0.4	-13.9	98
BH 10214	10-03-06	174 & 300	Open in SST1, SST2 & Kobe	CRT 72hrs	-7.1	-50		3.7 ± 0.1	-16.3	418
BH 10215	28-01-06	211.68-247.76	SST 1/Mud 2	CRT 72hrs	-7.7	-52		<1.2	-12.8	60
BH 10216	08-11-05	134	Mud 1	Strike 1	-6.7	-49	0.0 ± 0.1			
BH 10216	08-11-05	168	Mud 1	Strike 2	-7	-48				
BH 10216	14-11-05	173	Mud 1	Strike 3	-6.7	-48				
BH 10216	16-11-05	191	Mud 2	Strike 4	-6.6	-45				
BH 10216	19-02-06	173.15 – 185.40	SST1 & Mud 2	CRT 75hrs	-7.6	-52		1.0 ± 0.1	-12.7	464
BH 10217	25-11-05	169	Mud 1	Strike 1	-7.2	-49	0.0 ± 0.1			
BH 10217	25-11-05	182	SST 1	Strike 2	-7	-48				
BH 10217	25-11-05	188	SST 1	Strike 3	-7.4	-50				
BH 10217	26-11-05	229	SST 1	Strike 4	-7.2	-49				
BH 10217	28-11-05	275	SST 2	Strike 5	-7.3	-49				
BH 10217	05-12-05	335		Strike 6	-5.6	-45				
BH 10219	03-03-06	172.94-246.43	SST 1	CRT 51hrs	-7.3	-52		1.7 ± 0.2	-14.3	102
BH 10221	03-02-06	276-299.20	SST 1	CRT 72hrs	-7.5	-52		1.1 ± 0.1	-13.5	85
BH 10222	28-11-05	274.60-286.00	SST 1/2	CRT 72hrs	-7.1	-51				103
BH 10228	05-12-05	191.00-250.90	SST 1	CRT 115hrs	-6.5	-47	0.0 ± 0.1	1.6 ± 1.5	-8.3	41
BH 10229	15-11-05	183	SST 1	Strike 1	-7	-48	0.0 ± 0.1	0.0 ± 1.5	-12.1	
BH 10229	16-11-05	198	SST 1	Strike 2	-6.8	-48	0.0 ± 0.1			
BH 10229	21-11-05	253	Mud 2	Strike 3	-6.8	-48				
BH 10229	21-11-05	266	Mud 2	Strike 4	-6.9	-49				

BH 10229	21-11-05	282	SST 2	Strike 5	-7.1	-50				
BH 10229	21-11-05	289		Strike 6	-7.2	-49				
BH 10229	10-12-05	268.02-317.00		CRT 72hrs	-7.2	-50				88
BH 10314	26-01-06	173.15-185.4 & 191.52-216	MOS/KBSST/Mud2	CRT 72hrs	-7.2	-50		<0.5	-14.0	115
BH 10315	09-02-06	248.31-279	KWMud/KBSST/SST1	CRT 72hrs	-6.7	-45		<1.8	-12.2	41
BH 10316	21-02-06	173.09-215.99	SST 1	CRT 72hrs	-6.6	-45		6.5 ± 0.1	-12.9	13

12.2.5 TRITIUM AND CARBON 14

A limited number of samples were collected for tritium and ^{14}C (radiocarbon) analysis from the newly drilled boreholes: all in the Ecca. Tritium measurements were also obtained from the first water strikes of the three boreholes 10216, 10217 and 10229 as well as a few others that could conceivably contain some recent water. In none of the samples was any tritium detected (Table 12.3). This agrees with the observation during the Lokalane project when the only three boreholes from the Ecca for which tritium was measured, all showed zero (WCS 2001).

Radiocarbon data were obtained from some of the boreholes that were drilled in the course of this project (**Table 12.3**). Most of them showed negligible ^{14}C content (<2 pmc). This quantity represents a model age in excess of 28 000 years and this low level can very well be due to contamination during sample handling. The values in the range of 2-7 pmc must indicate real quantities that correspond to model ages in the 19 000 to 30 000 year age range (**Table 12.4**). This does not necessary imply that all the water is of that age: it is also likely that this water contains a small amount of younger water added to water of a greater age.

During the Lokalane project four samples from the Ecca in the north-eastern part of the present study area showed ^{14}C contents of 4 to 14 pmc (**Figure 12.7**). These boreholes are located much closer to the Ntane where ^{14}C contents between 21 and 58 were found (**Table 12.4**). This suggests that either there is recharge to the Ecca in the north eastern part of the present study area or there is connection between the Ntane and Ecca aquifer in this area.

Carbonate addition that will reduce the ^{14}C content of groundwater has been estimated from alkalinity increases underground. The average alkalinity of water from the Ntane sandstone in this area as analysed in 2000, is 304 mg/L (WCS 2001); that of the Ecca samples of the present and 2000 project average at 405 mg/L. An average worst case scenario of dead-carbonate addition to the Ecca groundwater would therefore be an extra 33% and has been accounted for in the calculation of MRT of the groundwater in Table **12.4**. The age calculations show that the Ntane water is of Holocene age (<11 600 years) while the Ecca groundwater is Pleistocene recharge (> 11 400 years

Table 12.4 Listing of ^{14}C Data and Derived Ages for the Project Area

Borehole	Year	Depth /Screen Zone	Aquifer	^{14}C pmc	^{13}C ‰PDB	MRT years
BH 8547	2000	Unknown	Mosolotsane/Kwetla	57.6 ± 0.5	-9.5	3 200
BH 9237 WS1	2000	Unknown	Ntane	39.2 ± 0.4	-8.4	6 400
BH 9237 T.P	2000	Unknown	Ntane	28.4 ± 0.4	-9.8	9 100
BH 9297	2000	Unknown	Ntane	20.9 ± 0.4	-9.0	11 600
BH 7755	2000	Unknown	Ecca	14.2 ± 0.3	-13.4	11 400
BH 7752	2000	Unknown	Ecca	9.0 ± 0.3	-14.0	15 900
BH 10316	2006	173.1-216.0	Ecca	6.5 ± 0.1	-12.9	18 800
BH 9297	2000	Unknown	Ecca	4.1 ± 0.2	-10.4	21 700
BH 7760	2000	Unknown	Ecca	3.7 ± 0.4	-10.5	22 600
BH 10214	2006	170	Ecca	3.7 ± 0.1	-16.3	22 600
BH 10212	2006	275 .5-281.6 & 284.7-297.0	Ecca	2.8 ± 0.4	-13.9	24 900
BH 10219	2006	172.9-246.4	Ecca	1.7 ± 0.2	-14.3	29 000
BH 10228	2005	191.0-250.9	Ecca	1.6 ± 1.5	-8.3	29 500
BH 10221	2006	276.0-299.2	Ecca	1.1 ± 0.1	-13.5	32 600
BH 10216	2006	173.15 – 185.40	Ecca	1.0 ± 0.1	-12.7	33 400
BH 10315	2006	248.3-279.0	Kwetla/Ecca	<1.8	-12.2	>28 000
BH 10229	2005	183	Ecca	<1.5	-12.1	>30 000
BH 10215	2006	211.7-247.8	Ecca	<1.2	-12.8	>32 000
BH 10314	2006	173.1-185.4 & 191.5-216.0	Mosolotsane/Kwetla	<0.5	-14.0	>39 000
Mean residence time (MRT) calculations are based on an initial ^{14}C content of 85pmc for the Ntane and 56 (=85*⅔) for the Ecca samples.						

Recharge rates based on the ^{14}C content of groundwater have the advantage that they show the integrated values that are suitable for water balance calculations. This is in contrast to the rates determined by CMB and D-offset methods which describe the localised recharge rates and are insensitive to those areas where no recharge is actually occurring.

The calculations shown in Table **12.5** all use a porosity of 20% based on data from neutron porosity logging data from the current project and previous projects (WCS 2001 and JICA 2002). The thickness of the aquifer is the difference between the water level depth and bottom of the aquifer The results are presented for both the confined and unconfined flow models. Since the aquifers in the study area are most likely a combination of these types one can set the acceptable range of recharge values by this method somewhere between the two models.

The data show that only a single Ntane borehole (BH 8547) reflects a high recharge (5-6 mm/yr). All of the other boreholes listed in Table 12.6 show recharge values from 1.5 mm/yr to nil. This range seems independent of the actual ^{14}C content (0 – 21 pmc) and indicates a good internal consistency. Even the samples with ^{14}C content less than 2 pmc fit the pattern.

Table 12.5 Calculation of Recharge from the ^{14}C Content of Groundwater

Sample	^{14}C pmc	Porosity %	Thickness m	Recharge mm/yr		Aquifer type
				confined model	unconfined model	
BH 8547	57.6	20%	100	6.2	5.1	NTANE
BH 9297	20.9	20%	83	1.4	0.7	NTANE
BH 7755	14.2	20%	100	1.4	0.5	ECCA
BH 7752	9	20%	100	1.1	0.3	ECCA
BH10316	6.5	20%	105.4	1.0	0.2	Ecca
BH10214	3.7	20%	149.85	1.2	0.2	Ecca & Kobe
BH10212	2.8	20%	165.74	1.2	0.1	Ecca
BH10315	1.8	20%	168.7	1.1	0.1	Ecca
BH10219	1.7	20%	204.6	1.3	0.1	Ecca
BH10228	1.6	20%	191.4	1.2	0.1	Ecca
BH10215	1.2	20%	128.09	0.7	0.0	Ecca
BH10221	1.1	20%	228.28	1.3	0.1	Ecca
BH10216	1	20%	125.37	0.7	0.0	E
BH10314	0.5	20%	203.74	1.0	0.0	MOS/KBSST/Mud2

12.3 CONCLUSIONS FROM ISOTOPES

- Total chloride deposition (both wet and dry precipitation) in the study area for the twelve month period from February 2005 to February 2006 for five sites ranged between 164 and 362 mg/m^2. The summer of 2005/6 was an exceptionally high rainfall season. Nevertheless the deposition rates measured for that season are comparable with the 300 mg/m^2/a determined in other years in this part of the country.
- Rainfall ^{18}O and deuterium (^2H) values for the 2005/6 rainy season (derived from cumulative rainfall collectors) are located along the Global Meteoric Water Line and fairly close to the Local water Line established for Lobatse between 1991 and 1995.

- The chemistry and isotope data of samples that were collected at different depths in Ecca boreholes during drilling, do not provide any evidence of vertical recharge.
- The oxygen-18 and deuterium content of Ecca groundwater is fairly uniform with a slight decrease towards the western part of the study area. There are no evident differences between SST1 and SST2.
- Groundwater in the Ecca within the project area represents recharge of 11 000 years and older (to beyond 30 000 years). There is no local evidence of recharge to the Ecca other than a single borehole (BH10316) with the highest ^{14}C content and the lowest chloride level. Any further search for recharge evidence should be directed towards the area with the lowest chloride levels and shallowest water table (western).
- Groundwater in the Ntane located in the north-east of the project area is of Holocene origin (age <11 000 years). Low chloride and high ^{14}C indicate that active recharge may still be taking place. The absence of tritium in the groundwater, however, implies that the bomb-tritium signal may still be located in the unsaturated zone here. Tritium and chloride profiling of the soils in this area might therefore be profitable.
- Recharge knowledge of the Ntane aquifer is based on the results of samples collected in 2000, since the present project did not sample there. The CMB and D offset methods both indicated a range of recharge values from 18 mm/yr to lower with a mean around 6 mm/yr. Both these methods indicate the recharge rate only for localised areas where recharge actually occurs.
- The recharge calculation for the Ntane using ^{14}C is based on only the two samples for which both borehole details and ^{14}C analyses are known (BH8547&9297). These yield rates of 6 and 1 mm/yr and therefore covers the range of the other methods. It is therefore likely that active recharge occurs in the Ntane, though it is low and very localised.
- In the Ecca (Otshe) the CMB method becomes less certain due to the great age of the groundwater and the likelihood of chloride uptake in the aquifer. Based on the assumption of the present chloride input, the borehole with the lowest chloride content shows a recharge of 38 mm/a and the others progressively smaller; with a mean of 5 mm/yr. As in the Ntane, this probably means that at some time localised recharge of this magnitude occurred here.
- The D-offset method of recharge determination could not be applied to the Ecca, since the small δD difference is very susceptible to the actual rain input values. It is also seems that evaporation enrichment of the Ecca groundwater has occurred some time in the past.
- The ^{14}C method of recharge determination in the Ecca (Otshe) yields fairly consistent numbers in the range of 0.7 to 1.4 mm/yr for the confined model. The absence of younger water and the hydrological observations in this aquifer indicate that the confined model is more applicable here. ^{14}C recharge calculations done in this manner yield the regional recharge (including areas of zero recharge) and can therefore be used for water balance calculations.

- Future recharge investigations should be directed to mapping the area of low chloride water, investigating its flow pattern and its isotopic content. The question of lateral inflow from the west and north needs exploration beyond the boundary of the present project. Soil moisture investigations in very selected areas may be useful.
- The great age of this water body and its low replenishment rate necessitates great caution in its future exploitation.

12.3.1 WATER LEVEL MONITORING

Water level monitoring is essential to the understanding of groundwater flow systems, evaluation of recharge, assessment of long term groundwater level trends, delineation of groundwater flow directions, evaluation of the groundwater head relationships between different aquifers (both laterally as well as vertically) and generating groundwater level data for input into numerical groundwater models. In this section water level responses in the project are discussed.

Groundwater level monitoring in the project area by WRC was initiated in November 2004 with installation of pressure transducers in existing boreholes while manual water level monitoring was started in March 2005. At the beginning of the project, most of the monitored boreholes were located in the Matlho-a-Phuduhudu Block due to the limited number of existing boreholes in the Ncojane Block. However as the project progressed and boreholes became available the monitoring network was expanded to cover the new boreholes mostly in the Ncojane Block. Responsibility for monitoring was handed over to the DWA Groundwater Monitoring Division in January 2008. Groundwater level monitoring was undertaken manually (using electric dippers) through periodic water level measurements as well as continuous monitoring using pressure transducers (**Table 12.5)**. The location of the monitored boreholes in the project area is shown in **Figure 12.1**.

Currently there are 11 functional transducers out of which 2 are monitoring the Ntane aquifer and 9 are monitoring the Ecca aquifer. DWA is advised to download data from these transducers on a regular basis and carry out the necessary maintenance like battery replacements every 6 months.

In addition to monitoring carried out by WRC, the Department of Geological Surveys (DGS) monitors boreholes in the Matlho-a-Phuduhudu Block (MAP), Okwa River Valley and the Matsheng Villages using data loggers as well as manually. Monitoring of these boreholes was initiated in September 1999 **(Table 12.6)**. There is however a problem with the data logger (diver) data obtained from DGS in that there is no continuity of the water levels after each down loading period and this data was not used for water level trend analysis.

In groundwater projects, it is important to have rainfall data for correlation with water level trends therefore during the project, five tipping bucket rain gauges were installed mainly in the Ncojane Block as shown in **Figure 12.1**. It is also strongly recommended that DWA should download these on a regular basis and carryout the necessary battery changes (once a year).

Groundwater level and rainfall data together with respective hydrographs from boreholes monitored during project are given in **Volume 2, Hydrogeological Report**. A digital copy of the water level monitoring data will also be submitted on CD to the DWA monitoring division. Results of regional groundwater level monitoring within the project area are discussed aquifer wise in the following sections.

Table 12.6 List of Project Boreholes Monitored with Transducers

BH No.	Location	Easting	Northing	Aquifer	Approx. SWL (m bgl)	Remarks
6342	Masetlheng	485971	7376597	Otshe	64.342	Transducer monitored since Dec 2004 till present date
8346	Ncojane	427458	7442545	Otshe	93.691	Transducer monitored since Jan 2005 till present date
8646	Ncojane Ranches	462698	7436099	Otshe	103.36	Transducer monitored since Dec 2004 till present date
10316	Ncojane West			Otshe	115.102	Transducer monitored since May 2006 till present date. Transducer not working since March 2007 and replaced by transducer at BH9241
9244	MAP Block	607706	7420856	Otshe	152.868	Transducer monitored since Dec 2004 till present date
9295*	Metsimantsho	503310	7439415	Otshe	132.728	Transducer monitored between Dec 2004 and Sep 2005. Transducer moved to BH10220 (monitoring).
9297	MAP Block	570320	7444043	Otshe	153.055	Transducer monitored between Nov 2004 and Feb 2006 & it was re installed on May 2006
9240*	MAP Block	608896	7449821	Ntane	134.78	Transducer monitored between March and October 2005. Transducer moved to BH10225 (monitoring).
10220	Metsimantsho	503304	7439407	Otshe	133.40	Transducer monitored since Nov 2005 till present date
9294*	MAP Block	516232	7457410	Otshe	129.365	Transducer monitored since March 2005 till May 2006 and moved to 10226
9298*	MAP Block	577042	7478359	Otshe	110.97	Transducer monitored since March 2005 till May 2006 and moved to 10317
8545*	Hunhukwe	562009	7408307	Otshe	126.8	Transducer monitored since September 2005 till May 2006 and moved to 10320
10225	MAP Block	608900	7449809	Ntane	135.36	Transducer monitored since Dec 2005 till present date
10320	MAP Block	570320	7444043	Otshe	153.02	Transducer monitored since May 2006 till present date
10226	MAP Block	570320	7444055	Ntane	147.98	Transducer monitored since May 2006 till present
10317	MAP Block	608875	7449516	Otshe	145.99	Transducer monitored since May 2006 till present date
9241*	MAP Block	542780	7460881	Ntane	136.06	Transducer monitored since November 2004 and moved to BH10316

**Transducer moved to another location*

Table 12.7 Boreholes Monitored by DGS

BH No.	Location	Easting	Northing	Aquifer	SWL (m bgl)	Remarks
7167	MAP Block	627215	7448697	Ntane	131.12	Lokalane Data Logger,
7752	MAP Block	542651	7480153	Ecca	105	Lokalane Data Logger
7826	North central	479319	7476847	Ecca	120	Lokalane Data Logger
9044	MAP Block (ADAS Station)	588027	7446659	Ntane	131.41	Lokalane Data Logger
9045	Ncojane Ranches	504756	7455359	Mosolotsane	133.3	Lokalane Data Logger
7761	Okwa Valley	525669	7493170	Ecca	105.32	Manually monitored
7763	Okwa Valley	560105	7496069	Ecca	99.2	Manually monitored
7764	Okwa Valley	560119	7496035	Ecca	98.6	Manually monitored
7768	Okwa Valley	525669	7493170	Ecca	114.33	Manually monitored
4237	Matsheng Villages	583187	7356026	Kalahari	17.8	Manually monitored
7868	Matsheng Villages	579344	7346881	Kalahari	11.52	Manually monitored
7872	Matsheng Villages	580299	7335804	Kalahari	17.1	Manually monitored
7889	Matsheng Villages	579270	7333595	Kalahari	15.55	Manually monitored

12.3.1.1 Water Level Trends in Kalahari Beds

Data is available for four boreholes completed in the Kalahari aquifer. Four of these boreholes are located in the Hukuntsi area (Matsheng villages) and are monitored by DGS. Data from these boreholes dates from 1999 to July 2005. The other Kalahari monitoring borehole is located in Ukwi (BH6326) and monitoring of this borehole commenced November 2004. The Kalahari aquifer is mostly saline and was not targeted in this project.

Two boreholes completed in Kalahari beds (Matsheng Villages) BH4237 and BH7868 recorded water level rises after the high rainfall events of the 1999/2000 rain fall season (**Figure 12.9**). The other two boreholes, BH7872 and BH7889 showed only groundwater recession despite the recorded rainfalls. After the 1999/2000 rainfall season no water level rises were observed in all the four boreholes monitoring the Kalahari Beds in the Matsheng Villages, indicating that only rainfall events with a certain magnitude actually results in groundwater recharge. The magnitude of water level rises in borehole which had response was between 0.5 and 1 m. Relatively high water levels were maintained in BH4237 and BH7868 throughout 2001 and 2002, with the recession trend only starting in 2003. The recession trends in boreholes monitoring Kalahari Beds are probably driven by evapotranspiration. The variable responses to rainfall events in a relatively small area of the Kalahari Beds aquifer indicate that recharge is heterogeneous.

Similar to Kalahari Beds aquifers in the Matsheng area, the project monitored borehole (BH6326) located near Ukwi pan did not show any response to 2004/2005 and 2005/2006 rainfall seasons (**Figure 12.10**). The water levels in this borehole are stable compared to the Matsheng boreholes indicating that there is little or no evapotranspiration in this area probably because of the highly saline groundwater in this borehole.

12.3.1.2 NTANE AQUIFER

Hydrographs of selected boreholes completed in the Ntane aquifer are given in **Figures 12.11** to **12.14.** These boreholes were selected to represent the central, northern, southern margins of the Ntane Sub- basin. In general water level trends in this aquifer are flat to declining. The magnitudes of water level fluctuation in this aquifer are very small probably because of its unconfined nature or possibly because it is the least actively recharged aquifer in the project.

12.3.1.3 ECCA (OTSHE) AQUIFER

Water levels in boreholes monitoring Ecca (Otshe) aquifer show a range of responses from stable, continuously rising and receding trends throughout the monitoring period. These trends are illustrated in hydrographs given in **Figure 12.15** to **12.18**.

BH8346 recorded continuously rising water levels since inception of monitoring in January 2005 with the water level having risen by 2.62 m by September 2007 (**Figure 12.16**). BH8646, which had a similar trend to BH8346 at the beginning of the monitoring period in December 2004, has been showing a receding to stable water level trend since December 2006. Another borehole also tapping the Ecca aquifer, BH10220 has similar response to the other two boreholes (BH8646 and BH8346) i.e. continuously rising water levels though of a smaller magnitude since November 2005 until a slightly declining to stable trend was observed from September 2007. Seasonal rises of between 0.14 to 2.62 m were recorded throughout the 3 year monitoring period (**Figure 12.18**). In terms of the hydraulic head between the two sandstone units of the Ecca, Sandstone 1 and 2, groundwater level monitoring data at a location in the Matlho-a-Phuduhudu block indicates that the head difference between the 2 sandstones is very minute with sandstone 2 having slightly higher head than sandstone 1.

Water levels for the Ecca aquifer show seasonal rises which usually occur around October to June as well as continuous rises. This could reflect that local rainfall events as well as long term regional inflow are recharging this aquifer. Some of the observed water level rises may in fact be a response to the high rainfall events of 1999/2000 season and can not be preferential recharge along fault planes or dolerite intrusions as the trend is not affected by local rainfall events.

12.3.1.4 SUMMARY OF WATER LEVEL TRENDS

Water level monitoring data indicates that the Ecca aquifer, particularly in Ncojane block is actively recharging probably through both regional inflow and local rainfall events.

Qualitatively, the magnitude of recharge responses for the Ecca (Otshe) and the Ntane aquifers are different, with the Ecca (Otshe) responses generally larger. This may relate to the confined nature of Ecca and the semi confined to unconfined nature of Ntane where for a given recharge quantum, water levels will rise less in an unconfined aquifer than in a confined aquifer. It may also reflect an actual greater amount of recharge to Ecca aquifers, which in the west tend to have thinner Kalahari overburden and is reportedly exposed in Namibia. Water level rises of 0.14 m to 2.62 were recorded throughout the monitoring period for the Ecca aquifer.

Figure 12.1 Location of Monitored Boreholes and Rain Gauges/Collectors

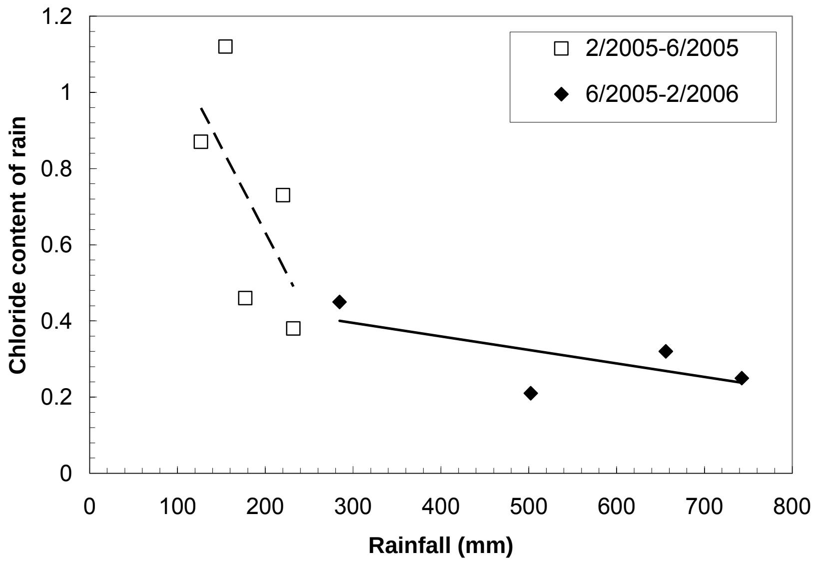

Figure 12.2 Chloride concentrations of rainfall samples collected in the cumulative rainfall samplers

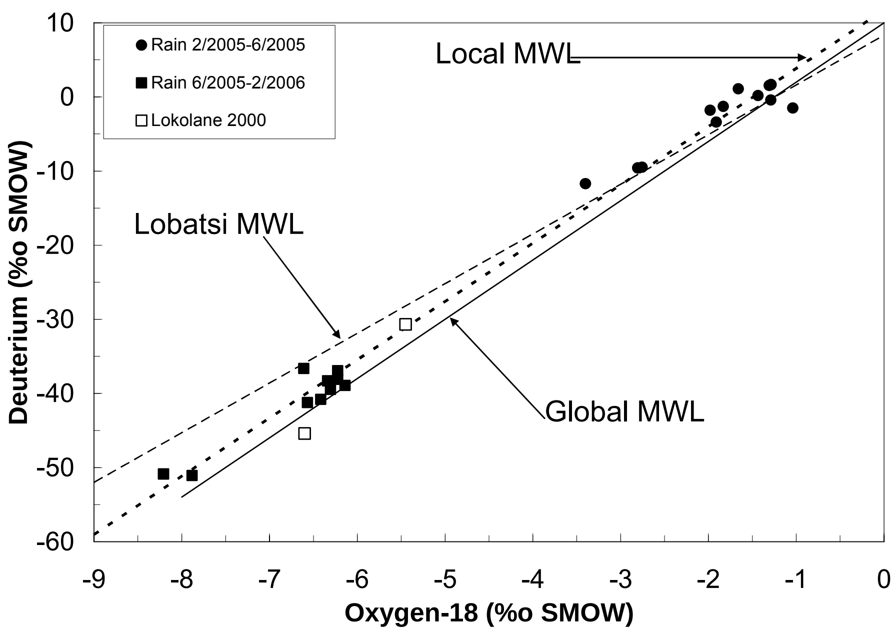

Figure 12.3 Plot of deuterium against ^{18}O of Rainwater Samples Collected During the present project[1]

[1] The local meteoric water line (based on a single high rainfall season) was calculated from these samples and compared to the well-known global meteoric water line and the Lobatse water line for 1991/5 (Selaolo 1998)

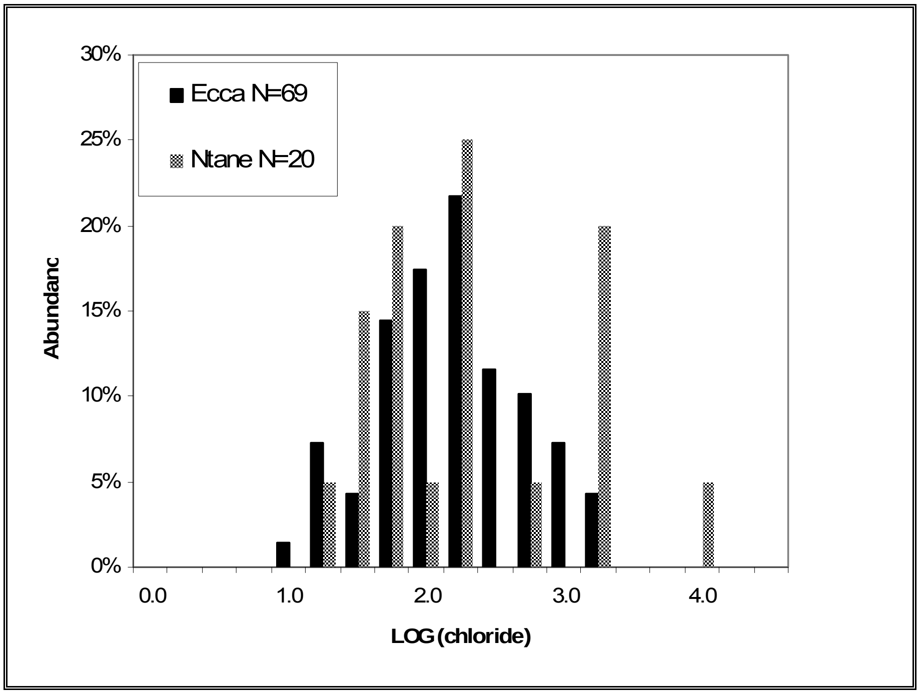

Figure 12.4 Distribution of chloride values in the two main aquifers of the project area[2]

[2] Based on data from current project and earlier work (WCS 2001)

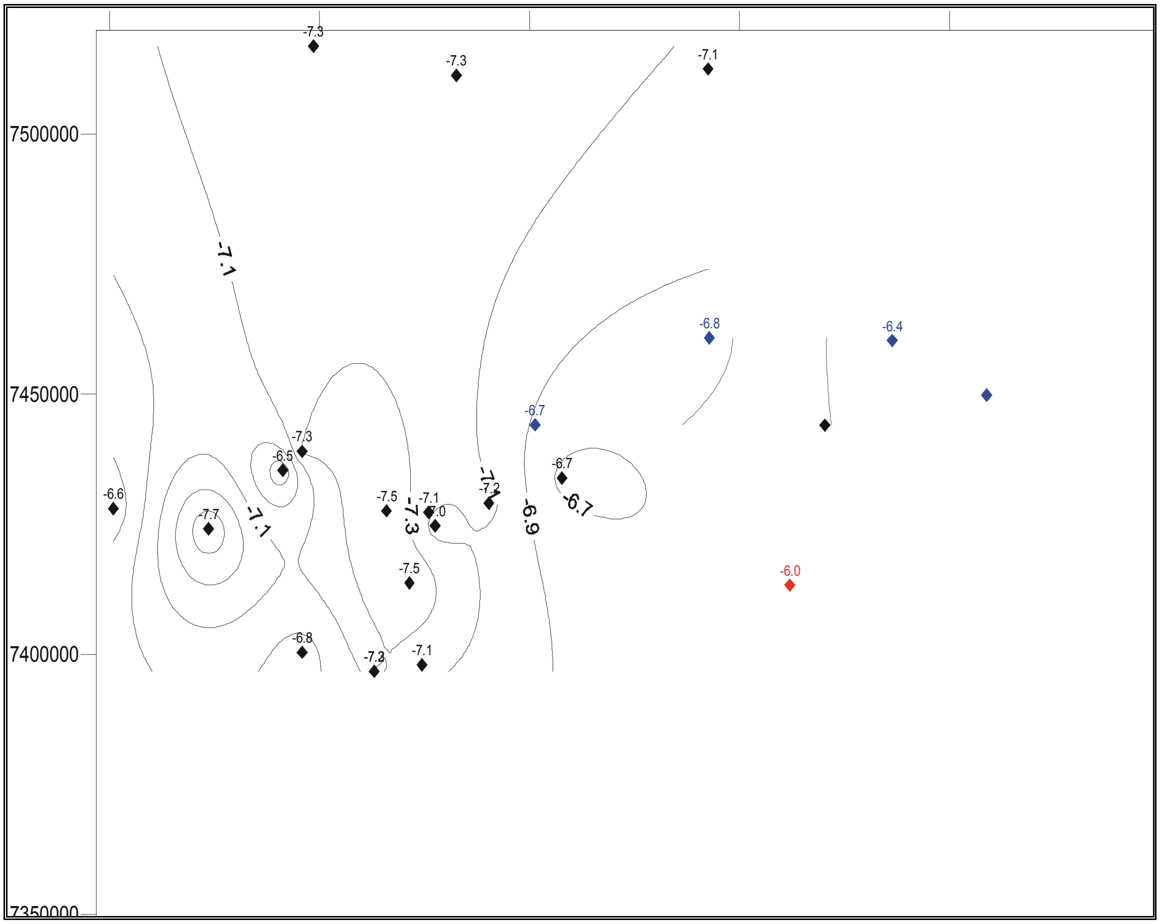

Figure 12.5 Distribution of ^{18}O in the Study Area[3]

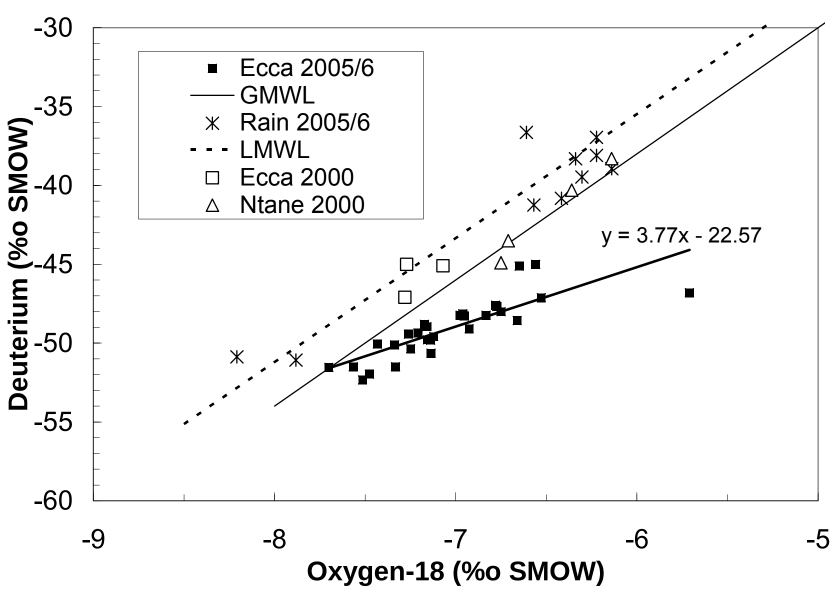

Figure 12.6 Plot of ^{18}O and deuterium in the present study area[4]

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[3] Contours Based on the 2005/6 Ecca, the Lokalane Project Samples are also included

[4] Based data from the present project and earlier work (WCS 2001).

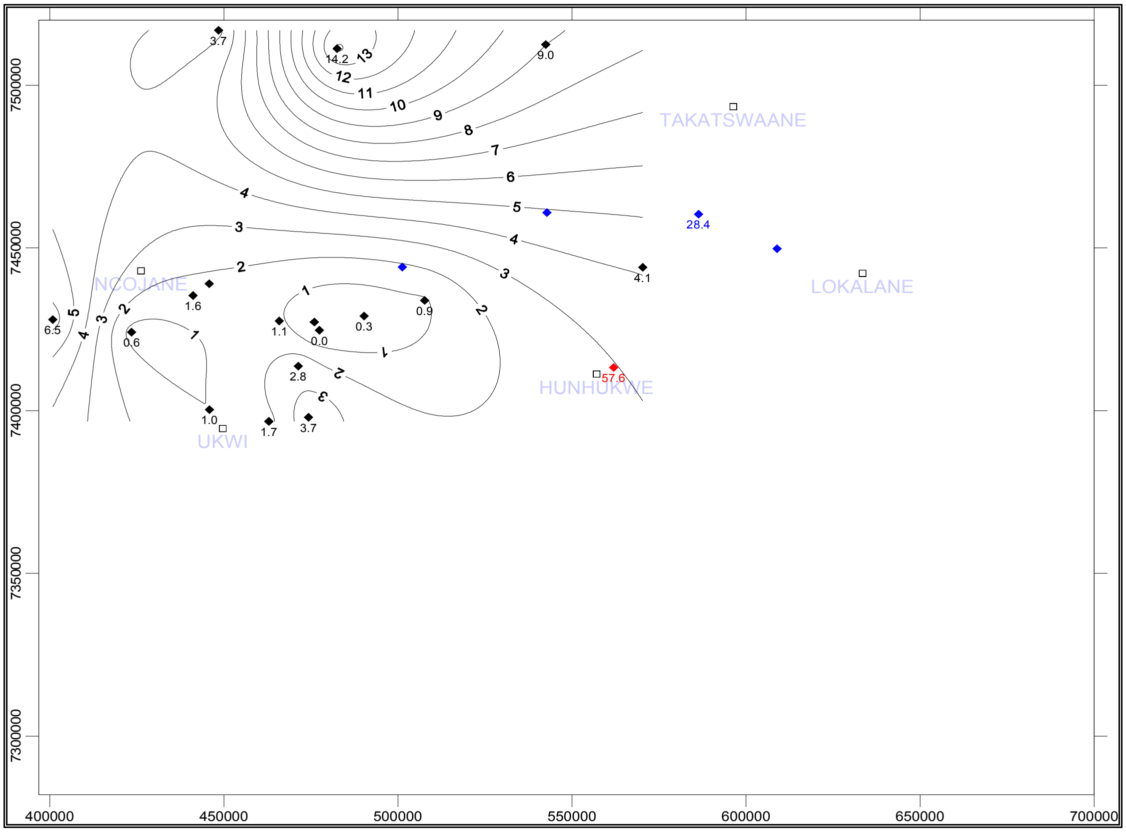


Figure 12.7 Distribution of ^{14}C content through the study area: based on the Present Project Data & WCS 2000[5]

5 All samples are indicated (Ntane & Ecca), but the contours only reflect the measurements from the Ecca aquifer

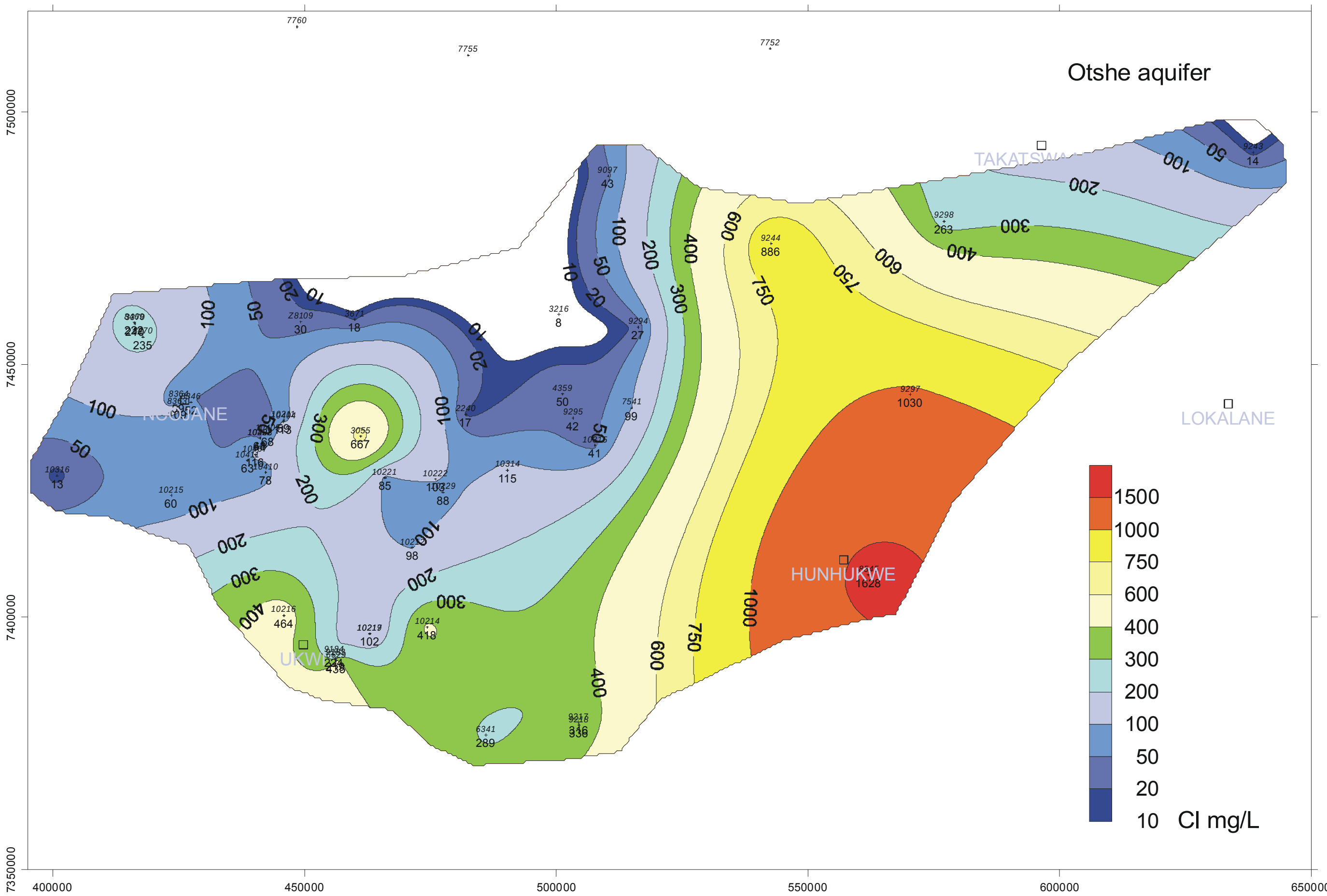


Figure 12.8 Chloride Distribution Ecca

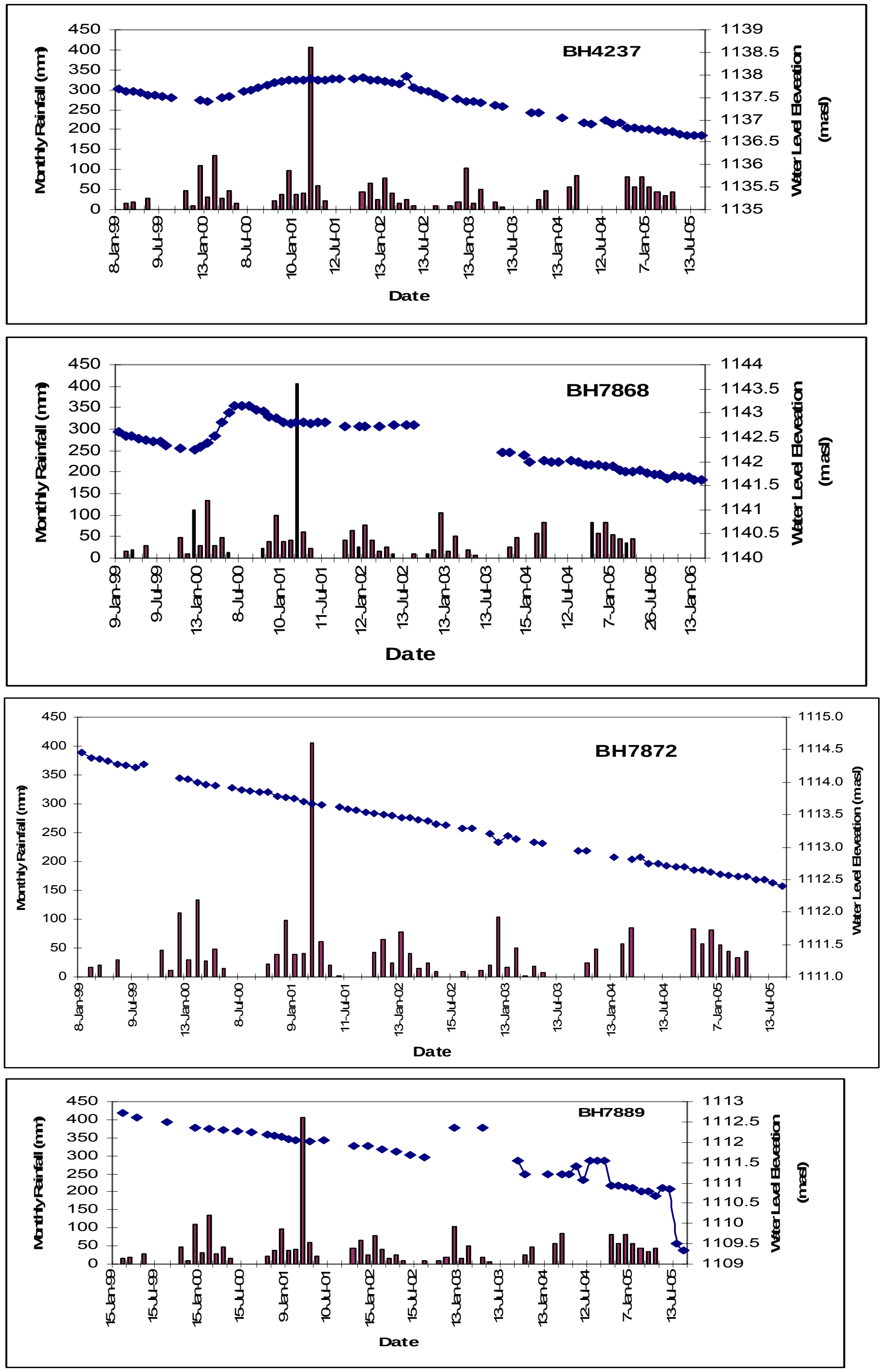


Figure 12.9 Hydrographs for Kalahari Beds aquifer (Matsheng Villages)

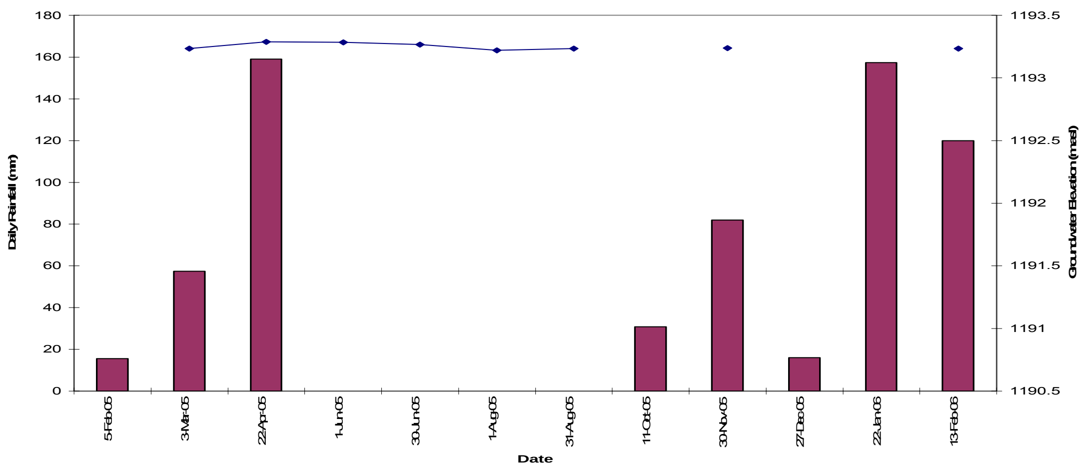


Figure 12.10 Hydrograph for Kalahari Beds aquifer in BH6326, Ukwi.

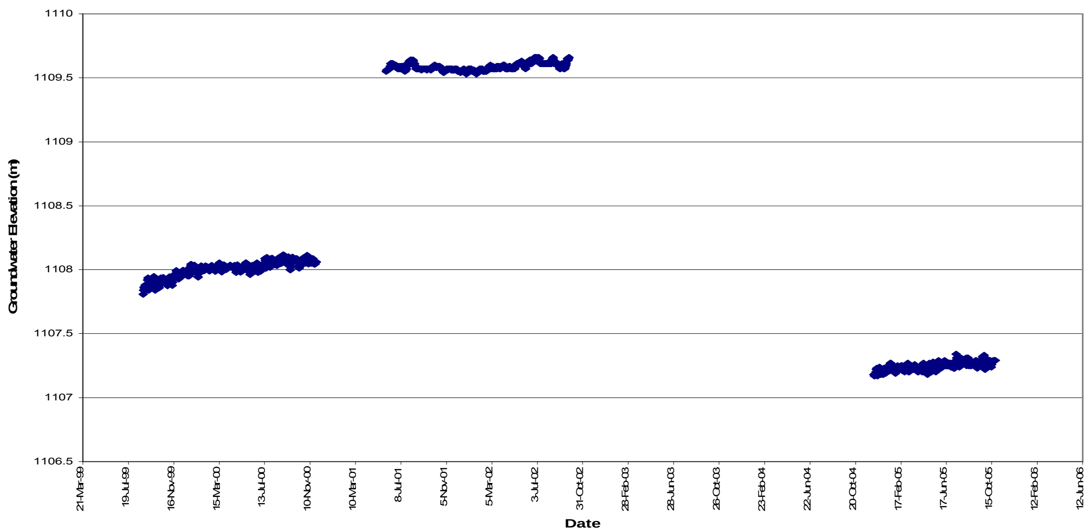
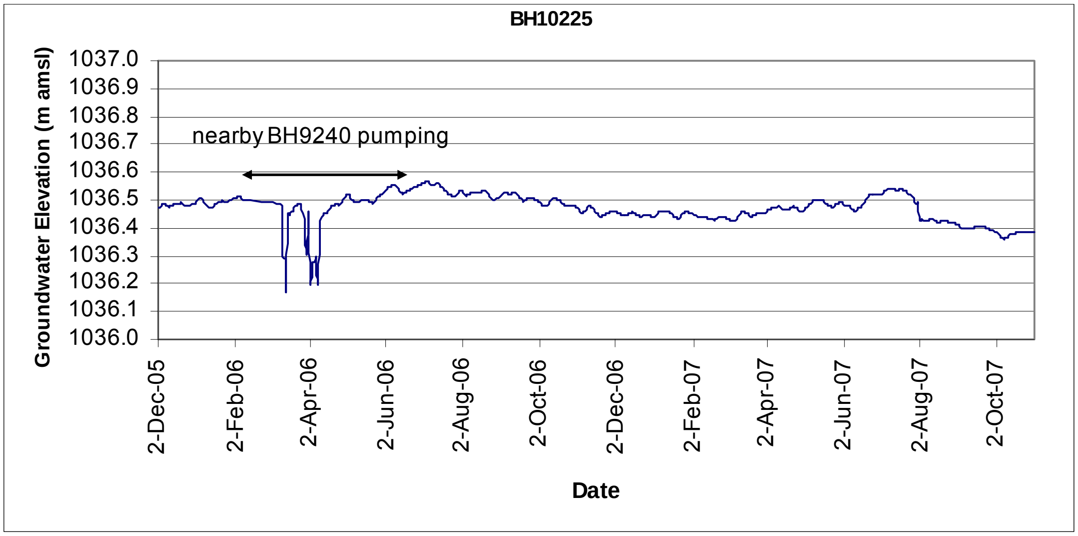


Figure 12.11 Water Level Data, BH9045 (DGS Diver Monitored), Matlho-a-Phuduhudu



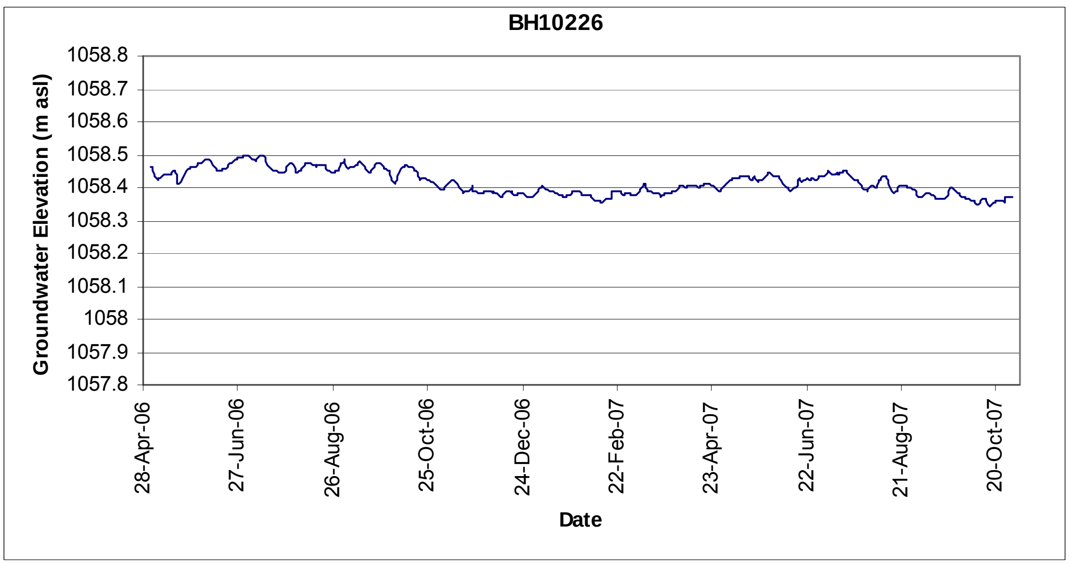
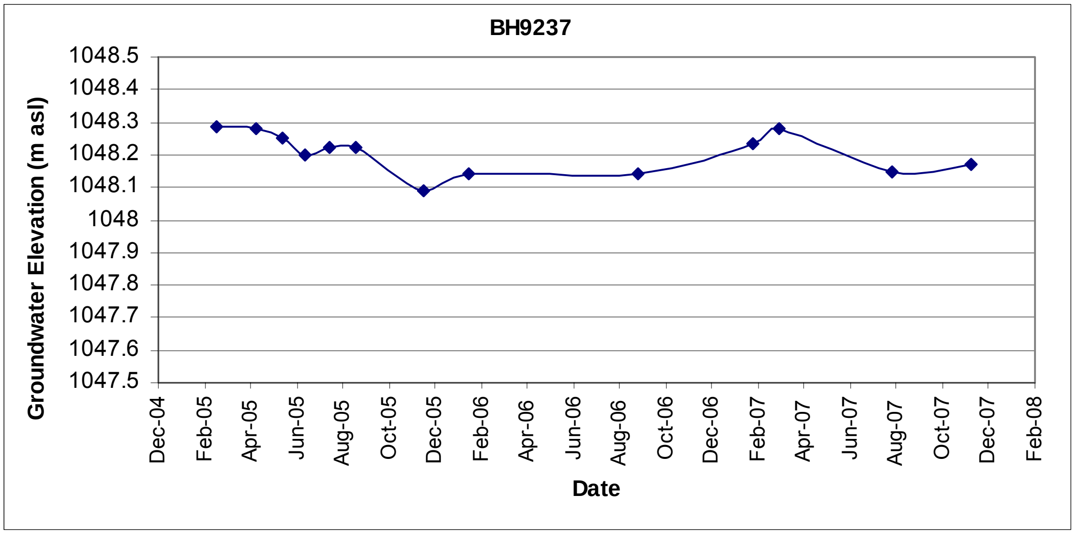
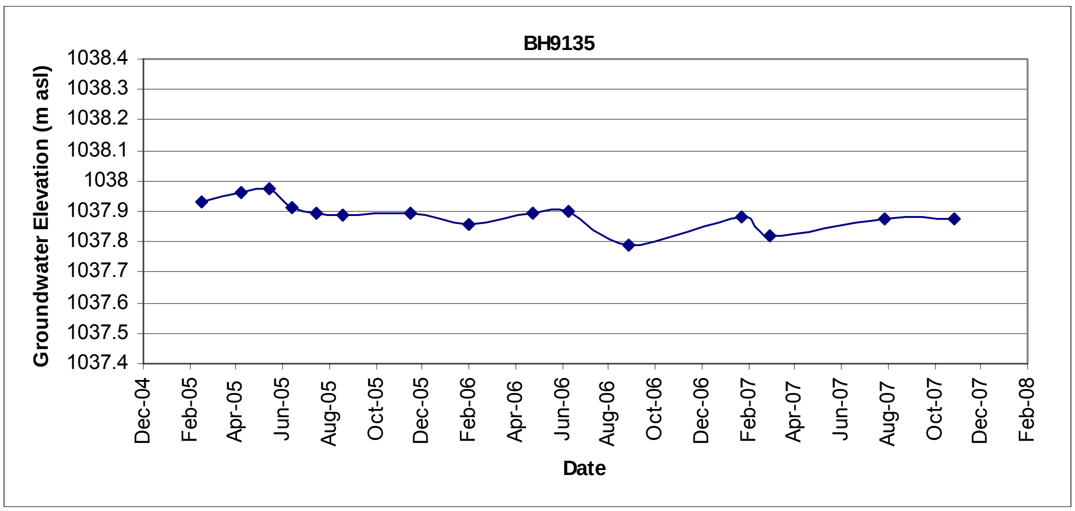


Figure 12.12 Hydrographs Central Ntane Sub-Basin, Matlho-a-Phuduhudu





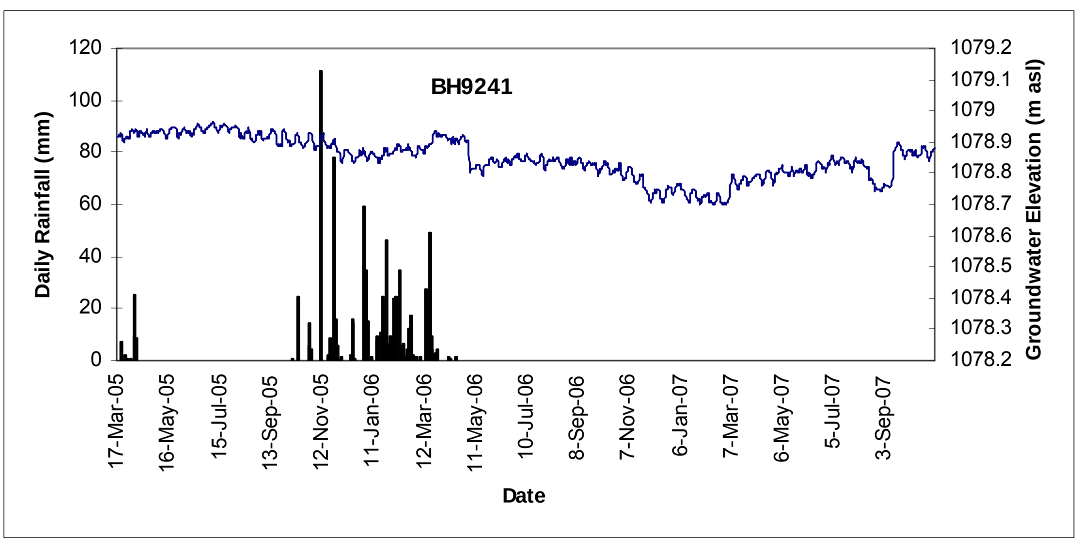
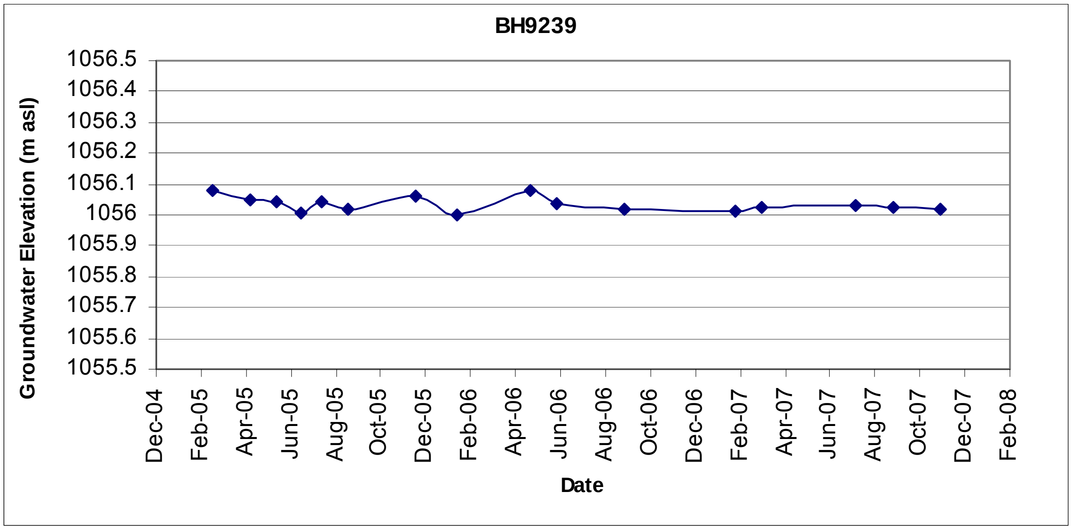
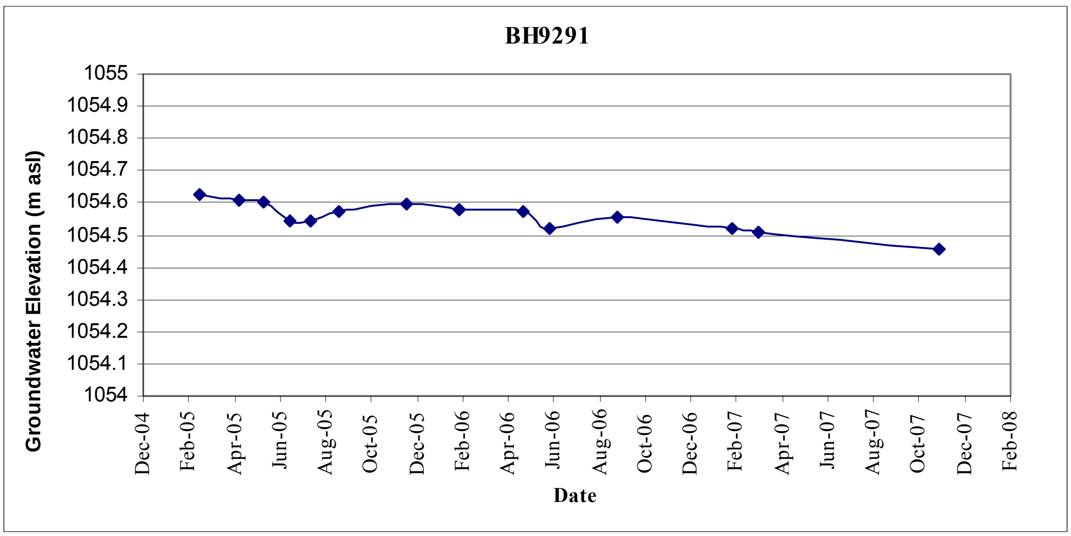


Figure 12.13 Ntane Hydrographs, Northern Margins of the Ntane Sub-Basin





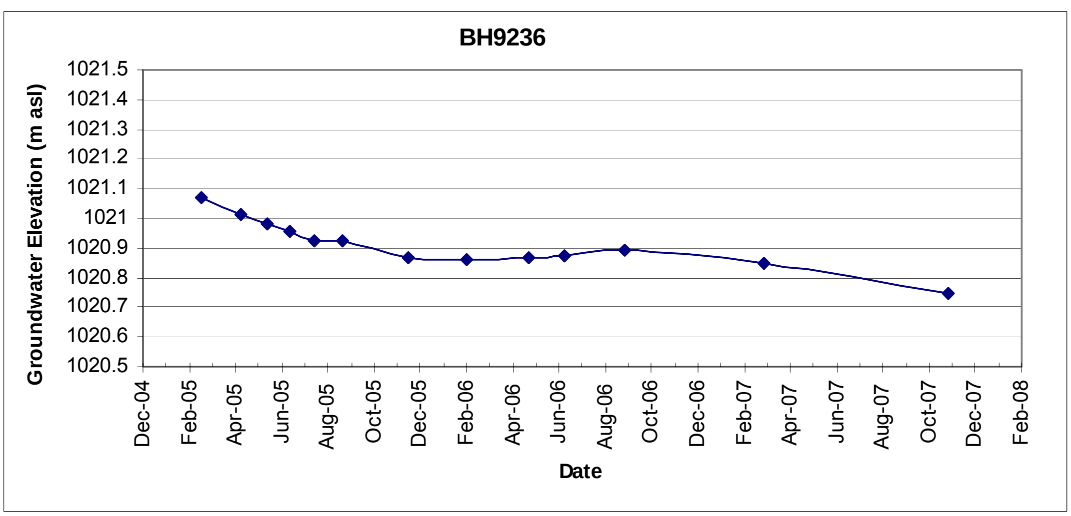


Figure 12.14 Ntane Hydrographs, Southern Margins of the Ntane Sub-Basin

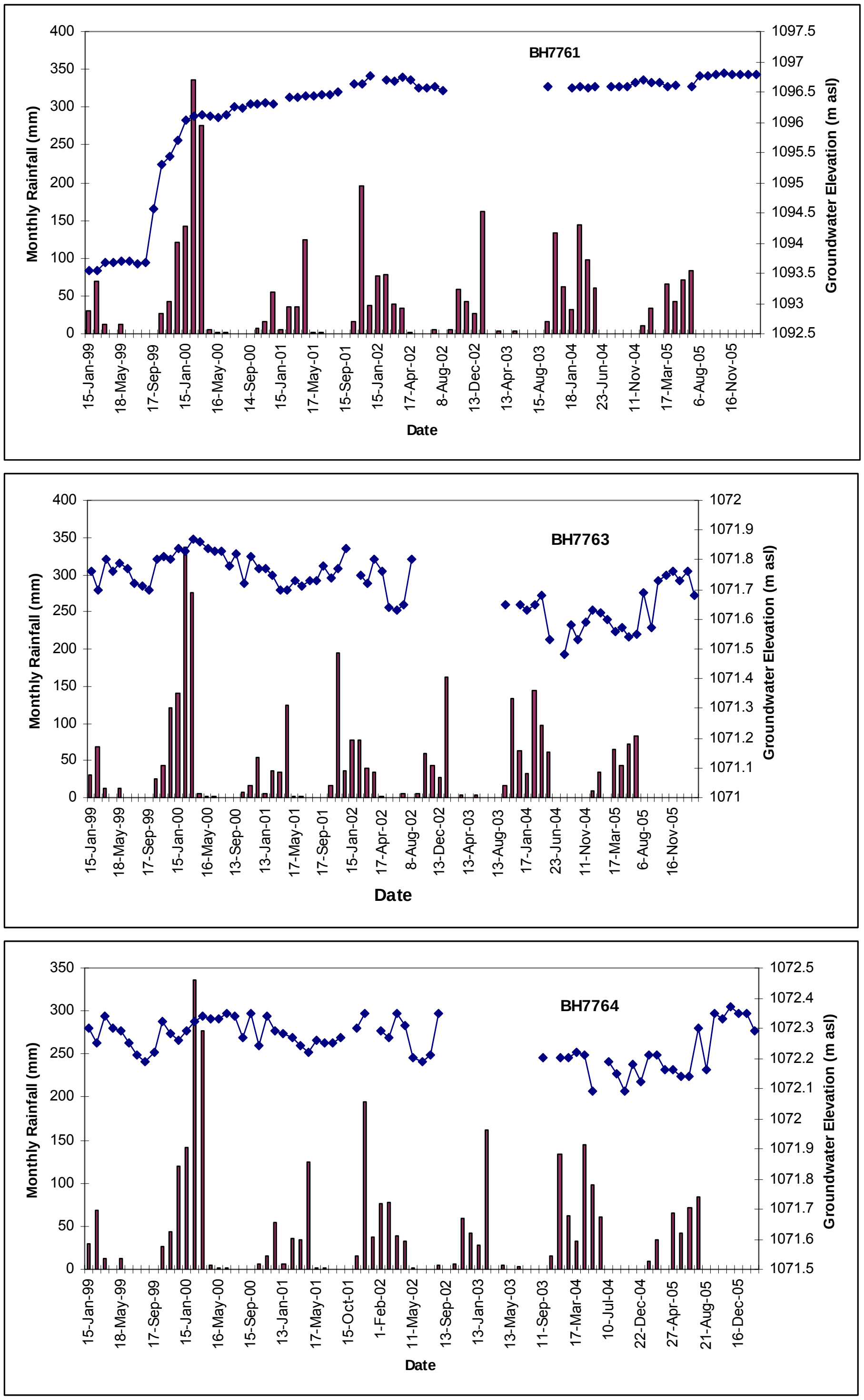


Figure 12.15 Hydrographs of the Otshe aquifer (Okwa Valley)

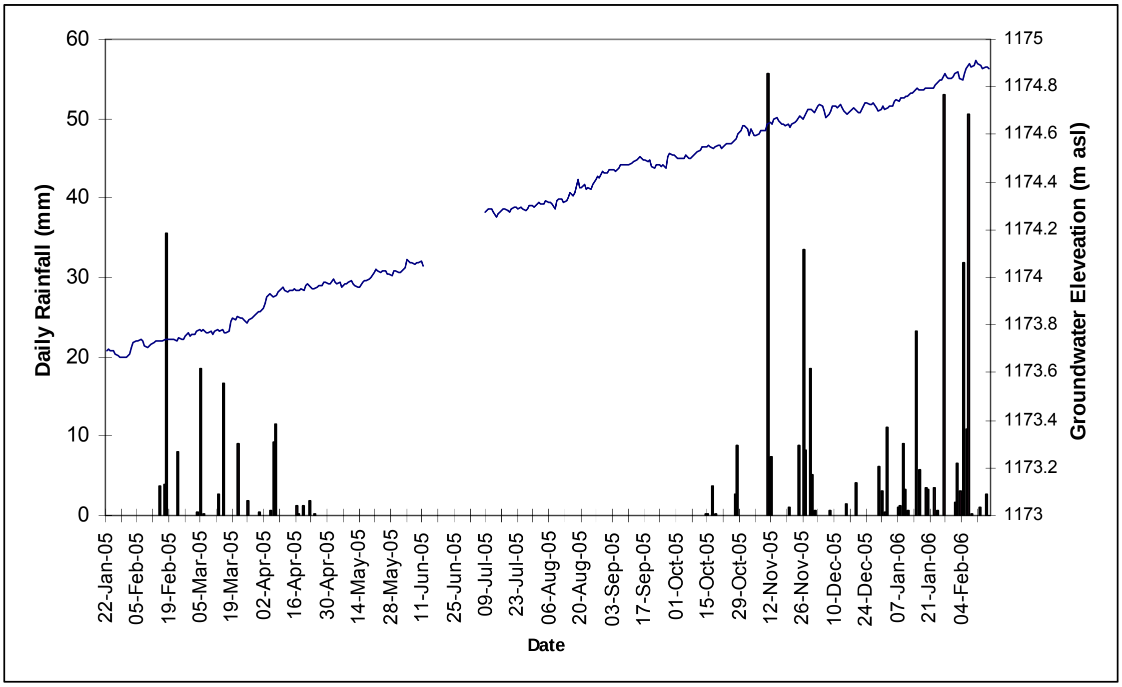


Figure 12.16 Continuously Rising Water Levels Otshe aquifer, BH8346 (Ncojane)

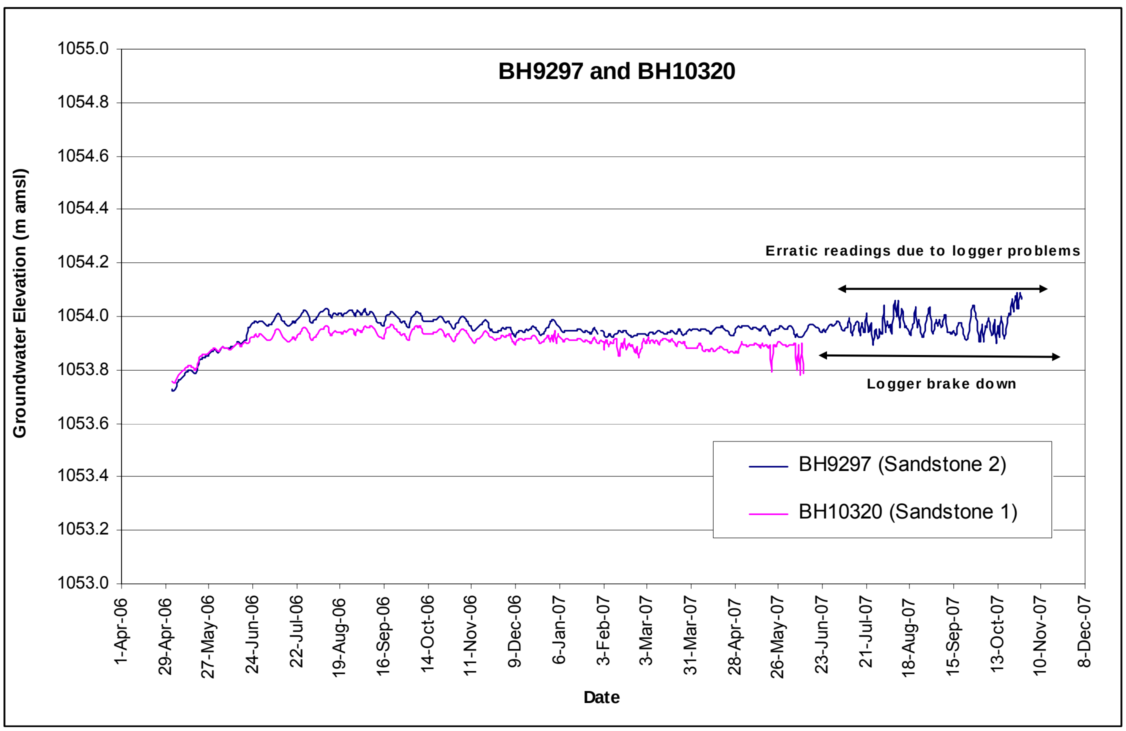


Figure 12.17 Hydrograph of the Otshe Sandstones 1 and 2 aquifer (Matlho-a-Phuduhudu)

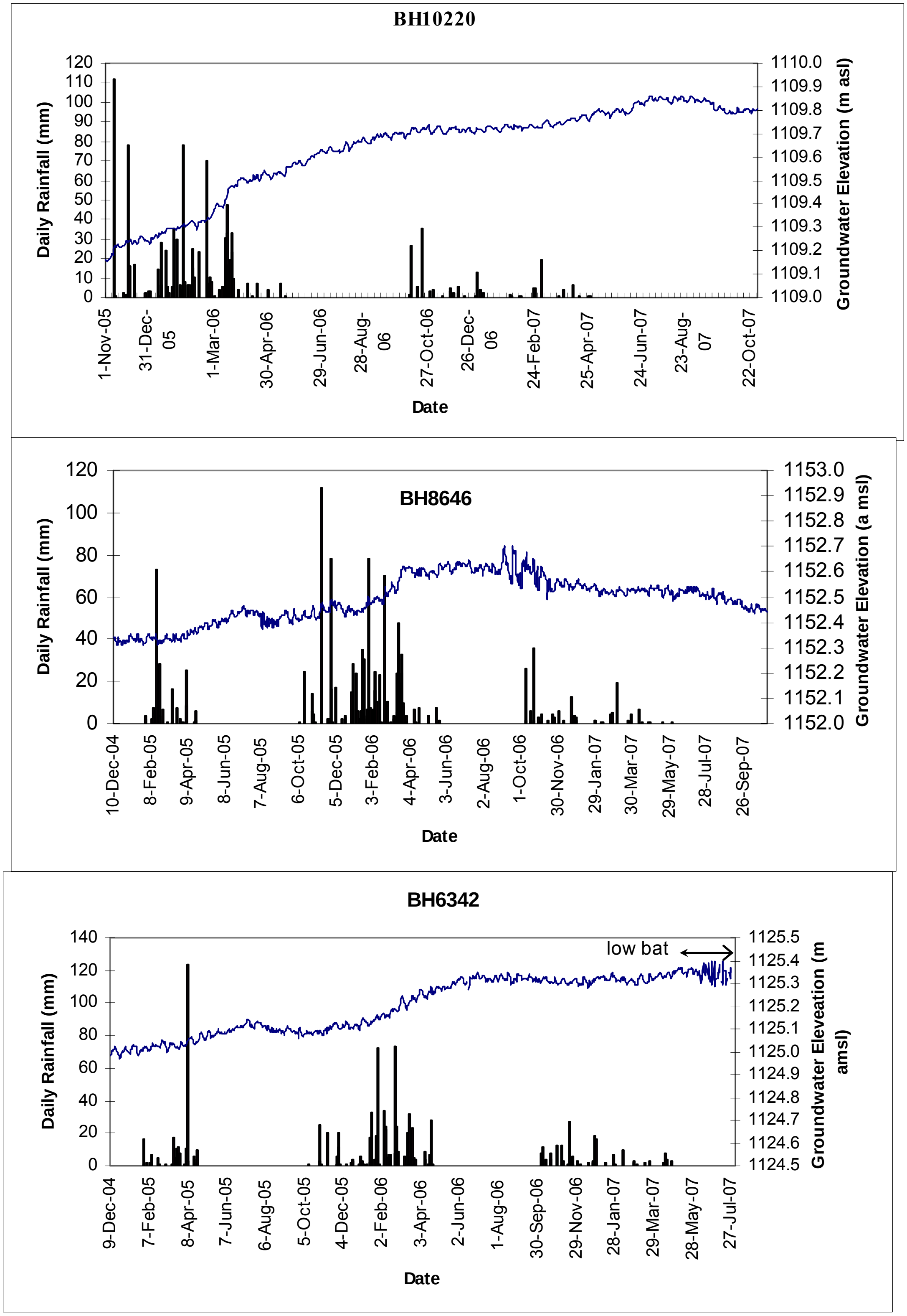


Figure 12.18 Typical Hydrographs of the Otshe aquifer in the Ncojane Block)

13 NUMERICAL MODELLING AND WELLFIELD SIMULATION

13.1 BACKGROUND

The numerical model which was developed and calibrated during the Exploration Phase (project review) of the project was subsequently updated at the conclusion of the production phase to allow assessment of wellfield abstraction. The model covers both the Ncojane Block and the Matlho-a-Phuduhudu Blocks (**Figure 13.1**).

The model was calibrated in steady state as the aquifer system is largely undeveloped and has only limited time series data. Boreholes used in the model calibration are completed in both Ecca and Ntane aquifers.

The calibrated model was then used to simulate potential wellfield abstraction from the new boreholes both in steady state and in transient mode (20 to 30 year time frames).

13.2 MODEL OVERVIEW

The project area aquifer system was conceptualised in terms of a four layer model. The top aquifer layer (layer 1) represents saturated formations overlying the Ecca, either Ntane, Kalahari Beds, or a combination. The layer is inactive to the west, where the Ntane aquifer is absent and the Kalahari Beds are primarily unsaturated. The underlying layers, 2 through 4 represent interpreted aquifer units in the Ecca Group, with layer 4 representing the deepest saline portion of the aquifer system (Kobe aquifer). All layers are truncated along the edge of the Ghanzi Ridge (**Figure 13.1**) where Karoo formations terminated against the emergent ridge of Ghanzi Group quartzites, arkoses and shales.

This new model is based on the old model which was developed during the project review stage. Some important observations were made about the old model as follows:

- There was outflow and inflow over the Southeast fixed boundary due (downstream) due to the fact that the fixed head values along the boundary decreased from South to North. Actually only flow out should occur given the regional flow pattern.

- The Northwestern (upstream) boundary was a fixed head. This type of boundary for the inflow was found to create water where there is none. In the model there was inflow and outflow over the fixed head boundary – inflow in one layer outflow in another with almost zero net flow altogether.

- Considerable flow was going through the fourth saline layer

- In the original model the downstream boundaries were given fixed heads in every layer according to the values obtained by interpolating the observed heads. This resulted in these boundaries not aligned with lines of constant head.

For the final modelling, model boundaries were refined as follows;

13.2.1 NORTHERN WESTERN BOUNDARY (UPSTREAM)

The northwestern fixed boundary was replaced with a no flow boundary. Although this boundary can equally be well modelled as a flux boundary, assuming no flux yields a conservative approach to the resource estimation. The flux is implicitly taken into account by the area recharge, which was fitted in the model during calibration. Inserting the flux originating on the Namibian side in the Ecca aquifer increases the model uncertainty since this flux is unknown, this observation was also made during the review stage.

13.2.2 DOWNSTREAM (OUTFLOW)

The complex distribution of heads along this boundary was replaced by a constant value, approximating the water level value interpolated from observed heads in the piezometric map. The boundary was assumed to coincide with a contour line in every layer. Therefore it was given one single value in every layer. Initially, different heads in layers 1, 2 and 3 were assumed but it was found out that a single value of 1025 m amsl in the three top-most layers works very well.

13.2.3 SIDES

The sides are assumed impervious (streamlines) as in the old model. This assumption may be somewhat invalid if a sizable amount of the total recharge is pumped. It is recommended that pumping should be on the order of one half of the recharge such that the streamline (flow line) boundaries do not move. The only rationale not to touch them is the probable compartmentalization of the aquifer, which will make inflow from the sides more difficult.

13.2.4 FOURTH LAYER

The fourth layer was isolated from the rest of the model by setting a lower leakance between layers 3 and 4 and by defining both the upstream and downstream boundaries in this layer as no-flow boundaries, effectively assuming a stagnant saline water body with the possibility to exchange water with the Ecca e.g. by up-coning if there is over pumping of the Ecca.

Basic model parameters are provided in **Table 13.1**.

Table 13.1 Model Parameters

Parameter	Value or Description	Comments
No. of Layers	4	Layer 4 is saline aquifer
Size range of layers	1 x 1 to 10 x 10 km	Small cell sizes centred on proposed wellfield areas, Ncojane Block
Layer thickness	layer 1: 10 to >200 m layer 2: 15 - 60 m layer 3: 20 m layer 4: 20 - 250 m	Thickness of layer 3 not presently well constrained; position of transition zone from fresh to saline groundwater also not well constrained.
Boundaries	NW: No flow SE regional sink: constant head North boundary with Ghanzi Ridge: no flow South Boundary: no flow (parallel to flow)	Single value in all aquifers, Constant head elevations based on borehole monitoring
Recharge	0.15 to 0.63 mm year	Only on west where Ecca sub-crops
Transmissivity	layer 1: 50 m^2/d layer 2 and 3: 25 m^2/d , with zone of high T (100 m^2/d) in central area based on test pumping data layer 4: 25 m^2/d	
Vertical Leakance	Layer 1-2: 0.00002 Layer 2-3: $1x10^{-5}$ Layer 3-4: $1x10^{-5}$	Leakance approximated based on lithologic logs
Evapotranspiration	0	
Time	Steady state	
Storativity	5×10^{-4}	
Specific yield	0.10	

13.3 CALIBRATION

Model calibration was undertaken based on the following information obtained during the project

- Time series water level data
- Water level elevation data from project boreholes
- Test pumping data from exploration and production boreholes (T and S)
- Lithologic and stratigraphic logs from existing boreholes as well as project boreholes

Transmissivity values, obtained from test pumping data were assumed to be representative and well constrained than the recharge. Therefore the transmissivity of the aquifers was based on test pumping data results, including a narrow zone of high transmissivity from the west through to the centre of the model area in the Ecca aquifer (**Figure 13.2**). Recharge was applied in two zones with values of recharge in each zone being recalibrated with the new model boundaries **Figure 13.3**.

The (rounded) calibrated values of recharge in the two zones are as follows;

Zone 1: 4E-07 m/d or 0.15 mm/year
Zone 2: 1.73E-06 m/d or 0.63 mm/year

The two zonal values are not independent. They are anticorrelated as can be seen from the covariance matrix. The reason is clear: It is important how much water arrives in zone 2 on the whole and not how it is divided up between the two zones. Zone 1 implicitly contains the neglected flux from the Namibian side.

The reproduction of the measured heads in the steady state modelling was better than before as shown in **Figure 13.4**. A variance of about 140 m^2 is obtained meaning that the mean absolute head error is less than 12 m. This compares favourably to the total head difference over the model domain of about 140 m. These deviations which can reach a maximum 20 m can be explained by the fact that while the aquifer system is hydraulically continuous it is compartmentalized by faults and intrusions.

The value of recharge itself is uncertain. If different transmissivity values are used, then correspondingly other recharge rates would be obtained. It is however suggested that the estimated value is a good as the minimum value.

The specific rates obtained, result in an estimated total inflow for average steady state conditions of roughly 18000 m^3/d (Exact figure in water balance: 1.7436705E+04). This is the upper limit of what can sustainably be abstracted. For safety reasons only half of this amount is recommended for abstraction.

13.4 WELLFIELD SCENARIOS

The planned wellfield abstraction from the new production boreholes in the Ncojane Block was simulated from the model. In addition to this, wellfield abstraction was also simulated from hypothetical wellfields Wellfield 1 and 2 in the Ecca and as well as the Ntane aquifer in the eastern margin of the model area. These are the areas which were assessed to have the best potential for wellfield development.

The simulated abstraction rates in the previous model developed during the project review stage, from the West Wellfield (Wellfield 1) was 16,800 m^3/d, the abstraction from the East Wellfield (Wellfield 2) was simulated at 13,200 m^3/d. An additional abstraction of 5000 m^3/d in the Ntane also simulated. These amounts add up to more than the total estimated recharge obtained from the modelling. Therefore they can only be maintained for shorter times of pumping and were analysed through the model.

13.4.1 NCOJANE WELLFIELD

The total recommended abstraction through the production boreholes drilled during the project is 9600 m^3/d (**Table 9.6**). This rate is in good agreement with the general recommendations that wellfield abstraction should be approximately half the recharge value assessed during model calibration.

The model was run in non-steady state with the recommended pumping rates for production boreholes BH10402, BH10404, BH10405, BH10407, BH10410 and BH10411. Cell-averaged drawdowns at steady state were determined and transformed to borehole drawdown based on the production borehole diameter of 8 inches. The temporal development of borehole drawdown is given in **Figures 13.5**. to **13.10**.

The cone of depression down to the diameter of the well is not resolved by the 1000 m grid. The drawdowns in these cells are obtained through a correction, adding another drawdown as computed by the formula given below.

$$\Delta h_{well} = 0.3665 \frac{Q}{T} \log(\frac{\Delta x}{4.81 r_{well}})$$

r_{well} is 8 inches (or 0.2032 m), $\Delta x = 1000$ m, Q = 1600 m^3/d, T = 100 m^2/d

The above equation yields an additional drawdown of $\Delta h = 17.65$ m. Together with the computed drawdown of about 24 m this makes a final drawdown value of about 42 m, which is compatible with the recommendation obtained from pumping testing data.

The well field will reach a long term steady state-equilibrium, as it is pumping at lower rate than the total recharge. This equilibrium is reached after a period of more than 80 years. For the equilibrium state the present model is not reliable, but it can however be used for the planning horizon of 30 years The reason for this is that in the first years the pumped water mainly comes out of storage and only later it is taken out of regional recharge. As long as the cone of depression remains a local feature the prediction of its evolution is reliable. Later other things like the regional resource availability, which is not yet well understood, will become more important.

The wellfield can be overdrawn with higher abstraction and creating a larger cone of depression at an earlier point in time. For such a strategy, the pumping has to be limited to a shorter time, say 20 years, in order to limit the drawdown.

13.4.2 OTHER WELLFIELD SCENARIOS

As a last experiment with the model, the status after 20 years of pumping with rates of 16,800 m^3/d in the West Wellfield (Wellfield 1) and 13,200 m^3/d in the East Wellfield (Wellfield 2) as well as 5000 m^3/d in the Ntane were investigated.

Results as shown in **Figures 13.11 and 13.12** indicate that pumping at these rates is just barely possible for the Ecca aquifer. It can be carried on for about 20 years with final drawdowns of about 50 m in the West Wellfield (30 m from grid plus about 20m for correction) and about 80 m in the East Wellfield (60 m from grid plus about 20 m for correction). Therefore if a wellfield is developed in potential wellfield 2 it is critical that it is pumped a lower rate to ensure sustainability.

For the Ntane aquifer, the drawdown looks small in the model, but as the cells are larger in that part of the model grid, the drawdown correction is larger. A drawdown of 75 m results (10 m from the grid and 65 m correction). This is more than the thickness of the Ntane aquifer and will result in the drying up of the boreholes. If sustainable abstraction is to be realised in the Ntane aquifer, it should be at much lower rates of perhaps 2500 m^3/d.

13.5 WELLHEAD PROTECTION ZONES DEFINITION AND DEMARCATION

13.5.1 DEFINITION

The study on wellhead protection zones (DWA, 1993) came up with 3 distinct zones of wellhead protection as follows. ,

Zone 1 – Inner Source Protection Zone (100 day travel time or 100m)
Zone 2 – fracture Flow Protection Zone (1 km radius from borehole)
Zone -3 – Outer Source Protection Zone (100 year travel time)

Protection zones for wells are defined through the use of particle tracking in ground water flow models.

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.

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. This zone is not applicable to the Ncojane wellfield as the aquifer is predominantly a primary porous media.

Zone 3

This zone is defined as the outer zone within which, certain controlled activities can be allowed. This zone is demarcated by a 100 year travel time.

13.5.2 DEMARCATION

To visualize the protection zone perimeters, the Matsheng model was refined from 1000 m grid distance to 100 m grid distance in the zones of the two wellfields in the Ncojane Block. The two wellfield are referred to as the western wellfield where the current production wells are located and eastern wellfield where a future wellfield can be installed (Figure **13.13**) The western wellfield was pumped at a design capacity of 18600 m^3/d distributed evenly over 10 boreholes while the eastern wellfield was pumped at a design capacity of 13200 m^3/d also evenly distributed over 10 boreholes.

The flow field was computed over a 50 year time frame after which the PMPATH particle tracking module of PMWIN was used to track particles backward from the wells. 36 particles were arranged on a 50 m circle around each pumping well. They were traced backward for 100 years and for 100 days respectively. The results are summarized as follows and illustrated in **Figures 13.14** to **13.17**.

The size of the protection perimeters depends crucially on the porosity used. All calculations were made for two different porosities, 25% and 10%, with 10% yielding the more conservative design.

Zone 1 is not resolved by the grid size. All particles set on a realistic well edge (say well radius 8 inch) will stay within the 100 m of the grid resolution. This means, that of the two criteria, 100 days or 100 m, the latter should be applied.

Zone 2 was not simulated as the aquifer is primarily porous.

Zone 3 was computed for two porosities in each of the wellfields. The results are shown in the **Figures 13.14** to **13.17**.

The results show that a radius of 4 km around each production borehole will certainly contain the capture zone for 100 years, even if the porosity is set at a conservative value of 10 % (conservative in the sense that the zone becomes larger than at the originally assumed 25%).

13.6 RECOMMENDATION

The numerical groundwater model for the project area was developed based on relatively short duration water level monitoring data and is considered reliable within the limits imposed by the available data. It is therefore recommended that, this groundwater model should be updated by DWA on a regular basis and should be used as a groundwater management tool.

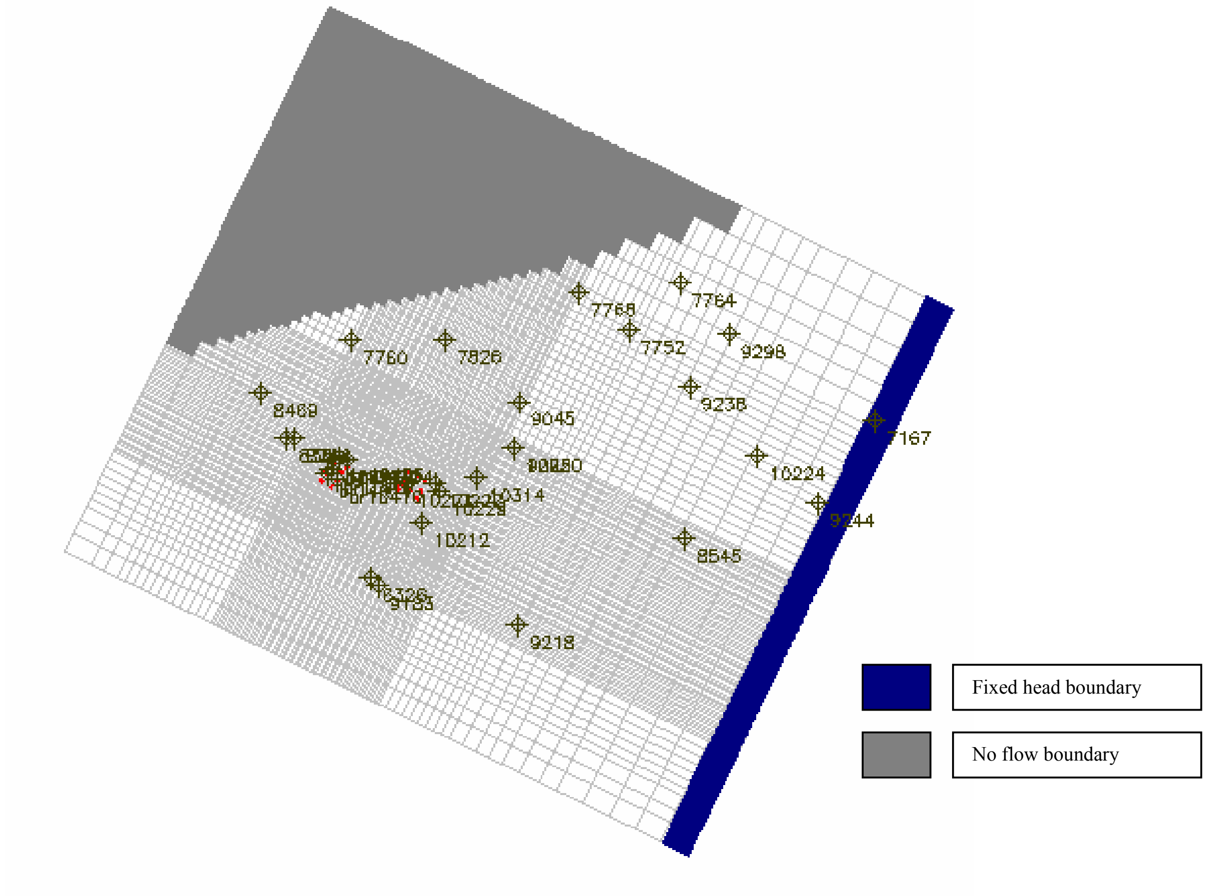


Figure 13.1 Model Area (Layer 2: Ecca)

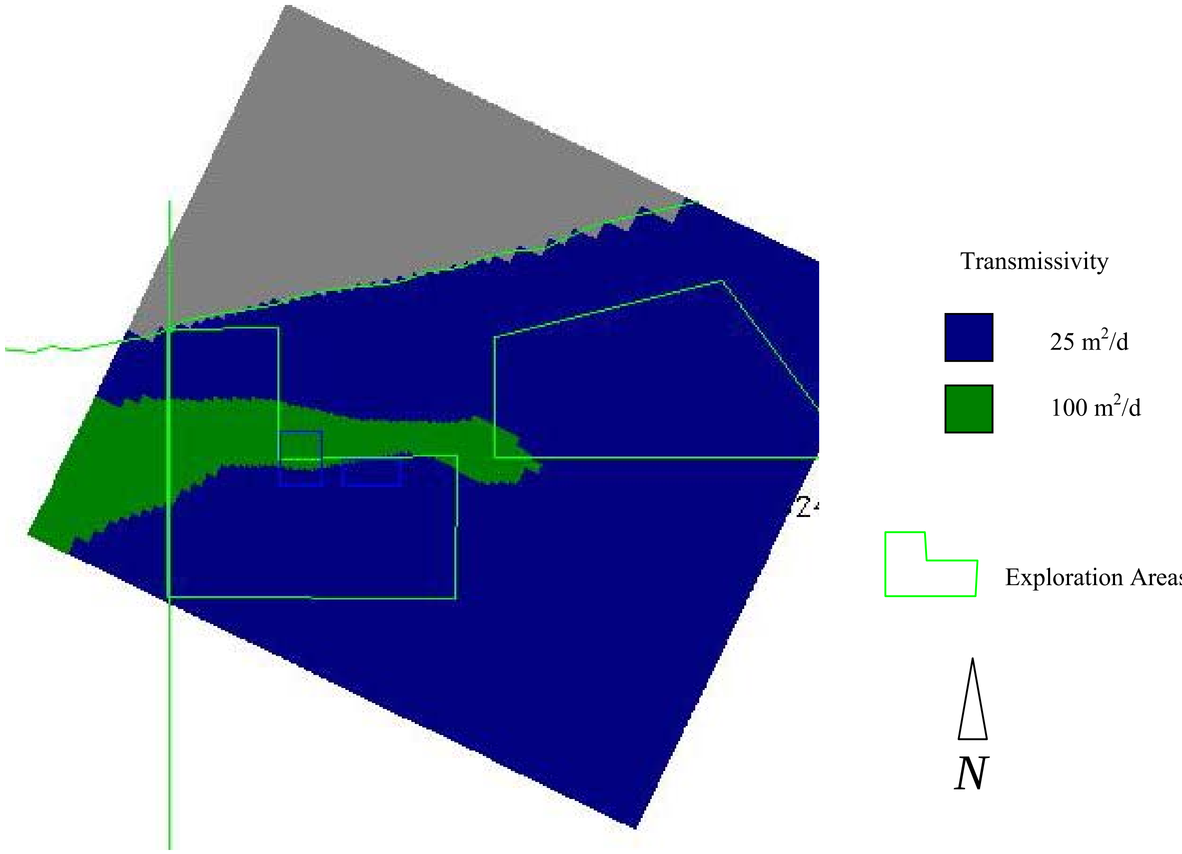


Figure 13.2 Transmissivity Distribution: Ecca Aquifer

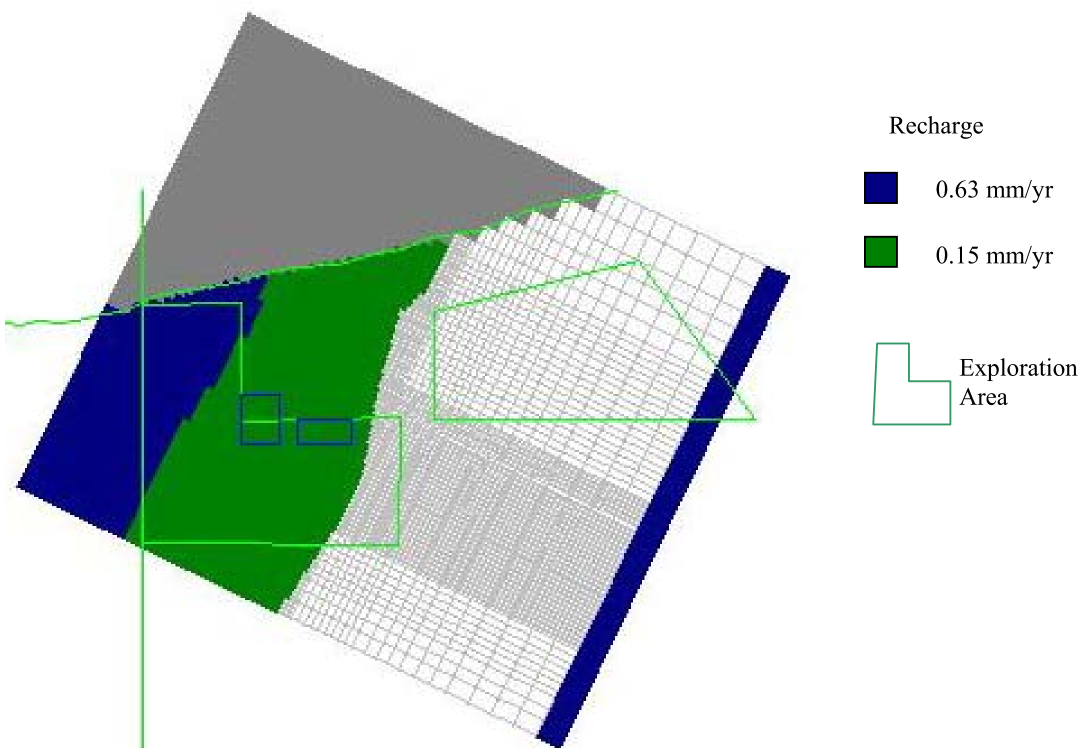


Figure 13.3 Recharge Zones

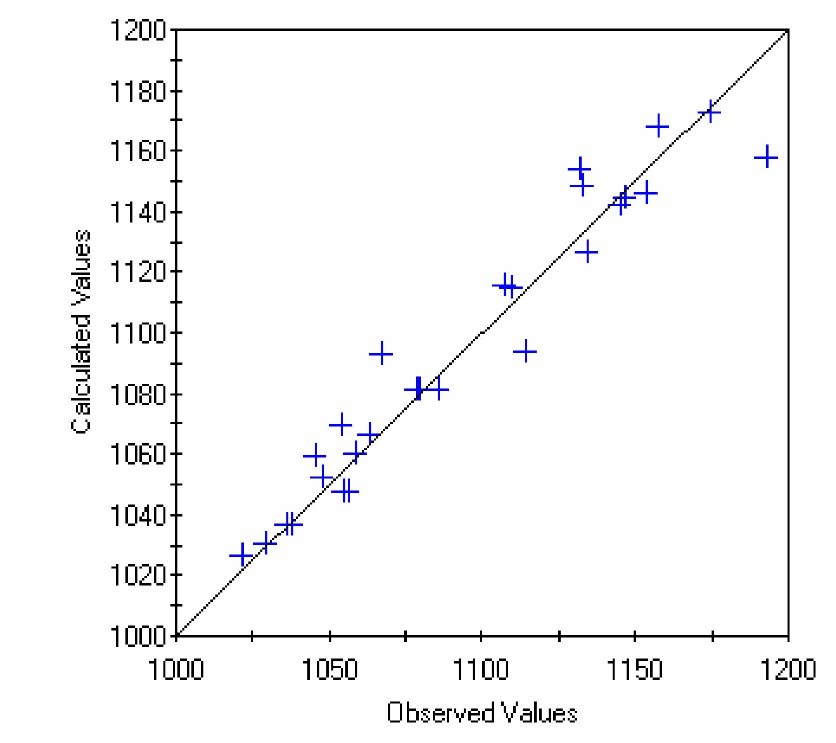


Figure 13.4 Comparison of Observed versus Calculated Heads after Fitting Recharge

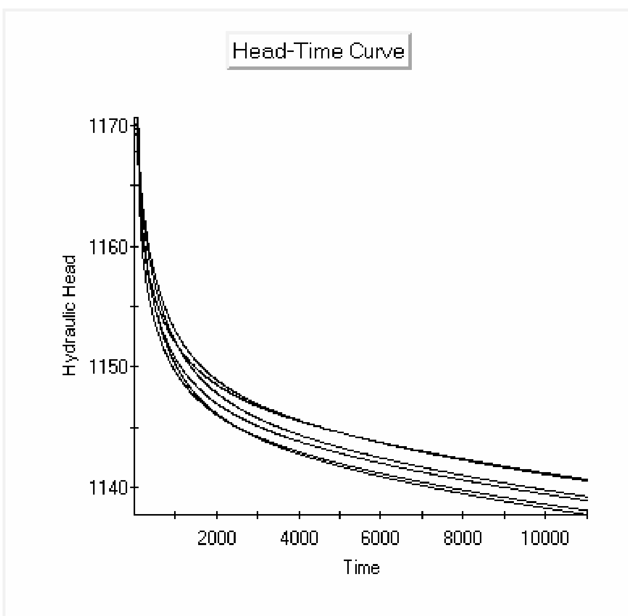


Figure 13.5 Temporal development of piezometric heads in well cells over a time of 30 years (Vertical axis in m amsl, horizontal axis in days)

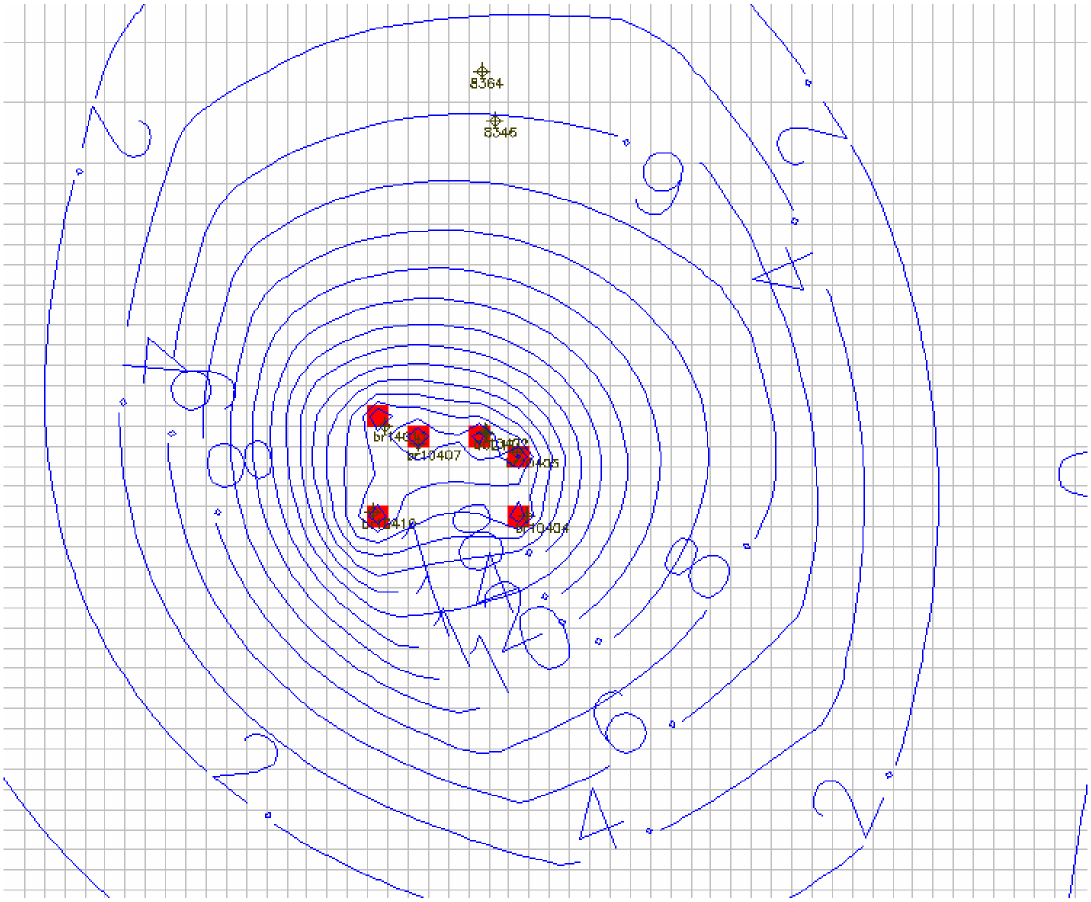


Figure 13.6 Cone of Depression Around the Wellfield after 30 Years of Pumping (9648 m^3/d)

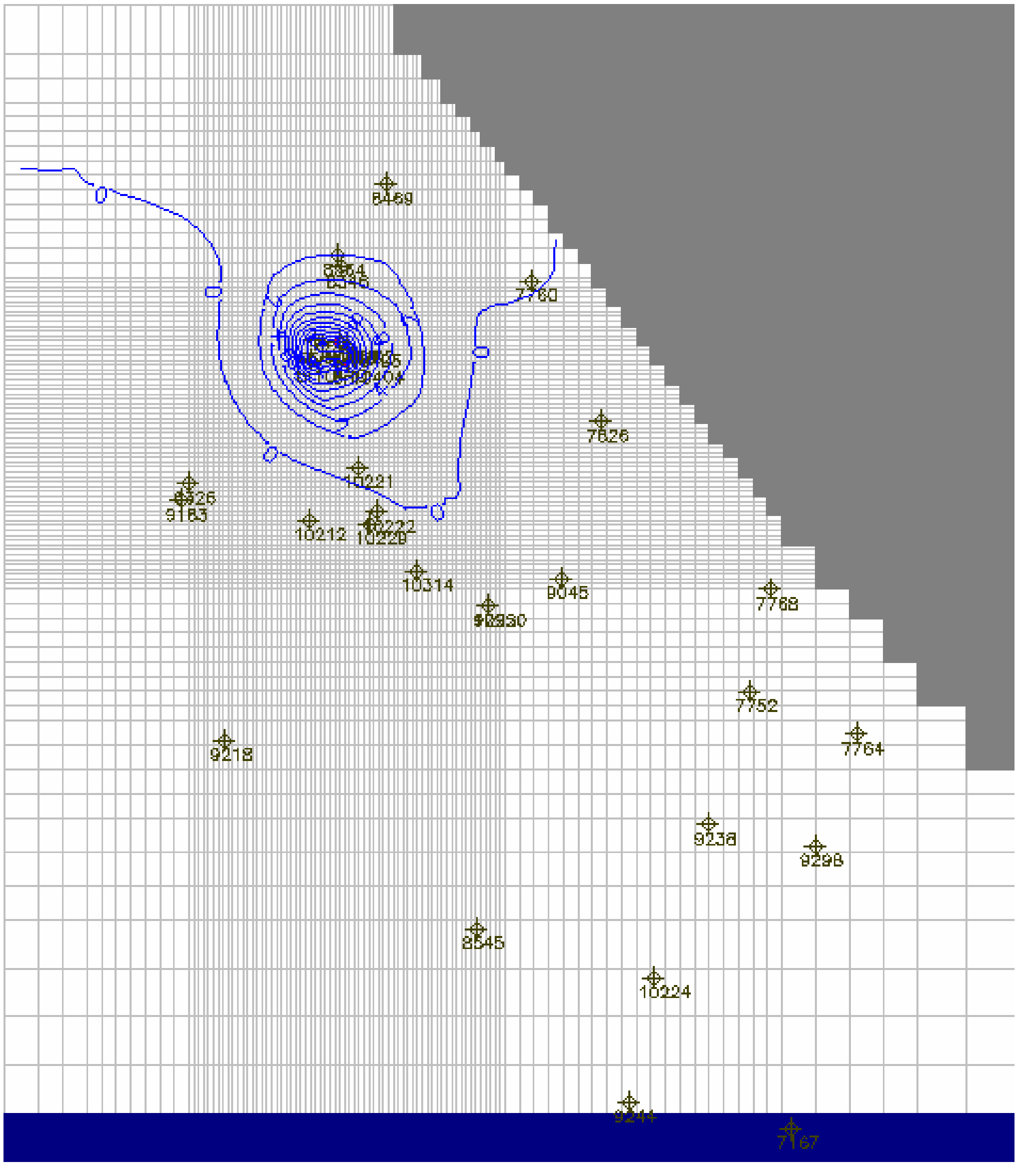


Figure 13.7 Cone of Depression after 10 years of Pumping (Layer 2 Ecca, contours every 2 m)

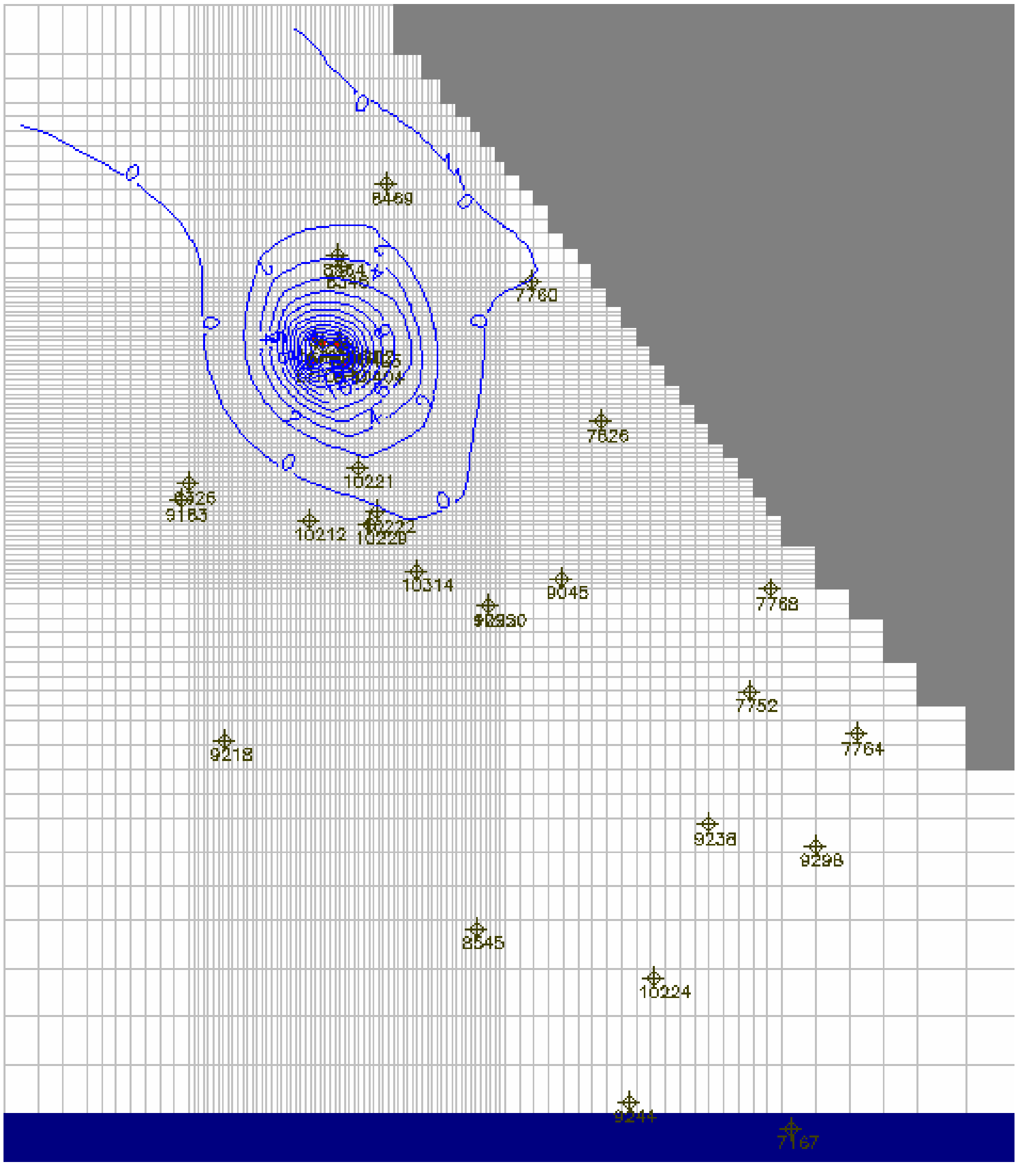


Figure 13.8 Cone of depression after 20 years of Pumping (Layer 2Ecca, contours every 2 m)

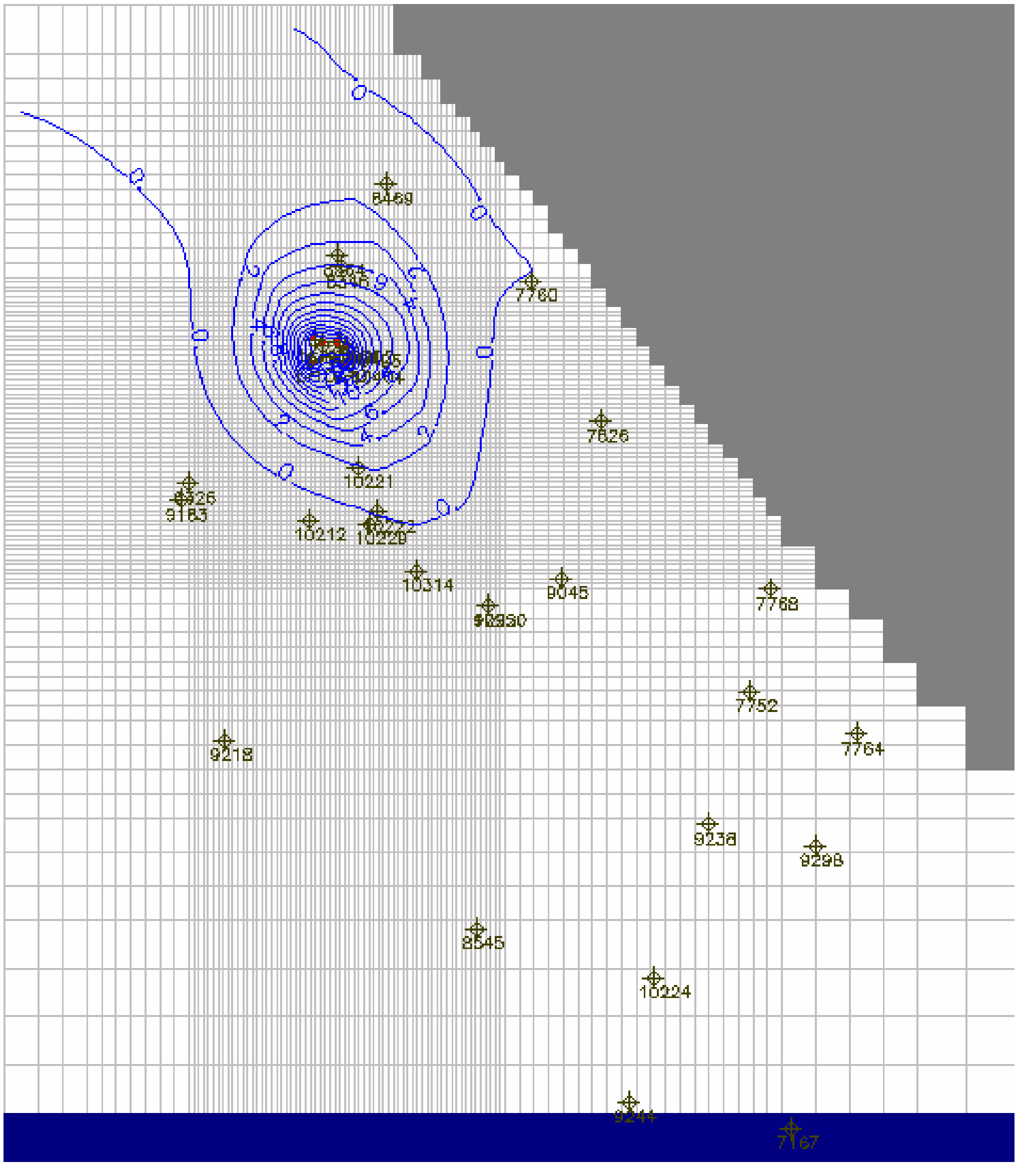


Figure 13.9 Cone of depression after 30 years of Pumping (Layer 2 Ecca, contours every 2 m)

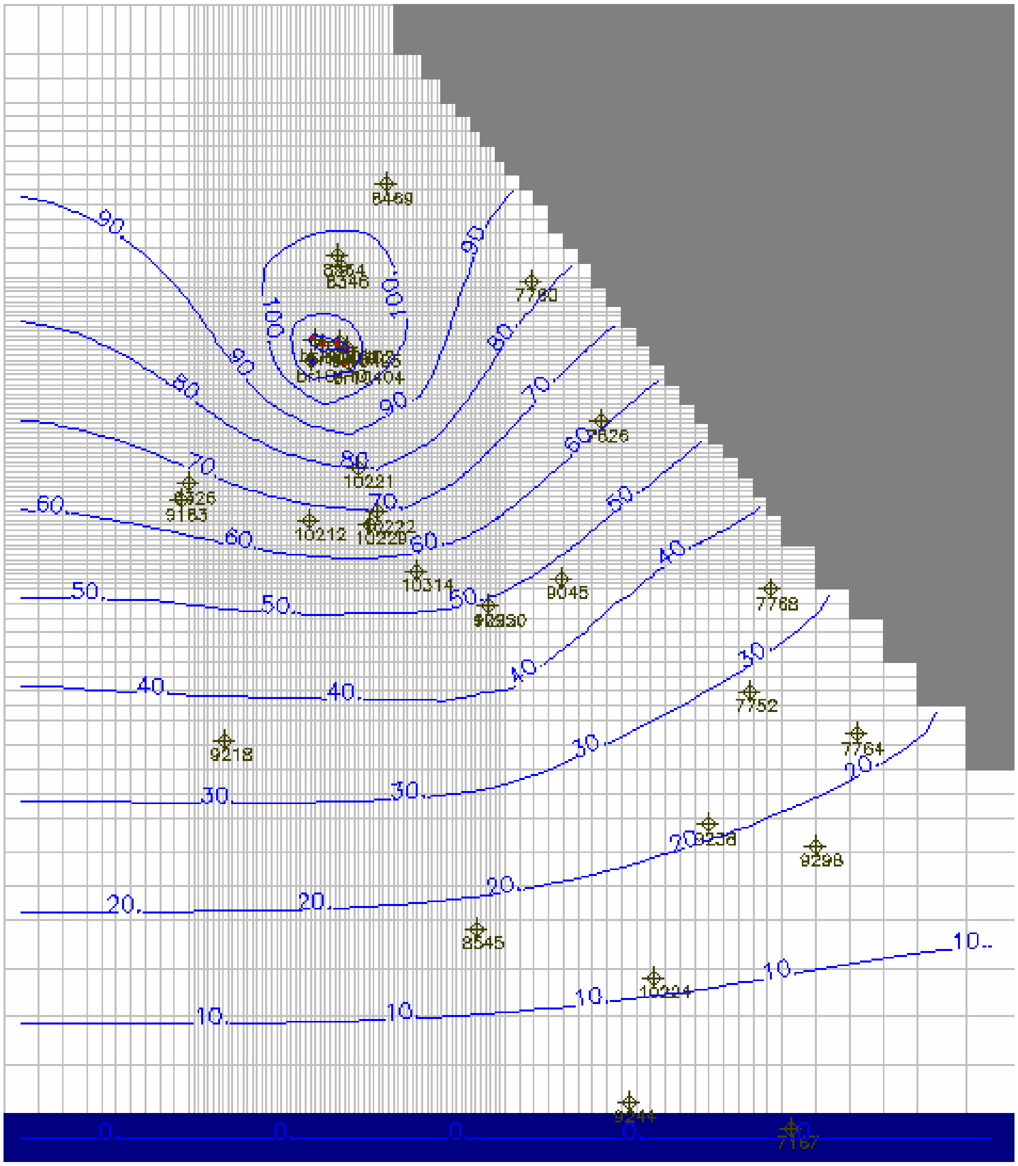


Figure 13.10 Steady state Drawdowns (Layer 2 Ecca, contours every 10 m)

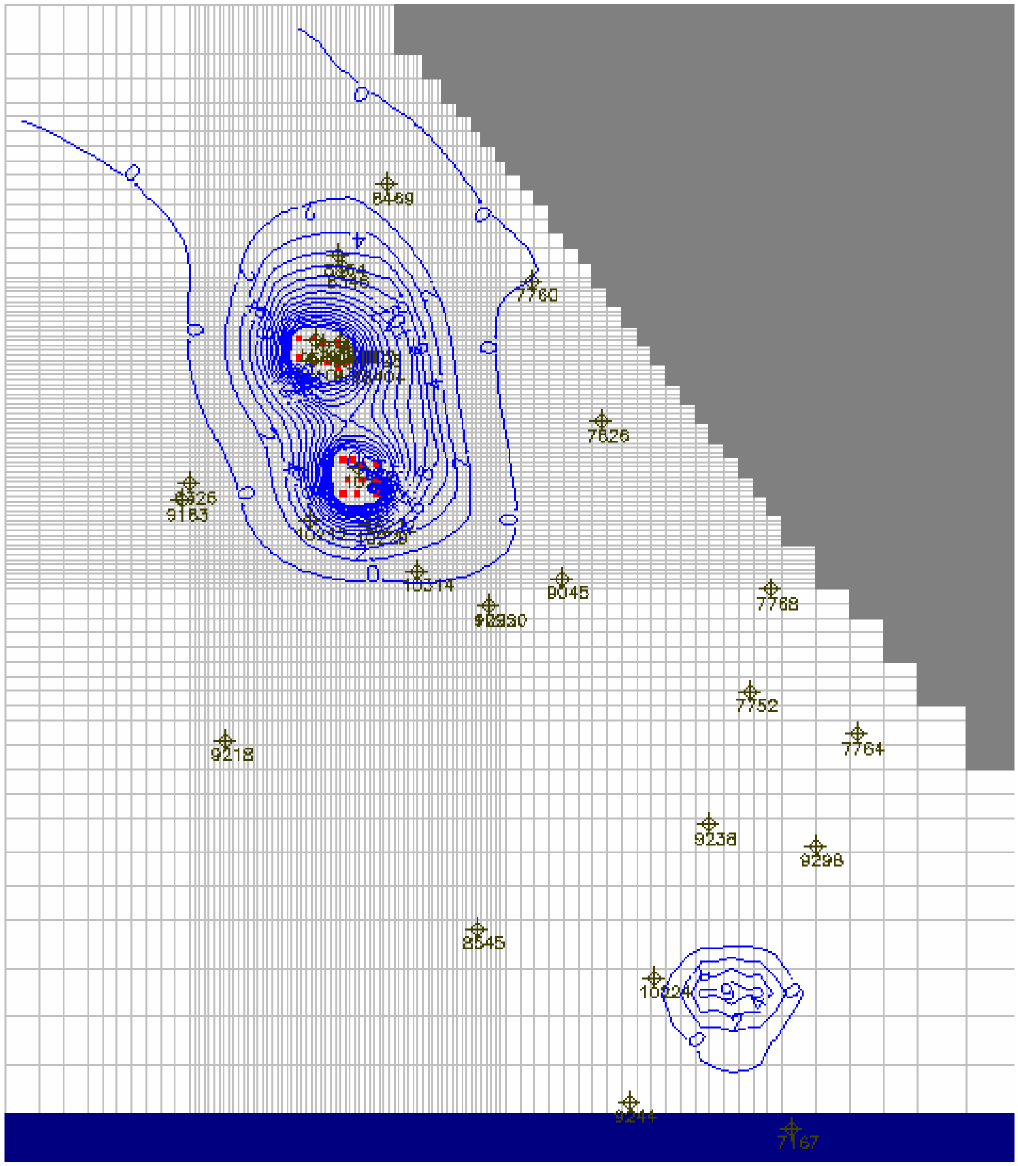


Figure 13.11 Drawdowns in the Ecca after 20 years of Pumping According to Pumping Rates in Previous Model (Contours every 4 m)

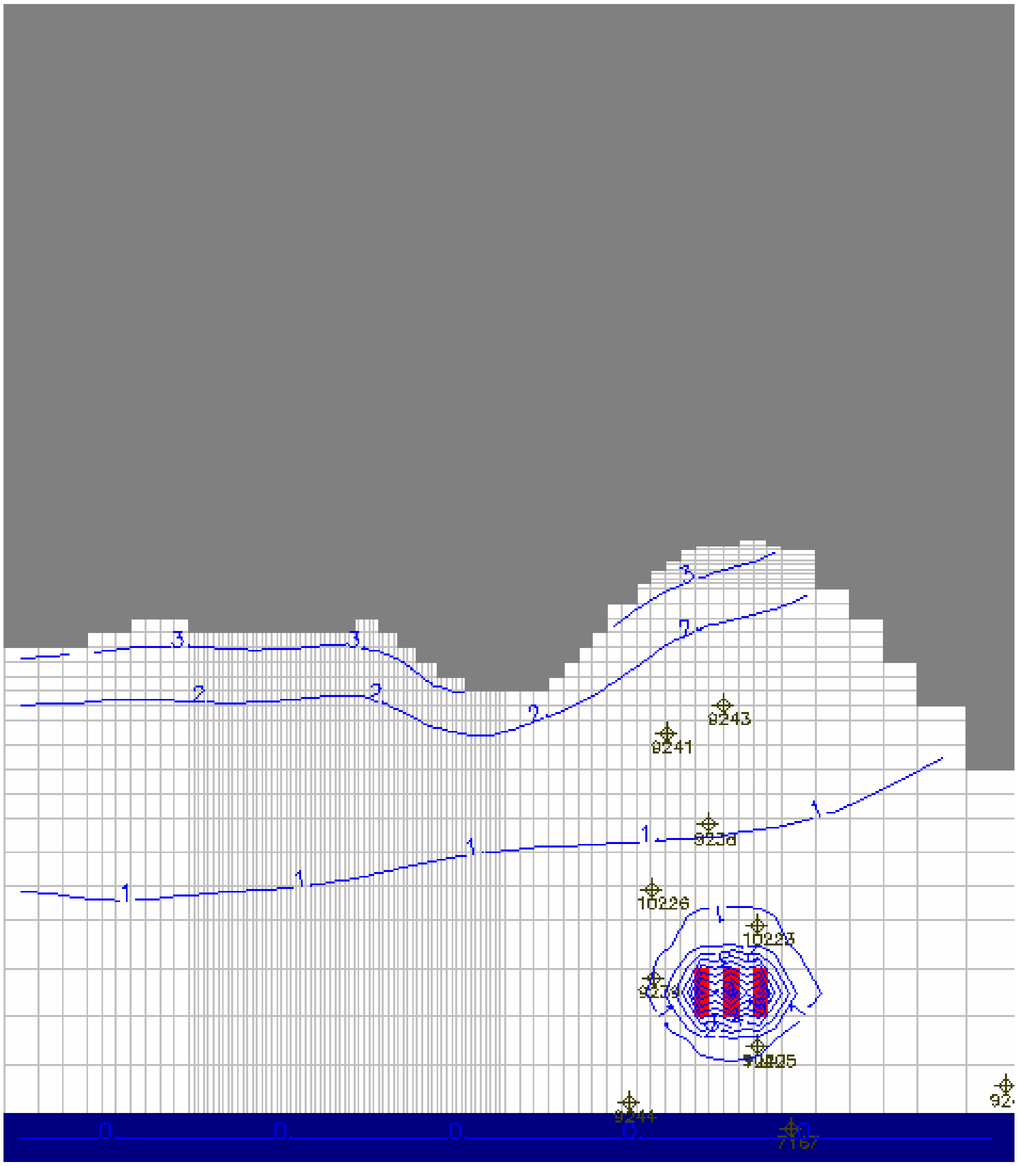


Figure 13.12 Drawdown in the Ntane after 20 years of Pumping According to Pumping rates in Previous model (Contour lines every 1 m)

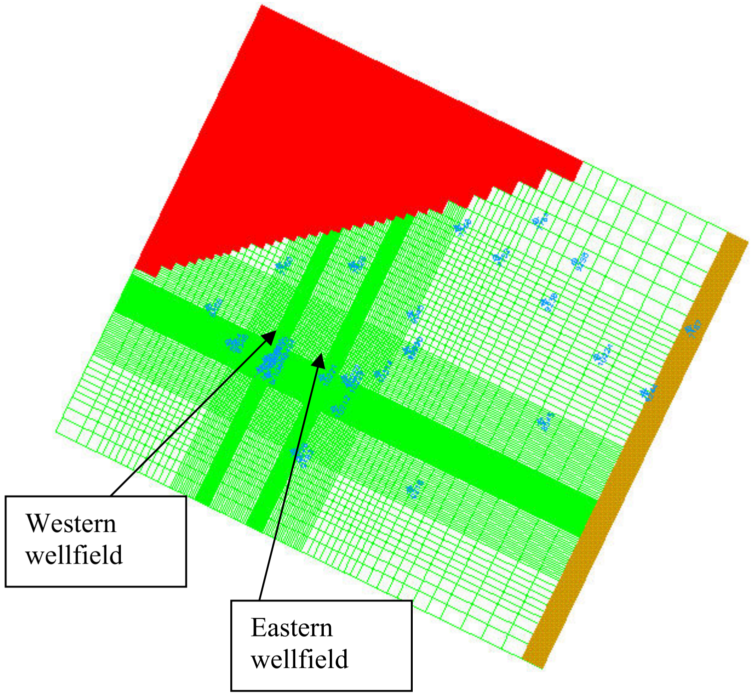


Figure 13.13 Location of Simulated Wellfields

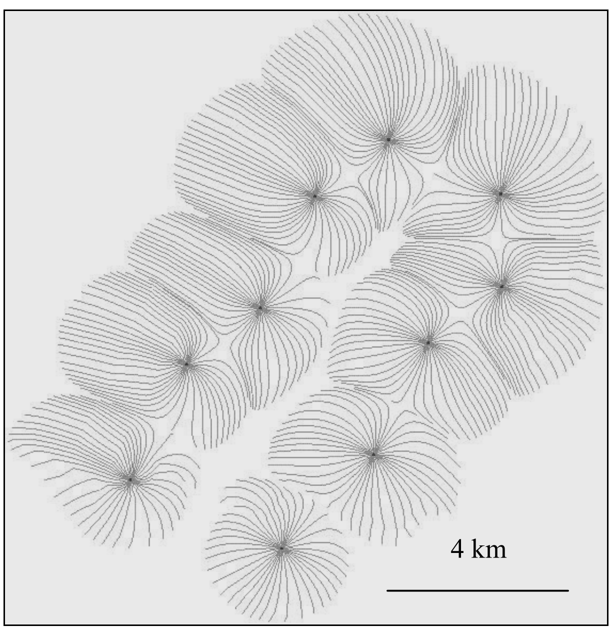


Figure 13.14 Pathlines, 100 year Travel Time Around Wells of the Eastern Wellfield (porosity 10%)

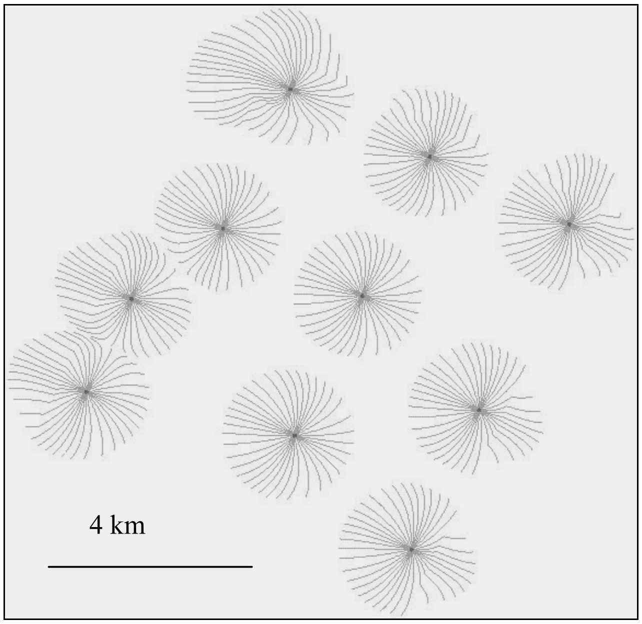


Figure 13.15 Pathlines fo 100 Year Travel Time Around Wells Of Western Wellfield (porosity 10%)

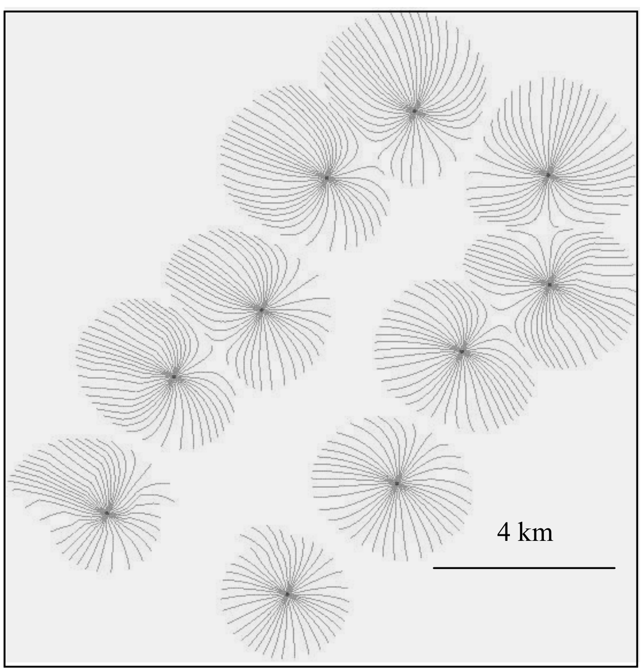


Figure 13.16 Pathlines, 100 Year Travel Time Around Wells Of Eastern Wellfield (porosity 25%)

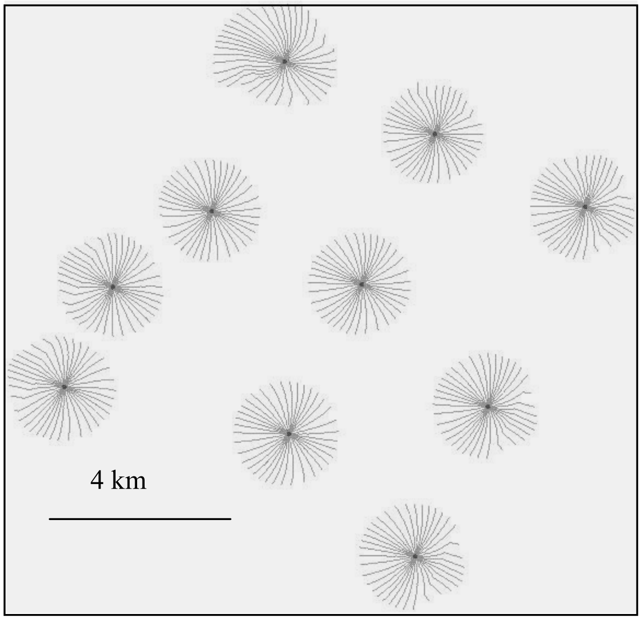


Figure 13.17 Pathlines 100 Year Travel Time Around Wells Of Western Well Field (Porosity 25%)

14 RESOURCE ASSESSMENT

Ultimately, the development of sustainable and reliable water supply for the Primary (Matsheng Villages), Secondary and Other Demand Centres is contingent on appropriate evaluation of the available resource. There are a variety of methods for resource assessment which must be considered to develop the most comprehensive and accurate assessment possible. The resource assessment carried out under this project, as described below, was guided by the goal of using a range of independent methods appropriate to the different hydrogeological environments (Unconfined in Ntane Aquifer and Confined in Otshe Aquifer) and consideration of various definitions of water resources to provide a meaningful and practical assessment.

The analysis was based on all available data from project boreholes as well as existing boreholes drilled in previous projects. Crucial data sets that were used for resource assessment include:

- Aquifer geometry obtained from aeromagnetic data, satellite imagery, ground geophysical data, borehole logging and drilling results
- Aquifer hydraulic parameters and borehole yield characteristics obtained from pump testing results
- Groundwater quality
- Long term water level monitoring data
- Groundwater abstraction simulation using the numerical model

The groundwater resources in the two exploration blocks were evaluated both analytically and using numerical modelling. The analytical methodology was employed to provide an estimate of the total groundwater reserves as well as the "extractable" portion of these reserves. The numerical model was utilised to understand the dynamics of the hydrogeological system under natural conditions as well as during wellfield abstraction. Using the numerical model, wellfield scenarios were evaluated to assess the sustainable abstraction rates.

The Ecca aquifer has been broadly divided into two compartments by fault **F6**. This fault exerts major control on both the depth to top of the Otshe aquifer as well as groundwater quality. Groundwater which falls within acceptable Class 1 and Class II limits occurs in the compartment located northwest of fault F6, while some parameters like sodium, TDS and fluoride exceed the Class II limit to the southeast of this fault. For the resource assessment for Ecca aquifer only the area falling northwest of fault F6 was considered.

For the Ntane sandstone, only areas where 1/3 of the saturated thickness is more than 20 to 25 m were considered a possible area for wellfield development. This is because for unconfined aquifers, only the bottom third of the aquifer can be screened to allow for dewatering. These areas are referred to as potential wellfield areas (PWA) and are shown in **Figure 14.1**.

14.1 RESOURCE ASSESSMENT

The methodology employed in assessing the water resources of the exploration areas consists largely of a volumetric estimation. The volumetric estimation incorporated aquifer area, thickness, calculation of matrix volume and aquifer storage. These were combined to provide an assessment of the total groundwater reserves of each PWA. The other criterion used was that the potential wellfield area had to be located in an area where groundwater quality is within drinking water standards. The need for future wellfield expansions was also taken into consideration while selecting the final wellfield areas.

14.2 METHODOLOGY

14.2.1 AQUIFER AREA AND THICKNESS

Accurate estimates of aquifer area and thickness are crucial in assessing the total groundwater resources for any given aquifer system. The aquifer thickness was obtained from interpretation of borehole geophysical logging data, drilling data and ground geophysical data sets and the physical boundaries (aquifer area), were based on available geological mapping data and drilling data.

For the Ecca aquifer, the saturated thickness was assumed to be the depth to the top of first unit of the Otshe Formation (Sandstone 1) minus the rest water level (available drawdown). The saturated thickness was taken as an average of all the boreholes located northwest of fault F6. The saturated thickness for the Ntane Aquifer was taken as 1/3 of the saturated thickness to allow for dewatering of a part of the aquifer during abstraction. Only areas where 1/3 of the saturated thickness was more than 20 m were considered as potential wellfield areas.

14.2.2 SATURATED MATRIX VOLUME, AQUIFER STORAGE AND RESERVES

The Matrix Volume (R), for each potential wellfield area, was calculated with based on the following equation

*R = Aquifer Area*Aquifer thickness*
Ecca aquifer, Thickness = Depth to Top Sandstone 1 minus Rest water Level (Ecca aquifer)
Ntane aquifer Thickness = 1/3 of saturated thickness (unconfined)

This method of estimating aquifer reserves is conservative and should provide an underestimate of the volumes of water in storage. Based on these assumptions the total reserves (TR) for each Potential Wellfield Area were calculated as follows:

$TR = R*S_{av}$
Where,
R = matrix volume
Sav= average storage coefficient
The storage coefficient (S_{av}) value was taken as the average of pumping test derived values for each aquifer

Under wellfield abstraction, only a part of these reserves can ever be practically exploited (exploitable resource versus total resource). The reasons for this include:

- Some water will remain trapped in the aquifer matrix
- Pockets of air will form and isolated patches of water will remain in the aquifer and will not be easily extracted

Most of these parameters are difficult to determine with any degree of accuracy and a value of 20% was used to estimate the extractable resources (ER) as follows.

$ER = TR*.20$

14.2.3 RESOURCE QUANTIFICATION

The groundwater resources of the PWAs were determined based on the calculated total reserves (TR) and exploitable reserves (ER). A summary of the calculated resources for each aquifer and the key parameters used in the calculations is provided in **Table 14.1**.

A comparison of the total reserves in each PWA indicates that the Ecca aquifer has the highest total reserves of 158 MCM in storage compared with Ntane aquifer which has a total of only 40 MCM in storage.

Table 14.1 Summary of Groundwater Resources Assessment for the PWAs

Aquifer	Surface Area m^2	Aquifer Thickness (m)	Saturated Matrix Volume (m^3)	Average S	Water Reserves (m^3)	Exploitable Reserves, m^3	Average Q (m^3/hr)	Average Q/s (m^2/hr)	Average T (m^2/d)
Ecca Aquifer (Otshe), Ncojane Block	4,391,115,829	81	307,378,108,012	4.43E-04	157,566,409	31,513,282	54	5	137
Ntane Aquifer	1,126,898,090	25	28,172,452,251	1.44E-03	40,427,469	8,085,494	33	3	52

14.3 POTENTIAL WELLFIELD AREA COMPARISON

There were two main components of the resource assessment in each PWA; a quantitative evaluation of the total and extractable volumes of groundwater in PWA and a comparative analysis of the two aquifer systems under consideration based on series of key hydraulic parameters. The main inputs to the volumetric assessment were aquifer area, aquifer thickness, calculated volumes of groundwater in storage and extractable volumes. The key hydraulic parameters that were considered for comparative analysis of the aquifers are:

- Borehole Yield Characteristics (Average Yields)
- Borehole and Aquifer Productivity Characteristics (Specific Capacity and Transmissivity)
- Recharge Potential
- Exploitable Reserves

In addition to these, the water quality, environmental considerations and the potential for future wellfield expansion were taken into consideration while selection the final wellfield area location.

14.3.1 BOREHOLE YIELD CHARACTERISTICS

The borehole yield characteristics of each potential wellfield area were analysed by collating constant rate test yields from project and existing boreholes for each aquifer system. The mean yield was derived by averaging the tested yield from all the boreholes in each area. The results show that the Ecca (Otshe aquifer) has the highest average yield of 54 m^3/hr compared to the Ntane aquifer where an average yield of 33 m^3/hr was obtained.

14.3.2 BOREHOLE AND AQUIFER PRODUCTIVITY CHARACTERISTICS

Borehole and aquifer productivity characteristics of each potential wellfield area were examined by collating pump testing data from project and existing boreholes. Parameters which were collated were the specific capacity and transmissivity.

The Specific Capacity (Q/s) of a borehole is its yield (Q) per unit drawdown (s). This parameter provides a useful measure of the productivity of a borehole and an aquifer. If the aquifer is large and has good transmissivity and storage characteristics, relatively large Q/s values will result from high yields and small drawdowns. A specific capacity of 5 m^2/hr was obtained for the Ecca (Otshe) aquifer compared to a value of 3 m^2/hr for the Ntane aquifer (**Table 14.1**).

Aquifer Transmissivity (T) is a measure of the rate of groundwater flow through an aquifer, and also the productivity of an aquifer. The mean T value was calculated from all tested boreholes (project and existing) for each area under consideration. A comparison of the two aquifers again indicates that the Ecca aquifer (Otshe) has higher average T values compared to the Ntane aquifer where values of 142 m^2/d and 52 m^2/d were obtained respectively for Ecca and Ntane aquifers.

14.3.3 Recharge Potential

The actual recharge potential of each potential wellfield area is difficult to quantify, although considerable qualitative understanding of recharge dynamics of the two aquifers under consideration has resulted from the project. Estimates based numerical modelling and isotope studies indicate that recharge values of 0.15 to 1.7 mm annum are possible. Water level monitoring data indicates that recharge is occurring to the Ecca (Otshe) while there is very little evidence for active recharge to the Ntane aquifer based on available monitoring data. Most of the Ntane aquifer monitoring boreholes indicates declining water levels, and pumping will accelerate the reduction of the saturated thickness, resulting in wellfield failure. For this exercise the recharge value was assumed to be zero for both aquifers which results in conservative estimates for the resources

14.3.4 Potential for Future Wellfield Expansion

The fact that the potential wellfield area for the Ntane aquifer is limited in aerial extent implies that the wellfield area has limited potential for wellfield expansion if the water quality deteriorates with time and borehole yields fail. Wellfield abstraction might also induce poor quality groundwater from the margins of the basin as these areas have relatively poor quality groundwater. Groundwater modelling indicates that a wellfield developed in the Ntane aquifer pumping at rate of 5000 m3/day will dry up in less than 20 years.

14.3.5 Exploitable Reserves

The exploitable reserves were taken as 20% of the total volumes of groundwater in storage for each potential wellfield area. Exploitable reserves in the Ecca aquifer were calculated as 32 MCM while for the Ntane aquifer an estimate of 8 MCM was obtained.

14.3.6 Potential Environmental Impacts

The Matlho-a-Phuduhudu Block, where the Ntane aquifer is developed, is located in an area identified as a possible wildlife migratory corridor between the Transfrontier Park and the Central Kalahari Game Reserve. Developing a wellfield in that area might have some impacts on wild life migration patterns. The water levels in the Ntane aquifer are naturally declining and operating a wellfield will accelerate the water level decline, and might have some effects on the vegetation.

14.4 Summary

The comparative analysis of the two aquifers indicates that the Ecca aquifer is the highest potential aquifer in terms of groundwater development, and wellfield has been developed as shown in **Figure 14.1**. Numerical groundwater modelling indicates that the wellfield can sustain abstraction rates of approximately 10,000 m^3/d for a period of up to 30 years. The potential for the Ntane aquifer to sustain large scale wellfield abstraction has been evaluated as limited and it is not considered as viable long term solution for sustainable water supply in the project area.

Figure 14.1 Location of Ncojane Wellfield and Other Potential Wellfield Areas

15 CONCLUSIONS AND RECOMMENDATIONS

15.1 CONCLUSIONS

The potential of the two main aquifers in the study area i.e. the Ntane Sandstone and Ecca (Otshe) to meet the long term water demand (2023) of the project area's primary demand centres (Matsheng Villages) and the secondary demand centres was assessed during the study.

A multi disciplinary approach involving review of previous groundwater studies in the area, aeromagnetic data interpretation, ASTER satellite imagery analysis, ground geophysical surveys, borehole geophysical logging drilling, pump testing, hydrochemistry analysis, water level monitoring, numerical groundwater modelling and recharge assessment based on environmental isotopes was used to assess the groundwater potential of the two principal aquifers in the project area. Based on an integrated assessment of the study results, the following conclusions have been reached.

15.1.1 GEOLOGICAL AND HYDROGEOLOGICAL

The study results indicate the following;

15.1.1.1 ECCA (OTSHE) AQUIFER

- Groundwater occurrence in the Ecca (Otshe) aquifer which occurs through out the project area is within two sandstone units which are separated from each other by variably thick argillaceous units.

- In the Ncojane Block and the northern parts of the Matlho-a-Phuduhudu Block, the median and average water strike depths in the two Ecca sandstones aquifers range from 198 to 289 m and 198 to 203 m respectively. TDS values in this area range from 176 to 1000 mg/L.

- For the central, eastern and southern parts of the Matlho-a-Phuduhudu Block water strikes are much deeper, ranging from 307 m and 328 m due to down faulting of the aquifer across aeromagnetic and satellite imagery data interpreted faults **F6** and **F7**. As well as the deeper water strikes, TDS values are also slightly elevated ranging between 1544 and 1761 mg/L.

- In Ngwatle and Masetlheng areas, water strikes have been recorded at depths of more than 440 meters with TDS values ranging between 922 and 2156mg/l

- In addition to the two main sandstone aquifers, water strikes with variable but slightly elevated TDS values (1065 to 6045 mg/L) were occasionally encountered in the two mudstone units of the Otshe Formation.

- In addition to the predominantly fresh water aquifers found in the Otshe Formation sandstone units, saline aquifers were encountered in sandstone units of the underlying Kobe Formation particularly in the southern part of the Ncojane Block

- Transmissivity values obtained for the Ecca (Otshe) aquifer throughout the project area range from a low as 4 to as high as 431 m^2/d

- Storativity values obtained from test pumping data analysis for the Ecca (Otshe) aquifer ranged from $1.00x10^{-4}$ to $4.05x10^{-6}$ which are values typical of confined aquifers

- Tested borehole yields ranged from 10 to 95 m^3/hr with an average value of

- Groundwater flow for the Ecca (Otshe) aquifer is primarily from the west to east with northwesterly to southeasterly components which are parallel to the orientation of aeromagnetic and remote sensing data interpreted faults, **F4** and **F5**.

- Regionally, the Ecca aquifer system is laterally continuous and groundwater inflow is from Namibia (in the west), where reported sub-cropping conditions and saturated Kalahari Beds result in enhanced recharge potential.

15.1.1.2 NTANE SANDSTONE AQUIFER

- The Ntane sandstone aquifer only occurs in the eastern part the project area in the Matlho-a-Phuduhudu Block while to the west, including the Ncojane Block, the sandstone has been removed through pre-Kalahari erosion. In the northern part of the area it is overlain by

- No water strikes were recorded in the Kalahari Beds while only minor water strikes were recorded in the overlying Stormberg Lava where present. Water strike depths range from 140 to 230 meters, while water levels range from 113 to 156 meters.

- Groundwater TDS values for the Ntane Sandstone aquifer ranges between 305 mg/L to 1918 mg/L. In general water level trends in this aquifer are flat to declining with very little evidence for active recharge. Currently there is very limited large scale groundwater abstraction from this aquifer.

- Transmissivity values for the Ntane sandstone aquifer ranged from 7 to 88 m^2/d with an average value of 43 m^2/d.

- Storativity values obtained from two observation boreholes, BH10223 and BH10225 are $6.70x10^{-4}$ and $2.20x10^{-3}$ respectively.

- Tested borehole yields range from 8 to 56 m^3/hr with average an value of 42 m^3/hr.

- The general direction of ground flow in for the Ntane aquifer is predominantly from west to east, with a north-easterly component in the central portion of the Matlho-a-Phuduhudu Block. Local flow variations occur in the southern part of the block with the flow patterns tending to a south-easterly direction.

15.1.2 RESOURCE ASSESSMENT

- Of the two aquifers assessed, the Ecca (Otshe) aquifer was found to have best potential for long term sustainable groundwater abstraction in terms of individual borehole yields, aquifer hydraulic characteristics, and groundwater quality.

- The exploitable groundwater reserves were calculated as 32 MCM and 8 MCM for the Ecca and the Ntane aquifers respectively.

- Numerical groundwater modelling results indicate that the new wellfield completed in Ecca aquifer can sustain daily abstraction rate of 9600 m^3/day.

- For the Ntane aquifer, numerical groundwater modelling indicates that a wellfield in this aquifer pumping at 5000 m^3/day would dry up in less than 20 years. The potential for the Ntane aquifer to sustain large scale wellfield abstraction is therefore evaluated as low and it is not considered as viable long term solution for sustainable water supply to the major demand centres of the project area. However it is a viable source for local (village scale) water supply.

- Numerical groundwater simulations indicate that the wellfield has as sustainable abstraction rate of **9600 m^3/day**

Recharge estimates through water level monitoring, isotope studies and numerical groundwater modelling were undertaken during the course of the study and the following observations were made.

- Water level trends indicate that the Ecca aquifer, particularly in the Ncojane block is likely recharging probably through both regional inflow and local rainfall events.

- In general, water level trends in the Ntane Sandstone aquifer are flat to declining with very small magnitudes of water level fluctuations probably because of its unconfined nature or possibly because it is the least actively recharging aquifer in the project area.

- Recharge estimates based numerical modelling and isotope studies indicate that recharge values of 0.15 to 1.7 mm annum are possible.

15.1.3 GROUNDWATER EXPLORATION

Ground geophysical surveys comprising of TEM soundings (200x200 m loop), magnetic profiling, and limited HLEM profiling were used to site exploration and production boreholes during the project with the following conclusions being reached:

- Magnetic profiling assisted in locating aeromagnetic and remote sensing data interpreted lineaments and faults, some of which were proven to have major control on the aquifer geometry, groundwater flow and water quality. Magnetic profiling was also very instrumental in locating some dolerite sills, though not always due the horizontal and weathered nature of these dolerites.

- TEM soundings together with magnetic profiling were found to be the most effective methods for hydrogeological investigations in the project area and should constitute the main ground geophysical techniques employed for siting water supply boreholes in the area

- HLEM profiling was found to be ineffective because a large portion of the project area is underlain by thick conductive units overlying the target aquifer, except near Ncojane and Kule villages where Kalahari Beds, Mosolotsane and Kule Mudstones are thinner and more resistive.

15.2 RECOMMENDATIONS

- The recommended daily abstraction rates for the 6 production boreholes (24 hrs pumping) are based on pumping test data which can not predict the pumping effects beyond the test duration. It is therefore recommended that once the boreholes are brought into operation, regular water level and water quality monitoring is carried out to establish the maximum sustainable yield of each borehole.

- Longer term monitoring of the groundwater level, groundwater quality and abstraction volumes is essential to protect the groundwater quality in the Otshe aquifer. The risk for pollution exists not only from faulty borehole construction, e.g. inadequate sealing in confining layers or incorrect placement of screens, but also from corrosion, and seepage from surface pollution points.

- Adequate protection zones should be maintained around the wellfields to prevent any pollution from surface to reach the aquifer. In particular sealing of the brackish /saline aquifers, overlying freshwater Ecca (Otshe) aquifer is paramount to protecting this aquifer.

- Drilling of new private boreholes within aquifer zone where the overlying aquifer is saline 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 saline aquifer and the freshwater aquifer.

- The possibility of anthropogenic pollution at BH8346, Ncojane needs to be established through re-sampling and analysis, as well as inspection of BH8346 by borehole camera and hydrochemical logging is recommended. It could be complemented by ^{15}N isotope investigations in order to identify the likely sources of nitrogen. This is essential for developing a protection plan to safeguard the aquifer against pollution.

- The numerical groundwater model for the project area was developed based on relatively short duration water level monitoring data and is considered reliable within the limits imposed by the available data. It is therefore recommended that, the groundwater model should be updated by DWA on a regular basis and should be used as a groundwater management tool.

- Future recharge investigations should be directed to mapping the area of low chloride water, investigating its flow pattern and its isotopic content. The question of lateral inflow from the west (Namibia) and north needs investigation beyond the boundary of the present project (Transboundary).

- Groundwater "ages" determined through isotope measurements indicate that the water body is very old and has very low replenishment rates necessitating great caution in its exploitation.

16 BIBLIOGRAPHY

Abrams, M., and Hook, S.J., ASTER Users Handbook, Version 1. ASTER User Handbook, on Aster web.jpl.nasa.gov.

Akanyang, L., 2004: Environmental Management in The Matsheng: Ecological Perspectives MAPOSDA, Gaborone Government Officers Workshop, unpublished

Allison, G.B., Barnes, C.J., Hughes, M.W., and Leaney, F.W.J., 1984: Effect of climate and vegetation on oxygen-18 and deuterium profiles in soils. Isotope Hydrology 1983, pp 105-123. International Atomic Energy Agency, Vienna.

Chilume, C.J., 2001: Hydrogeological Assessment of the South-western Karoo basin. A case study from Lokalane, Botswana.

Drury, S.A., 2001: Image Interpretation in Geology. Blackwell publishers. 296p.

DWA., 1994: Palla-Road Groundwater Resources Investigation. Phase 1. CBT 10/3/26/91-92. Final Report. Appendix 10. Environmental Impact Assessment.

Ellis, C.J.R., 1979: Report on the Exploration of Block “W” Botswana. Shell Coal Botswana (Pty) Ltd.

Eriksson E & **Khunakasem V 1969**. Chloride Concentration In Groundwater, Recharge Rate And Rate Of Deposition Of Chloride In The Israel Coastal Plain. Journal of Hydrology 7, 178-197

Exploration Consultants Ltd, 1998: Oil and Gas Stratigraphic Drilling Project. The report submitted to the Department of Geological Survey, Lobatse, Botswana.

Exploration Consultants Ltd, 1998b: Petroleum Potential of the Karoo of Botswana. The report submitted to the Department of Geological Survey, Lobatse, Botswana.

Gat JR 2005. Some Classical Concepts Of Isotope Hydrology. In: Aggarwal, PK, Gat JR & Froehlich, KFO (Eds), Isotopes in the Water Cycle: Past, Present and Future of a Developing Science, 127-138. Springer, Dordrecht, 381p

Geotechnical Consulting Services (GCS), 2000: Integrated Rural Village Water Supply Project. Boreholes Siting Supervision of Drilling Construction and Test Pumping Works for Ukwi and Ngwatle, Kgalagadi District. Draft Final Report, submitted to the Department of Water Affairs, Gaborone, Botswana.

Gieske, A., 1992: Dynamics of Groundwater Recharge-A case study in semi-arid Eastern Botswana. Ph.D. Thesis, Free University of Amsterdam.

Gillespie, A. R., Rokugawa, S., Hook, S.J, Matsunaga, T., and Kahle, A.B., 1999: Temperature / Emissivity Separation Algorithm Theoretical Basis Document, Version 2.4. ATBD-AST-05-08.pdf, on asterweb.jpl.nasa.gov.

Hurst A. et al, 1992: Geological Applications of Wireline Logs

JICA, 2002: The Groundwater Potential Evaluation and Management Plan in the Southeast Kalahari (Stampriet) Artesian Basin in the Republic of Namibia, Final Report submitted to the Department of Water Affairs, Namibia.

Jolly, J., Engelbrecht, P. and Uys, J., 2001: Biofouling in boreholes in the Klein Karoo Rural Water Supply Scheme, Oudtshoorn (South Africa) and the effect on well scheme management, Borehole Water Journal, vol. 49, pp. 15-17

Kirchner, J., Tredoux, G., Wierenga, A., and Christelis, G., 2002: Applying environmental isotopes to a Hydrogeological model of the Stampriet Artesian Basin. IAEA regional model project RAF/8/029. Department of Water Affairs, Windhoek.

Kulongoski JT & Hilton DR 2004. Climate Variability in the Botswana Kalahari from the Late Pleistocene to the Present Day. Geophysical Research Letters 31, L10204, 1-5

Kumar, H., Sarma, D., and Carlsson, L., 2000: Geophysical Perspective of Siting High Yielding Boreholes in the Lower Karoo Aquifers in Western Botswana; Groundwater: Past Achievements and Future Challenges, Edited by Sililo, O., et al., 193-198, Balkema, A. A., Rotterdam/Netherlands.

Loewenthal, R.E., Wiechers, H.N.S., and Marais, G.V.R., 1986: Softening and stabilization of municipal waters. Water Research Commission. Pretoria.

McKelvey V. E., 1976: United States Department of Interior, Geological Survey

Morosini, M., 1996b: Chemical-Isotopic Character, Origin and Evolution of Groundwater in Western Ghanzi District, Botswana. Hydrogeochemical Report for the TGLP Ghanzi/Makunda Groundwater Survey. Department of Geological Survey.

Morosini, M., 1995: Groundwater Quality in Western Ghanzi District, Botswana. TGLP Ghanzi/Makunda Groundwater Survey. Department of Geological Survey.

Moorman, J.H.N., Colin, M.G., and Stuyfezand, P.J., 2002: Iron precipitation and clogging of a recovery well following nearby deep well injection. Management of aquifer recharge for sustainability. Peter J. Dillon (ed.) Proceedings of the 4th international symposium on artificial recharge of groundwater, ISAR-4, Adelaide, South Australia, 22-26 September 2002. Pp209-214.

PCIAC-DGS., 1990: Interpretation of the Results of Stratigraphic Well Masetlheng Pan-1 in the Nosop-Ncojane Basin of South West Botswana, prepared by Stoakes Campbell Geo-consulting Ltd. and Boyd Exploration Consultants Ltd. The report submitted to the Department of Geological Survey, Lobatse, Botswana.

PCIAC-DGS., 1988: Report on Interpretation of Geophysical Surveys in Western Botswana, Nosop-Ncojane Basins, prepared by Petro-Canada International Assistants Corporation. Report submitted to the Department of Geological Survey, Lobatse, Botswana.

Peterson B. R., 2004: Borehole Geophysics for the Geologist and Hydrogeologist (*Century Geophysical Handbook*)

Press, F., and Siever, R., 1985: EARTH. W H Freeman, 656p.

Rahube, T.B., 2003: Recharge and Groundwater Resources Evaluation of the Lokalane-Ncojane Basin (Botswana) Using Numerical Modelling, M.Sc. Thesis - International Institute for Geo-Information Science and Earth Observation, Enschede, the Netherlands, 113 pp.

Renshaw, C.E., 1998: Sample bias and the scaling of hydraulic conductivity in fractured rock. Geophysical Research Letters, **25**, 121-124.

Resources Services, 2001: Tsabong Groundwater Investigation Assessment and Development. Final Report. Department of Water Affairs. Gaborone. Botswana.

Reynolds J.M., 1997: An Introductory to Applied and Environmental Geophysics

Selaolo, E.T., 1998: Tracer Studies and Groundwater Recharge Assessment in the Eastern Fringe of the Botswana Kalahari: The Letlhakeng-Botlhapatlou Area. Ph.D. Thesis. Free University of Amsterdam

Smith, 1984: The Lithostratigraphy of the Karoo Supergroup in Botswana – DGS bulletin 26, Botswana.

STUTE, M and TALMA, AS (1996). Glacial Temperatures and Moisture Transport Regimes Reconstructed from Noble Gases and 18O in Stampriet Aquifer, Namibia. In: Isotope Techniques in the Study of Environmental Change: Proceedings of a Symposium, 14-18 April 1997. 307-318. IAEA, Vienna, 932pp

Tredoux, G., Cave. L. C., & Engelbrecht, J. F. P., 2000: In-Situ measurements of physico-chemical parameters down a borehole as a tool for resource evaluation, Groundwater: Past Achievements and Future Challenges, A. A. Balkema/Rotterdam/ Brookfield. P667.

Verhagen, B. Th., Bredenkamp, D.B., and Botha, L.J., 2001: Hydrogeological and isotopic assessment of the response of a fractured multi-layered aquifer to long term abstraction in a semi-arid environment. Water Research Commission, Report 565/1/01. ISBN 1 86845 710 9. Pretoria. 42p.

Verhagen, B. T., Mazor, E., & Sellschop, J. P. F., 1974: Radiocarbon and Tritium evidence for direct recharge to groundwater in the Northern Kalahari, Nature, 249:643-644

Verhagen, B. T., 1985: Isotope hydrology of ground waters of the Kalahari, Gordonia. Trans geol soc S Afr 88 (3):517-522.

Wellfield Consulting Services (WCS), 2003: Werda- Mabutsane- Sekoma TGLP Groundwater Survey. Final Report (Volume 1). Department of Geological Survey, Lobatse, Botswana.

Wellfield Consulting Services (WCS), 2001: Hunhukwe/Lokalane Groundwater Survey Project (TB 10/2/1/98-99), Wellfield Consulting Services, Final Report submitted to the Department of Geological Survey, Lobatse, Botswana.

Wellfield Consulting Services (WCS), 1996: Matsheng Area Groundwater Investigation (TB 10/2/12/92-93), Wellfield Interconsult, Revised Final Report submitted to the Department of Geological Survey, Lobatse, Botswana.

Weaver, J.M.C., and Talma, A.S., 2002: Cumulative rainfall collectors – a tool for assessing groundwater recharge. Conference: Tales of a hidden treasure; Somerset West, 16 Sept. 2002. Groundwater Division, Western Cape.

Wood, W.W., and Sanford, W.E., 1995: Chemical and isotopic methods for quantifying ground-water recharge in a regional, semi-arid environment. Ground Water 33(3) 458-468.

Wrabel, J., 1999: Determination of groundwater recharge in a semi-arid area in Namibia with the chloride mass balance method (in German). PhD thesis. University of Wurzburg.

Water Resources Consultants (WRC), 1998: Groundwater Development in Ncojane and Kule Villages, Ghanzi District. Final Report submitted to the Department of Water Affairs, Gaborone, Botswana.

Table 6.6 Summary of Geophysical Interpretations

Profile Line	Layer	Resistivity	Top (m)	Base (m)	Interpreted Lithology	Colour Scheme	Remarks
R1	1	10 to 40 Ω-m		60	Unsaturated Kalahari Beds and Upper Mosolotsane		Unit missing NE of 9000 m. Drilling Results (BH8469 & BH8470) confirmed Layer 1 as Kalahari and Mosolotsane Sandstone
	2	20 to 80 Ω-m	60	100 m (NE) to 150 m (SW)	Basal Conglomeritic Sandstone Mosolotsane and Kwetla Sandstone	Yellow to Red	This units have higher resistivity relative to rest of Project Area due to their erinaceous nature in this area
	3	10 to 60 Ω-m	100 m (NE) to 150 m (SW)	220 m (NE) to 340 (SW)	Ecca Group Rocks and Possibly Dwyka	Blue to Red	
	4	60 to > 900 Ω-m	220 m (NE) to 340 (SW)	> 400 m	Ghanzi Group	Pink	
R2	1	10 to 40 Ω-m		20	Unsaturated Kalahari Beds	Yellow to Red	
	2	< 10 Ω-m	20	140 m (NE) to 300 m (SW)	Mosolotsane and Kwetla Formations and Top of Ecca (Mudstones)	Dark Blue to Light Green	Interpreted Dolerite Intrusions ~ 80 to 300 m mbgl between 26000 & 28000 m stations
	3	10 to 25 Ω-m	140 m (NE) to 300 m (SW)	340 m NE of 1600 m and poorly constrained to SW of 16000 m	Otshe Formation	Green to Yellow	Possible dolerite intrusion at 140 to 300 mbgl between 3000 and 12000 m stations
	4	25 to < 100 Ω-m	340 m NE of 1600 m and poorly constrained to SW of 16000 m		Dolerite Sill	Red to Pink	Top of Dolerite is ~ 340 m NE of 1600 m and does not occur SW of 16000 m
R3 Zone 1 (NE of 10000 m)	1	20 to > 100 Ω-m		120 m	Kalahari and Unsaturated Ntane	Red to Pink	
	2	<10 to 20 Ω-m	120 m	135 m	Unsaturated Mosolotsane and Kwetla Formations and Top of Ecca (Mudstones)	Yellow	Unit is very thin
	3	10 to 15Ω-m	135 m	300 to 450 m	Otshe Formation	Green to Yellow	low to moderate resisivity may be due to thick Ecca mudstones as observed in boreholes BH10210 and W3
	4	15 to 80Ω-m	30 to 450 m		Upper Dwyka	Red	
R3 Zone 2, South West of 10000 m	1	20 to > 100 Ω-m		120 m	Kalahari Beds	Red to Pink	
	2	<10 to 20 Ω-m	120 m	145 m	Mosolotsane and Kwetla Formations and Top of Ecca (Mudstones)	Green to Yellow	Unit is relatively thicker SW of 10000 m station as compared to the counterpart North East of Fault F4 (Station 10000 m)
	3	20 to 50Ω-m	145 m	280 m	Otshe Formation (Ecca)	Yellow to Red	Higher Resistivity layer ~ 140 to 280 m SW of 10000 m station interpreted as coarse sandstone. Zone was confirmed to also contain weathered dolerite.
	4	<15 Ω-m	280 m	440 m	Otshe Formation (Kobe)	Green	Layer interpreted as the Upper Kobe Mudstones and comfimed at Borehole BH10227
	5	15 to 80Ω-m	440 m		Dolerite Sill	Red	Multiple Dolerite Sills
R4	1	> 15 Ω-m		40 to 60 m	Unsaturated Kalahari Beds		
	2	<10 Ω-m	40 to 60 m	40 to160 m from 5500 to 21000 m 0 to 5500 m poorly constrained might be > 240 m	Mosolotsane and Kwetla Formations and Top of Ecca (Mudstones)	Dark Blue	
	3	10 to 20 Ω-m	40 to 160 m	~ 300 m where not intruded by dolerite	Otshe Formation Sandstone	Yellow to Red	Unit is Poorly Developed along this profile and there are indications of multiple dolerite intrusions
	4	5 to 15 Ω-m	~ 300 m where there are no intrusions		Saline Kobe Formation	Light Blue to Light Green	The layer is intruded by dolerites

Profile Line	Layer	Resistivity	Top (m)	Base (m)	Interpreted Lithology	Colour Scheme	Remarks
R5 Zone 1 (West of 11000 m)	1	15 to 30 Ω-m		20 to 40	Kalahari Beds	Green to Yellow	
	2	30 - > 400 Ω-m	20 to 40 m	120 to 140 m	Dolerite Sill	Red to Pink	
	3	10 to 25 Ω-m	120 to 140 m	290 to 320 m	Otshe Formation	Green to Yellow	
	4	< 10 Ω-m	290 to 320 m	> 400	Kobe or Saline Otshe Formation	Dark Blue to Light Blue	
R5 Zone 2 (East of 11000 m)	1	20 to 45 Ω-m		20 to 80	Kalahari Beds	Green to Orange	
	2	< 10 Ω-m	80 to 140 m	80 to 230 m	Mosolotsane and Kwetla Formations and Top of Ecca (Mudstones)	Dark Blue to Light Blue	Between 11000-14000 m & 20000 -22000 m stations this unit is intruded by dolerites (~40 to 120 m)
	3	10 to 25 Ω-m	80 to 230 m	Poorly defined	Otshe Formation	Green to Yellow	The response in this line complex with multiple dolerite intrusions, see text
R6	1	20 to 60 Ω-m		40 to 60 m	Kalahari Beds	Red	
	2	< 10 to 20 Ω-m	40 to 60 m	60 m (SE) to 110 m (NW)	Kwetla Formations and Top of Ecca (Mudstones)	Dark Blue to Light Blue	
	3	30 to 200 Ω-m	60 m (SE) to 110 m (NW)	240 m (SE) to 340 (NW)	Dolerite Sill	Red to Pink	
	4	10 to 25 Ω-m	240 m (SE) to 340 (NW)	320 (NW) and > 600 (SE)	Otshe Formation	Green to Yellow	
	5	<10 Ω-m	320 (NW) and > 600 (SE)		Kobe Formation	Dark Blue to Light Blue	
R7	1	30 - >100 Ω-m		40 m (SE) to 80 m (NW)	Kalahari Beds	Red to Pink	Dolerite intrusion between 2000 to 5000 m stations (~20 to 80)
	2	< 10 to 20 Ω-m	40 m (SE) to 80 m (NW)	160	Kwetla Formations and Top of Ecca (Mudstones)	Dark Blue to Yellow	
	3	10 to 20 Ω-m	160	340	Otshe Formation	Green	
	4	< 10 Ω-m	160	Poorly defined	Kobe or Saline Otshe Formation	Blue to Light Blue	
R8	1	30 - >70 Ω-m		20 m (N) to 100 m (S)	Kalahari Beds	Red to Pink	Dolerite intrusion between 10000 and 14000 m stations (~20 to 100 m)
	2	< 10 to 20 Ω-m	20 m (N) to 100 m (S)	200 m (N) to 260 m (S)	Mosolotsane and Kwetla Formations and Top of Ecca (Mudstones)	Dark Blue to Yellow	Dolerite intrusion between 5000 and 8500 m stations (~40 to 140 m)
	3	5 to 20 Ω-m	200 m (N) to 260 m (S)	Poorly defined	Otshe Formation	Light Green to Light Blue	
R9	1	20 - 110 Ω-m		40 m (NW) to 80 m (SE)	Kalahari Beds	Red to Pink	Dolerite intrusion between 8000 and 11000 m stations (~60 to 100 m)
	2	< 10 to 25 Ω-m	40 m (NW) to 80 m(SE)	220 m (SE) to140 m (NW)	Mosolotsane and Kwetla Formations and Top of Ecca (Mudstones)	Dark Blue to Yellow	
	3	10 -50 Ω-m	220 m (SE) to140 m (NW)	420 m (SE) to 480 m (NW)	Otshe Formation	Light Green to Red	
	4	< 10 Ω-m	420 m (SE) to 480 m (NW)	Poorly defined	Kobe or Saline Otshe Formation	Dark to Light Blue	
R10 Zone 1 (NW of 12000 m)	1	10 to 30 Ω-m		40 m	Kalahari Beds	Green to Orange	
	2	< 5 Ω-m	40	100 to 260 m	Mosolotsane and Kwetla Formations	Dark Blue	
	3	10 to 25 Ω-m	100 to 260 m	320 m	Otshe Formation	Green to Yellow	
	4	< 10 Ω-m	320 m	Poorly defined	Kobe or Saline Otshe Formation	Dark Blue to Light Blue	
R10 Zone 2 (SE of 12000 m)	1	20 to 45 Ω-m		40 to 80 m	Kalahari Beds	Green to Red	
	2	10 to 110 Ω-m	40 to 80 m	120 to 280 m	Mosolotsane and Kwetla Formations and Top of Ecca (Mudstones)	Light Blue to Pink	Between 14000-16500 m & 20000 -23000 m stations this unit is intruded by dolerites (~40 to 100 m)
	3	< 20 Ω-m	120 to 280 m	Poorly defined	Kobe Formation NW of 19000 m & Otshe Formation to SE	Dark Blue to Green	Between 20000-23000 m stations this unit is intruded by dolerites (~280 m)

Profile Line	Layer	Resistivity	Top (m)	Base (m)	Interpreted Lithology	Colour Scheme	Remarks
R11	1	25 to 105 Ω-m		180 m (W) to 60 m (E)	Kalahari Beds	Red to Pink	Between 0-10000 m & 26000 -33000 m stations this unit is intruded by dolerites (depth ~40 to 180 W & 30 to 60 m E)
	2	15 to 60 Ω-m	180 m (W) to 60 m (E)	340 m (W) to 140 m (E)	Mosolotsane and Kwetla Formations	Dark Blue to Yellow	
	3	10 to 50 Ω-m	340 m (W) to 140 m (E)	Poorly defined	Otshe Formation	Green to Yellow	Between 0-8000 m & 34000 -41000 m stations this unit is intruded by dolerites (depth ~440 W & 140 to 290 m E)
L1 Zone 1, South West of 14000 m (F4)	1	20 to <60 Ω-m		110 m	Kalahari Beds	Yellow to Red	
	2	<10 to 20 Ω-m	110 m	140 m	Mosolotsane and Kwetla Formations and Top of Ecca (Mudstones)	Blue to Green	Unit is relatively thicker SW of 14000 m station as compared to the counterpart North East of Fault F4 (Station 14000 m)
	3	20 to 50Ω-m	140 m	260 m	Otshe Formation (Ecca)	Yellow to Red	Higher Resistivity layer ~ 140 to 260 m SW of 14000 m station interpreted as coarse sandstone. Zone was confirmed to also contain weathered dolerite at BH10407 and BH10411
	4	<15 Ω-m	260 m	430 m	Otshe Formation (Kobe)	Green	Layer interpreted as the Upper Kobe Mudstones and comfimed at Borehole BH10407
	5	15 to 80Ω-m	430 m		Dwyka Formation	Yellow to Pink	Possible dolerite intrusion within the pink zones
L1 Zone 2 (NE of 14000 m)	1	20 to <60 Ω-m		110 m	Kalahari Beds	yellow to Pink	
	2	<10 to 20 Ω-m	110 m	430 m	Mosolotsane Formations	blue to yellow	This unit appears to be merged with the upper Kobe Formation due to the uplifting of the kobe formation by faultt F4 as observed at BH10402/228
	3	10 to 15Ω-m	430 m		Upper Dwyka	Yellow to Pink	
L2 Zone 1, South West of 17800 m (F4)	1	20 to <60 Ω-m		120 m	Kalahari Beds	Yellow to Red	
	2	<10 to 20 Ω-m	120 m	140 m	Mosolotsane and Kwetla Formations and Top of Ecca (Mudstones)	Blue to Green	
	3	20 to 50Ω-m	140 m	280 m	Otshe Formation (Ecca)	Yellow to Red	Higher Resistivity layer ~ 140 to 280 m SW of 17800 m station interpreted as coarse sandstone. Zone was confirmed to also contain weathered dolerite at BH10410.
	4	<15 Ω-m	280 m	420 m to 510	Otshe Formation (Kobe)	Green	
	5	15 to 80Ω-m	430 m		Dwyka Formation	Yellow to Pink	Possible dolerite intrusion within the pink zones
L2 Zone 2 (NE of 17800 m)	1	20 to <60 Ω-m		110 m	Kalahari Beds	yellow to Pink	
	2	<10 to 20 Ω-m	110 m	430 m	Mosolotsane Formations	blue to yellow	This unit appears to be merged with the upper Kobe Formation due to the uplifting of the kobe formation by faultt F4 as observed at BH10402/228 in Line L1
	3	10 to 15Ω-m	430 m		Upper Dwyka	Yellow to Pink	
L3	1	20 to 70 Ω-m		40 m (SW) to 80 m (NE)	Kalahari Beds	Yellow to Red	Pink Zones within this interpreted Kalahari/ Unsaturated Ntane beds are Possible Dolerite Sills
	2	<20 Ω-m	40 m (SW) to 80 m (NE)	120m (SW) to 160 m (NE)	Saturated Mosolotsane and Kwetla Formations	Blue to Green	
	3	20 to 80 Ω-m	120m (SW) to 160 m (NE)	240 m SW to 230 m NE	Ecca Group (Otshe Formation)	Yellow to Red	
	4	< 20 Ω-m	240 m SW to 230 m NE	480 m	Ecca Group (Upper Kobe Formation)	Dark Blue to Light Blue	

Profile Line	Layer	Resistivity	Top (m)	Base (m)	Interpreted Lithology	Colour Scheme	Remarks
	5	30 to 60 Ω-m	480 m	Poorly defined	Dwyka Formation	Red	

Profile Line	Layer	Resistivity	Top (m)	Base (m)	Interpreted Lithology	Colour Scheme	Remarks
L4	1	20 to 40 Ω-m		40 m (SW) to 100 m (NE)	Kalahari Beds	Green to Red	
	2	<20 Ω-m	40 m (SW) to 100 m (NE)	110m (SW) to 200 m (NE)	Saturated Mosolotsane and Kwetla Formations	Blue to Light Green	
	3	20 to 50 Ω-m	110m (SW) to 200 m (NE)	240 m SW to 300 m in the NE	Ecca Group (Otshe Formation)	Green to Red	
	4	< 20 Ω-m	240 m SW to 300 m in the NE	480 m	Ecca Group (Upper Kobe Formation)	Dark Blue to Light Blue	
	5	20 to 60 Ω-m	420 m	Poorly defined	Dwyka Formation	Red	
MAP1	1	30 to 70 Ω-m		100 m	Kalahari Beds and Unsaturated Ntane Formation	Yellow to Red	Pink Zones within this interpreted Kalahari/ Unsaturated Ntane associated with Sandunes
	2	15 to 30 Ω-m	100 m	260 m (West) to 220 m (East)	Saturated Ntane Formations	Green to Yellow	
	3	<10 to 15 Ω-m	260 m (West) to 220 m (East)	440 m (West) to 400m (East)	Mosolotsane and Kwetla Formations	Dark Blue to Light Green	
	4	15 to 40 Ω-m	440 m (West) to 400m (East)	Poorly defined	Ecca Group	Green to Red	
MAP2	1	30 to 80 Ω-m		100 m	Kalahari Beds and Unsaturated Ntane Formation	Red to Pink	Pink Zones within this interpreted Kalahari/ Unsaturated Ntane associated with Sandunes
	2	15 to 30 Ω-m	100 m	260 m (West) to 240 m (East)	Saturated Ntane Formations	Green to Yellow	
	3	<10 to 15 Ω-m	260 m (West) to 240 m (East)	420 m (West) to 360m (East)	Mosolotsane and Kwetla Formations	Blue to Light Green	
	4	15 to 40 Ω-m	420 m (West) to 360m (East)	Poorly defined	Ecca Group	Green to Red	
MAP3	1	30 to 80 Ω-m		100 m	Kalahari Beds and Unsaturated Ntane Formation	Yellow to Red	
	2	15 to 30 Ω-m	100 m	260 m	Saturated Ntane Formations	Green to Yellow	
	3	<15 Ω-m	260 m	420 m	Mosolotsane and Kwetla Formations	Dark Blue to Light Green	
	4	15 to 40 Ω-m	420 m	Poorly defined	Ecca Group	Green to Yellow	

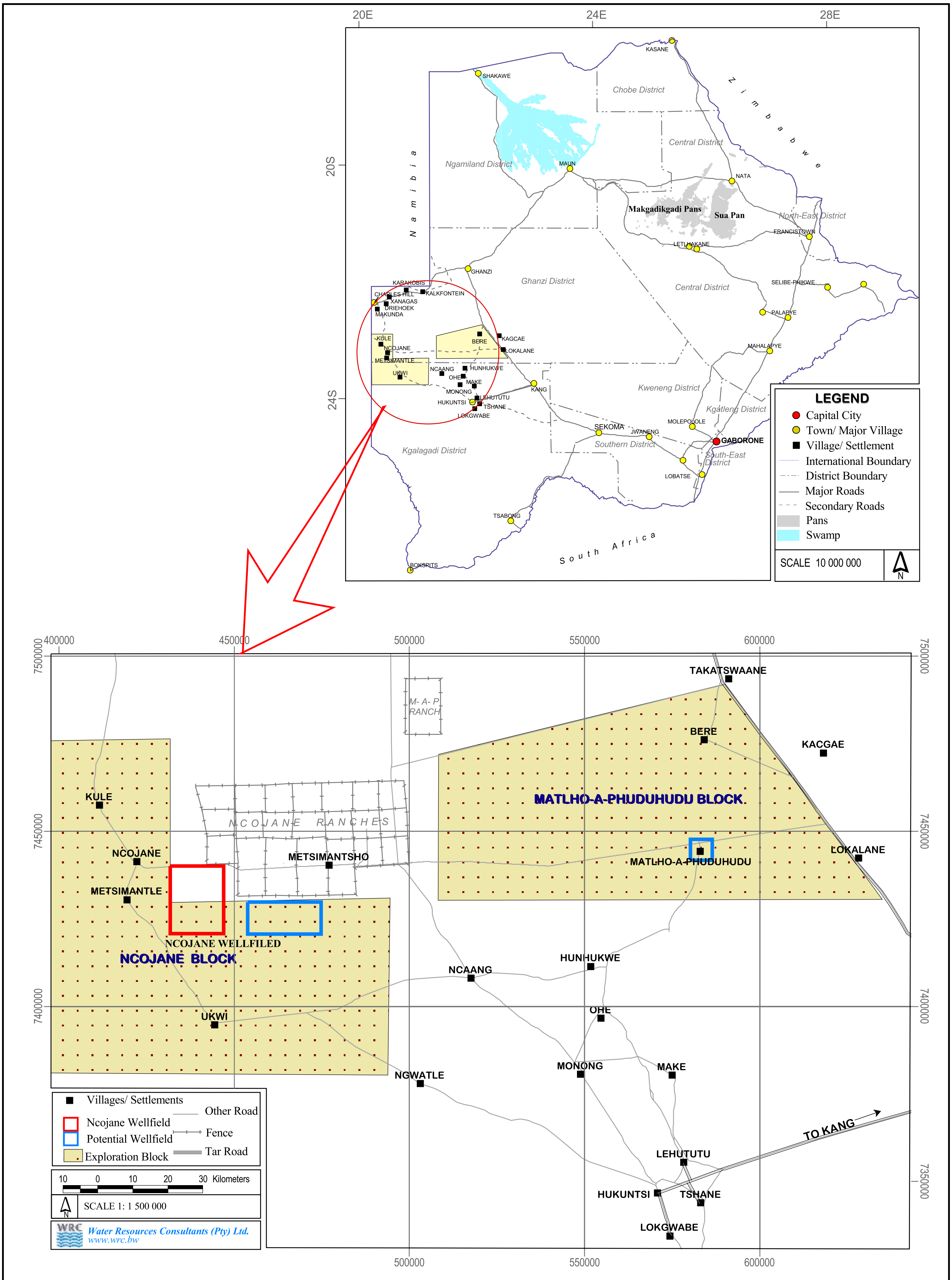


Figure 1.1 : Project Area Location Map

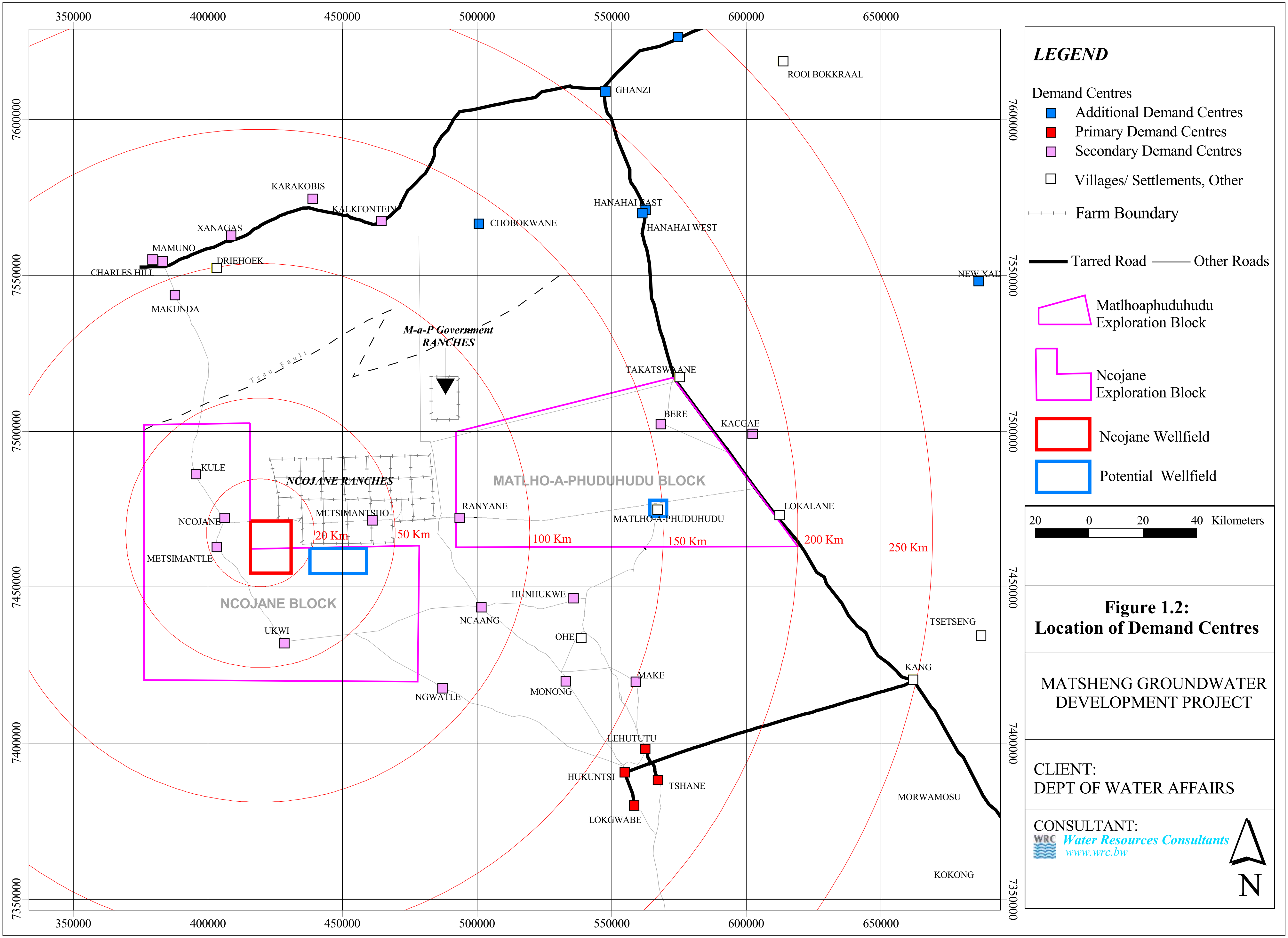


Figure 1.2: Location of Demand Centres

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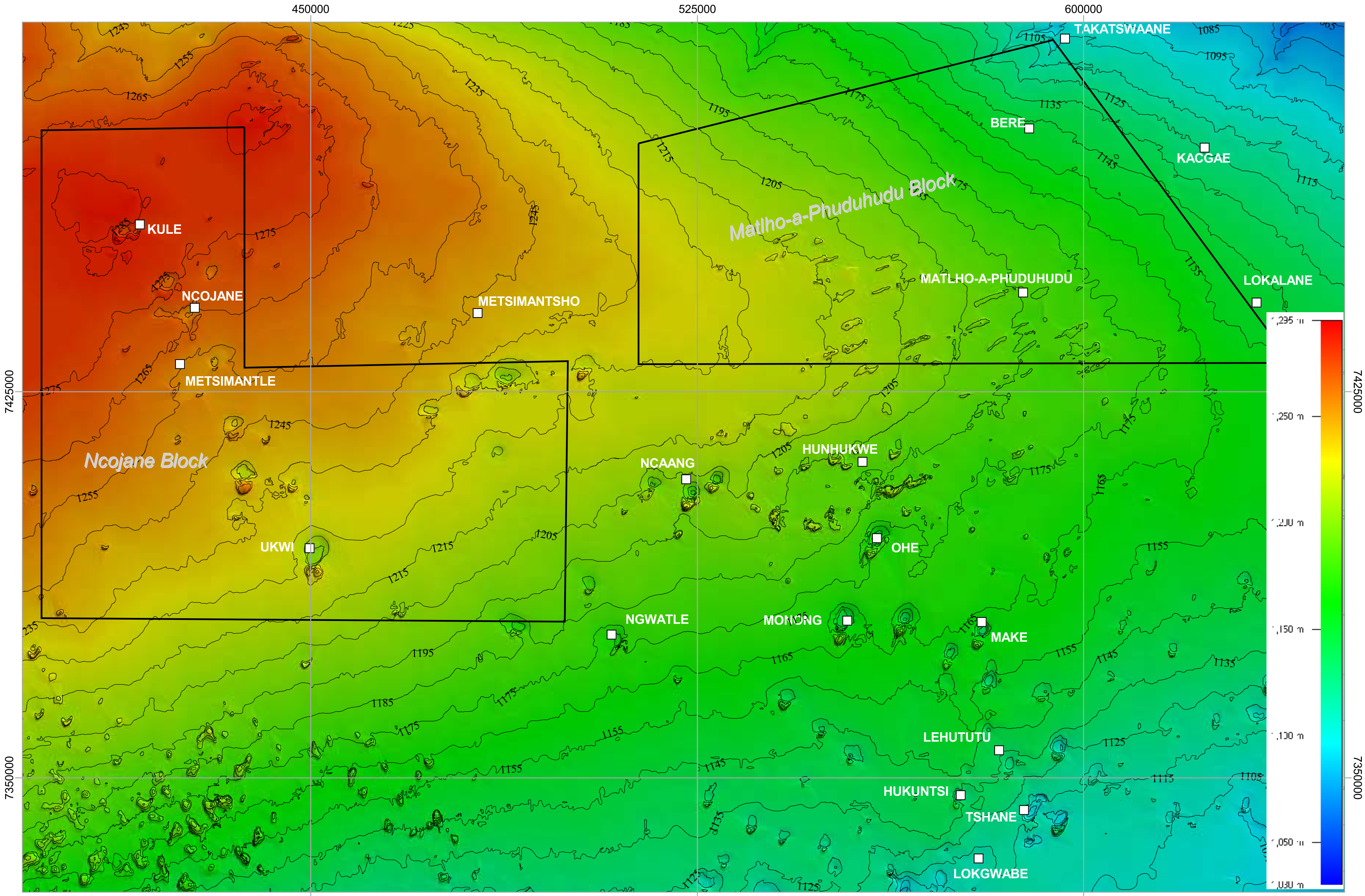

Figure 2.1: Topographic Map of the Study Area

20 0 20 40 Kilometers

N

(DEM generated from 5m interval digital contour data obtained from Department of Surveys & Mapping, Govt. of Botswana)

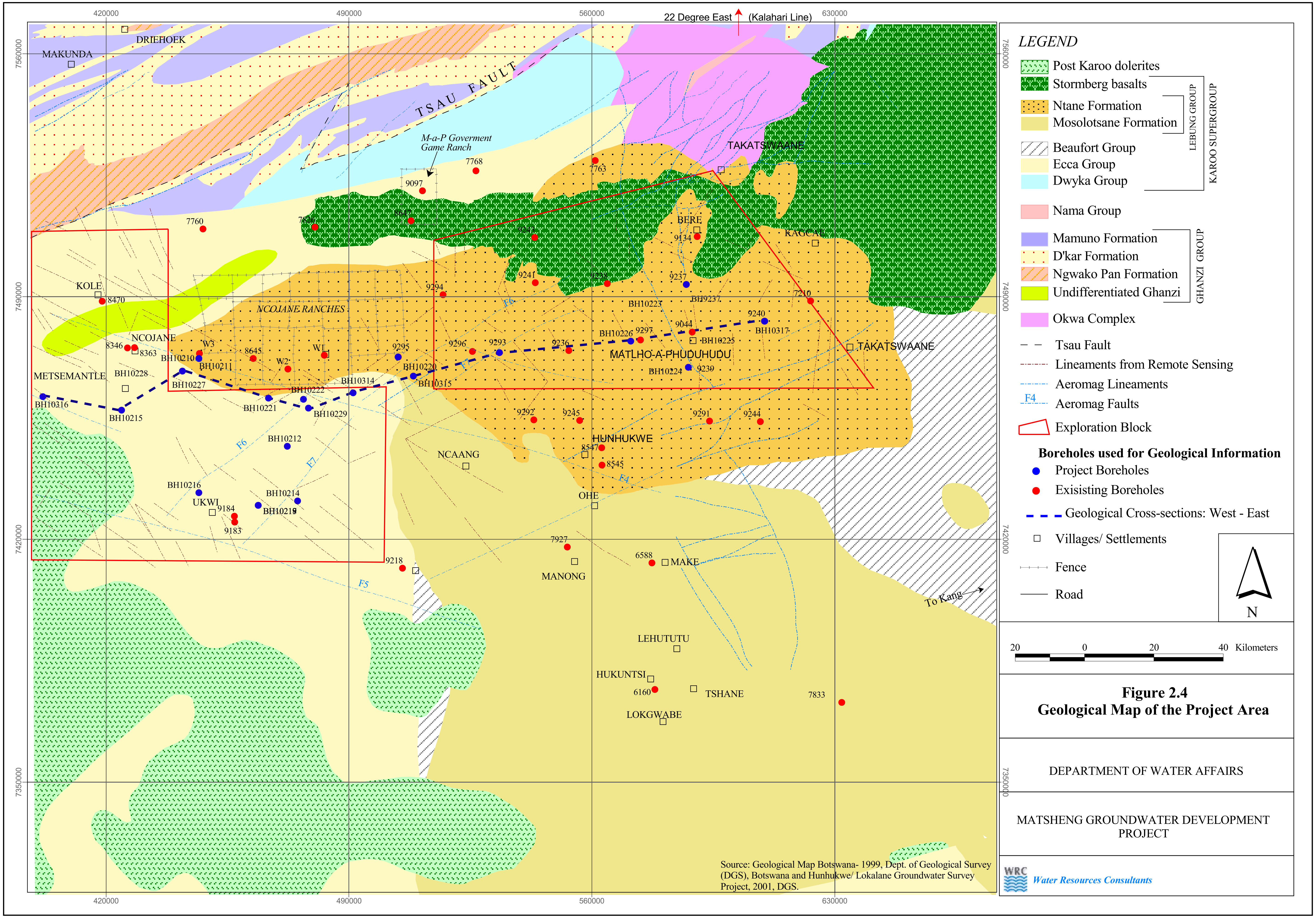

Figure 2.4
Geological Map of the Project Area

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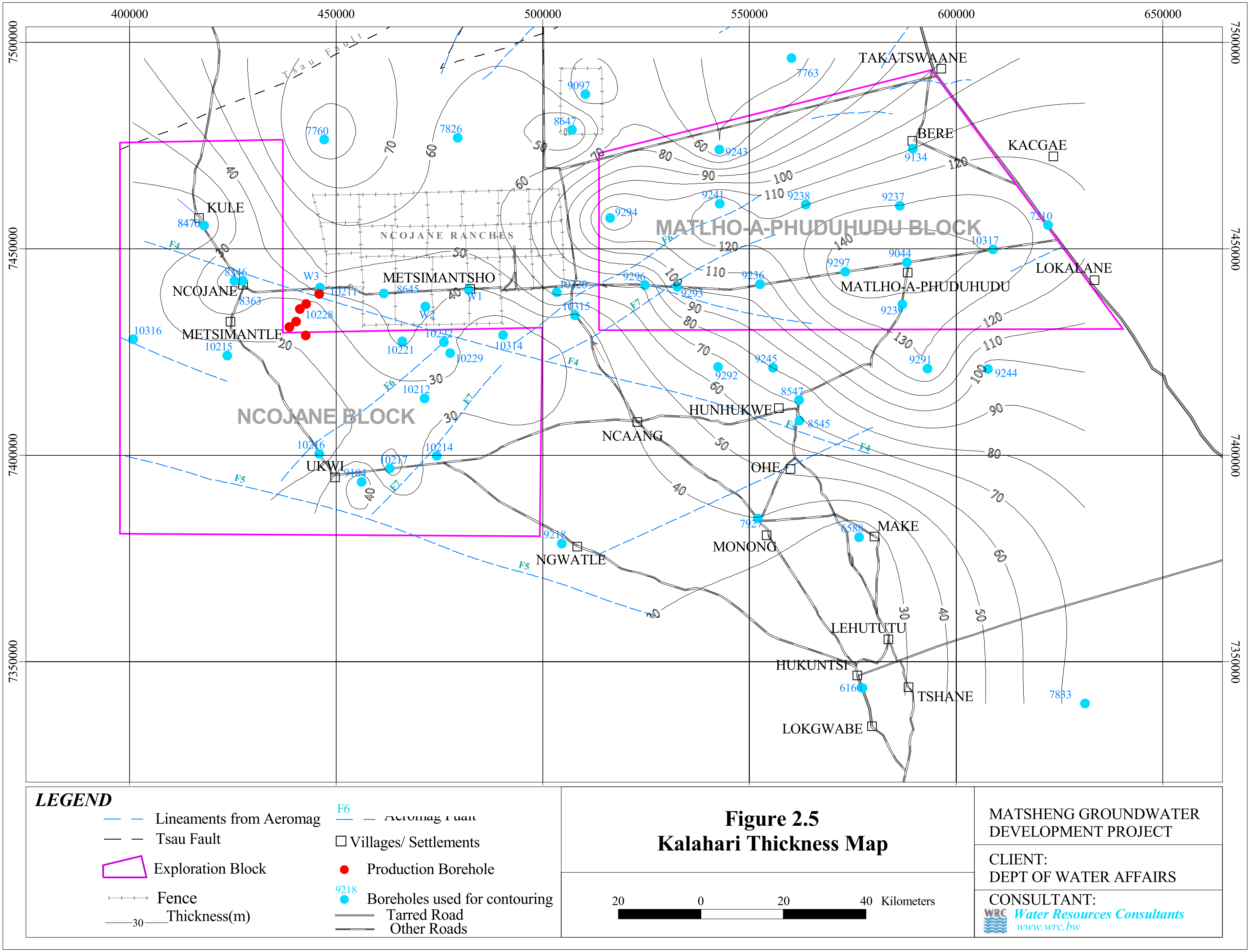

Figure 2.5
Kalahari Thickness Map

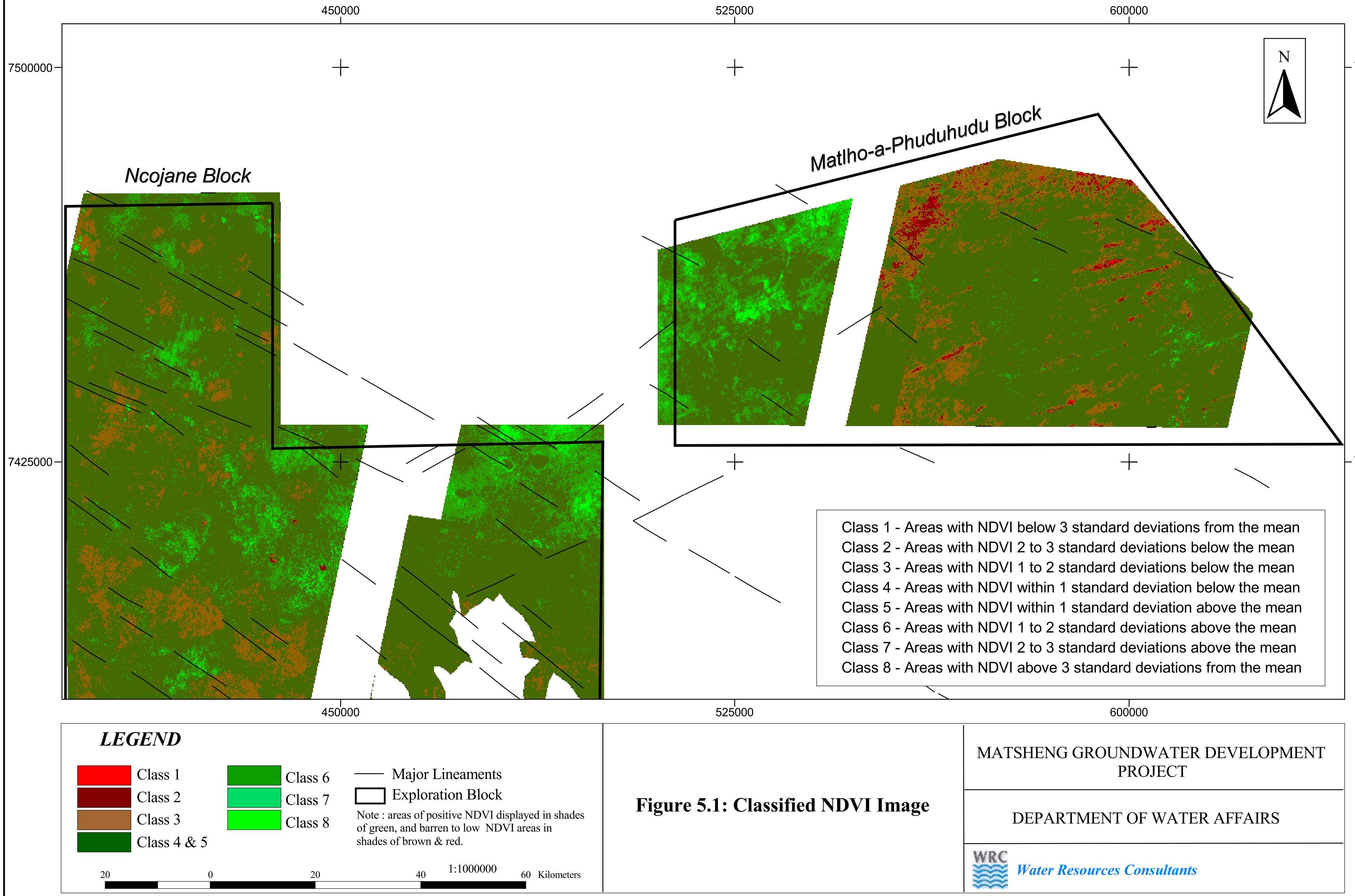

Figure 5.1: Classified NDVI Image

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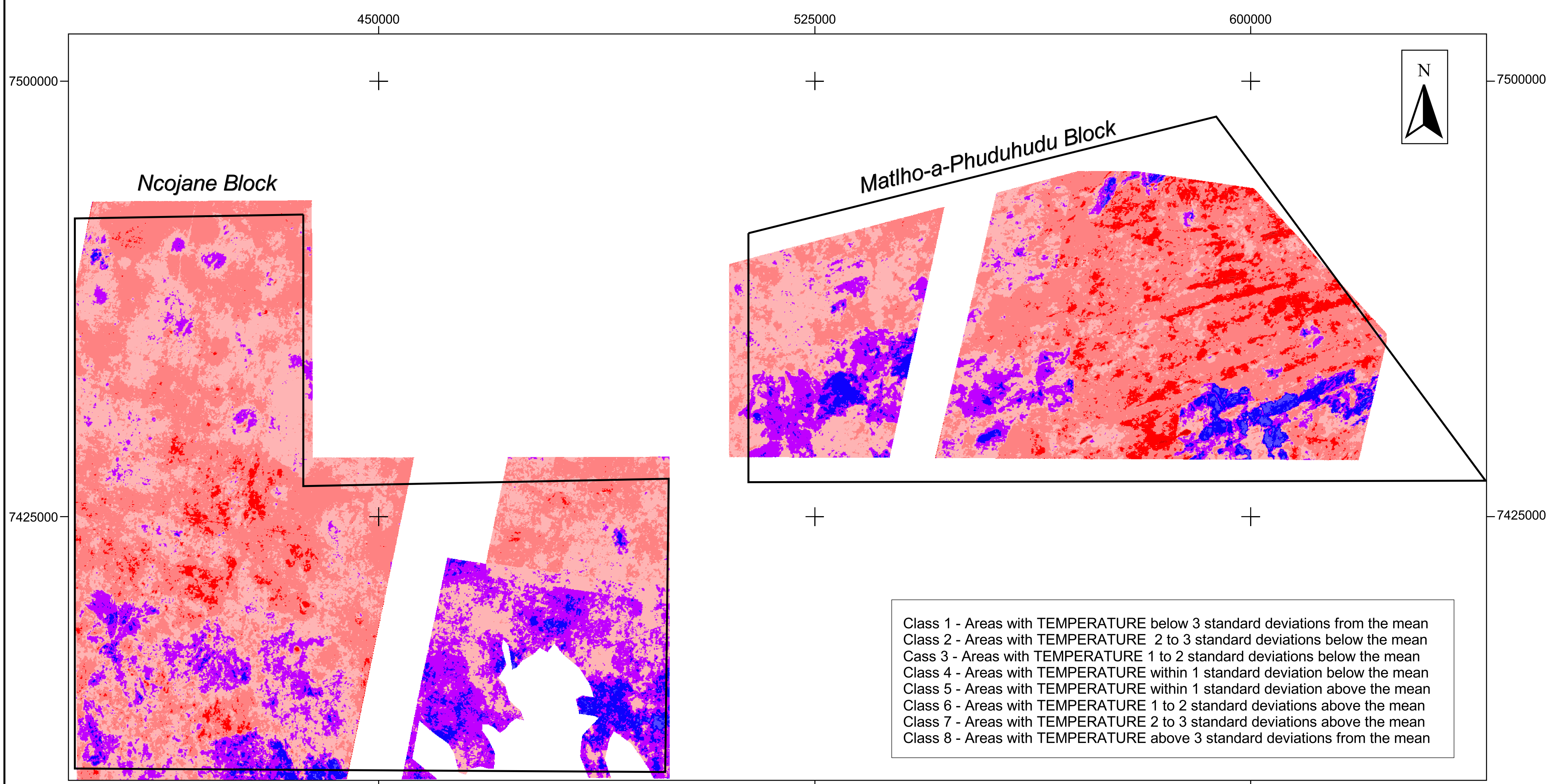

LEGEND

Class 1
Class 2
Class 3
Class 4
Class 5
Class 6
Class 7
Class 8

Exploration Blocks

Note : Thermal lows- blue and highs - red

20 0 20 Kilometers

Figure 5.2: Classified Temperature Image

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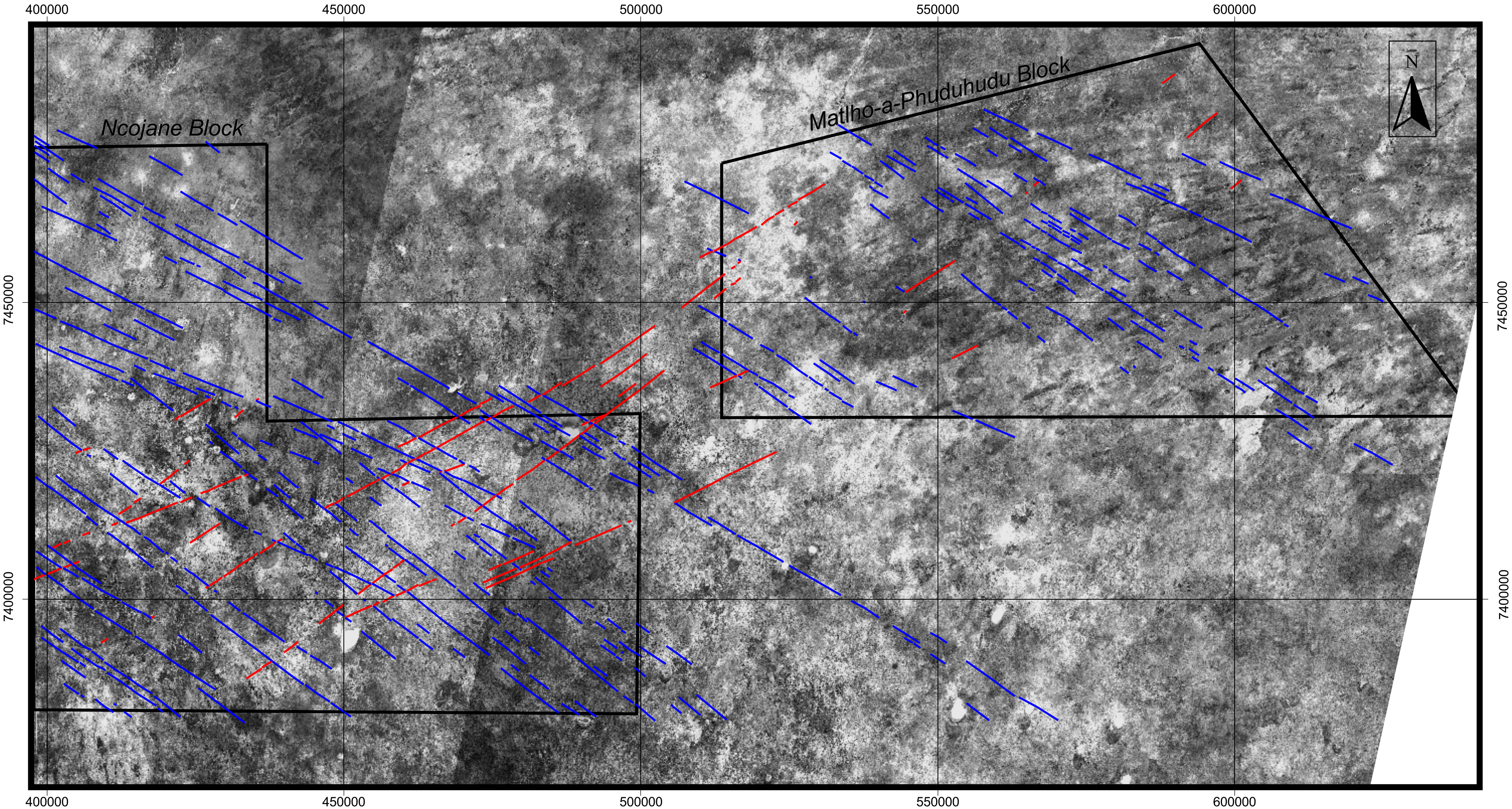

LEGEND

Lineaments
Strike- 240
Strike- 300

Exploration Blocks

(Background: Landsat ETM Band 8 Image)

20 0 20 Kilometers

Figure 5.3:
Filtered and Classified Lineaments

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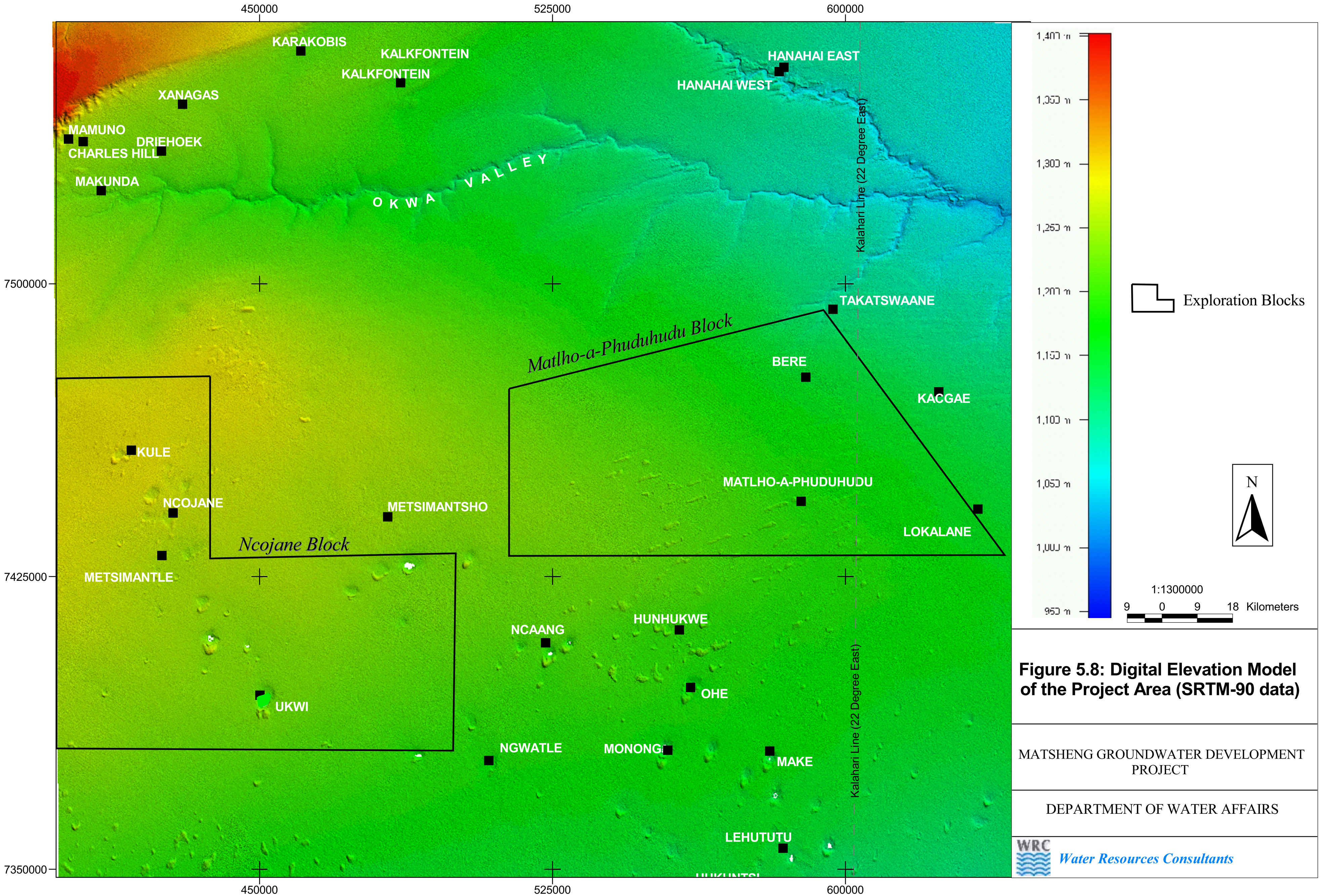

Figure 5.8: Digital Elevation Model of the Project Area (SRTM-90 data)

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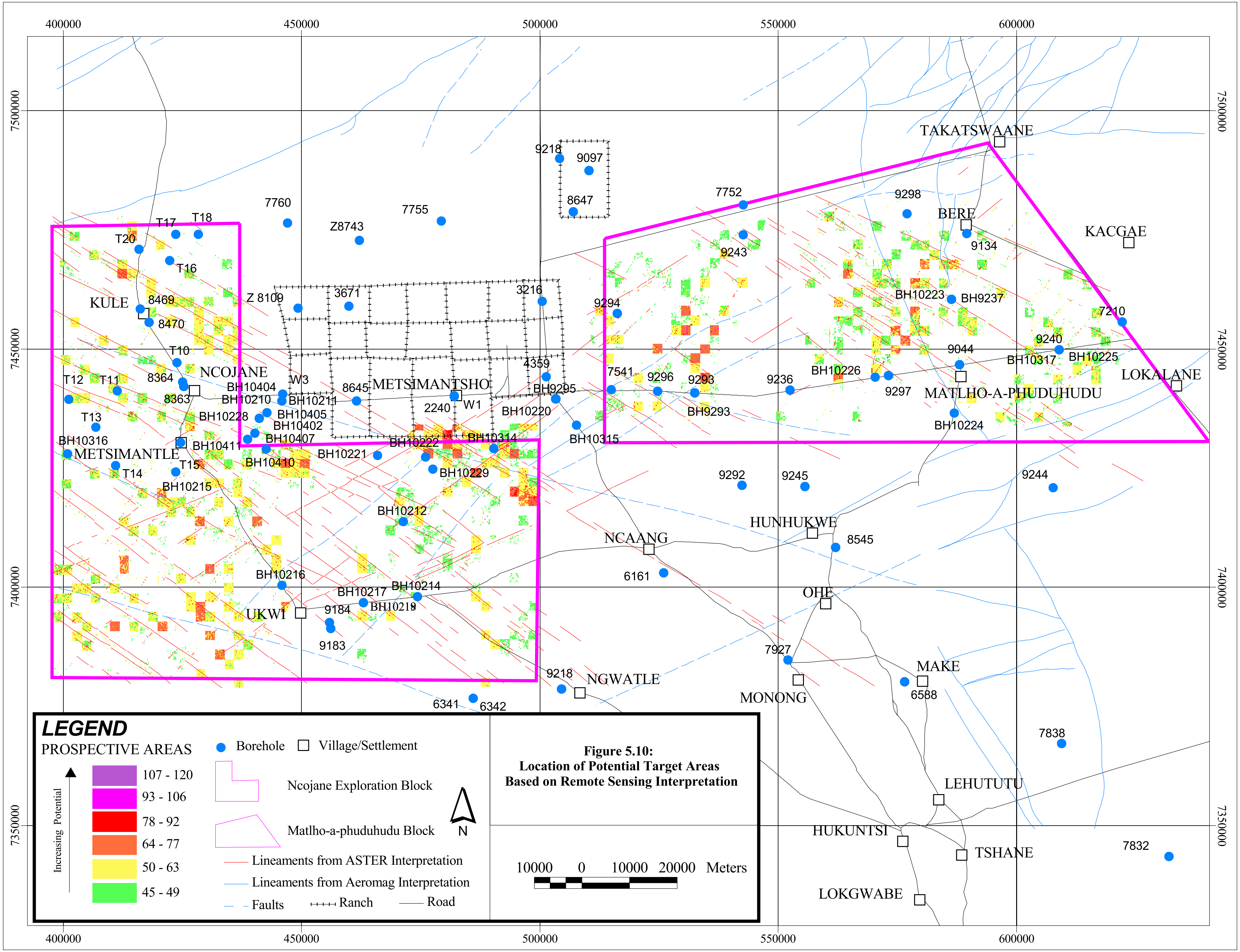
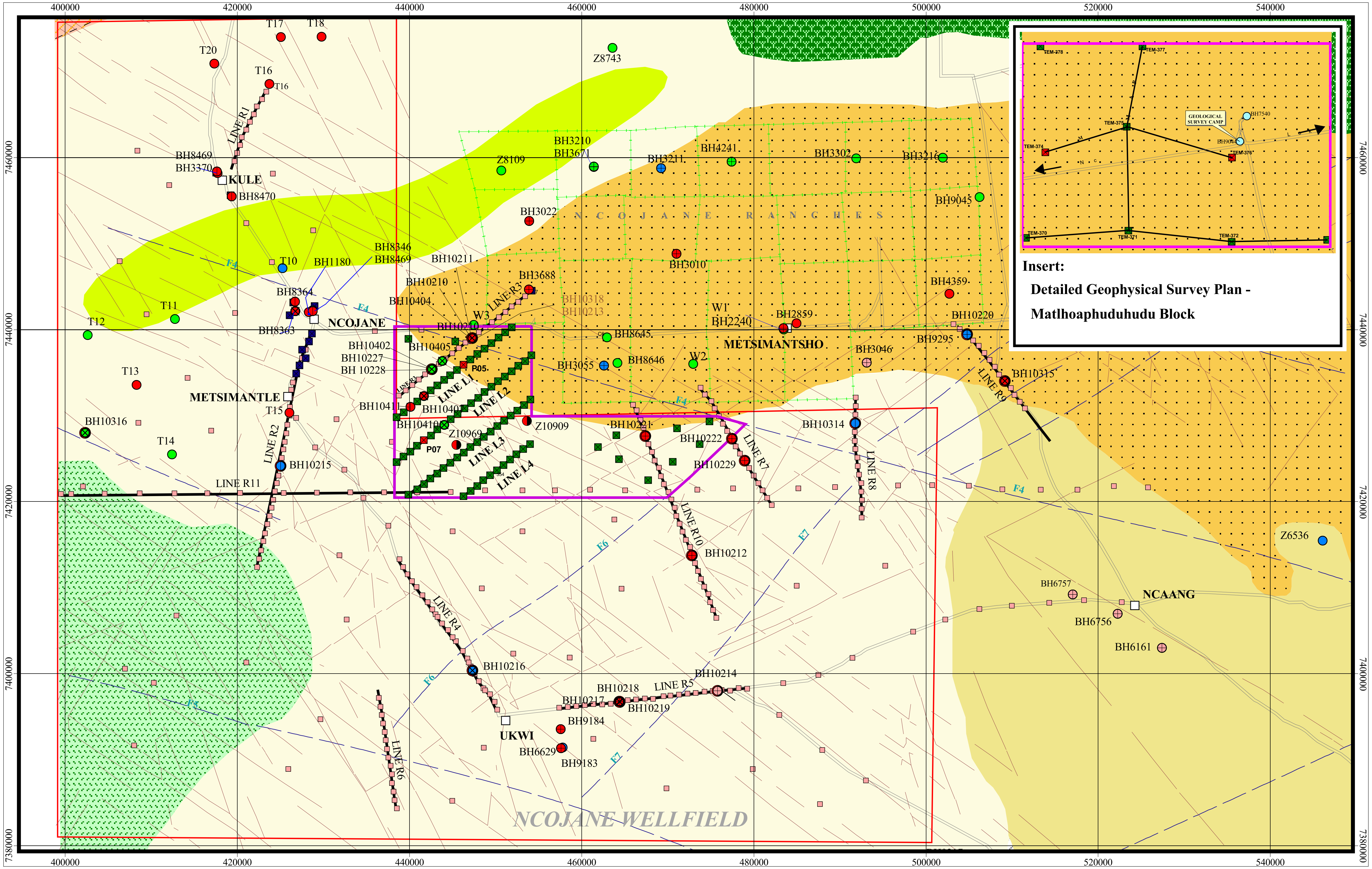


Figure 5.10: Location of Potential Target Areas Based on Remote Sensing Interpretation



LEGEND

- Post Karoo Dolerites
- Stormberg Basalts
- Ntane Formation
- Mosolotsane Formation
- Ecca Group
- Ngwako Pan Formation
- Undifferentiated Ghanzi

LEBUNG GROUP

KAROO SUPERGROUP

- Recommeded Production Drilling Sites
- TEM Soundings (Exploration)
- TEM Soundings Production
- Calibration Soundings
- Calibration Soundings
- Possible Boundary (Remote Sensing)
- F6 Lineaments from Aeromag
- Lineaments from Remote Sensing
- LINE R8 Profile Lines Surveyed
- Welfield Area
- Fence
- Road
- Villages/ Settlements

Boreholes:

- TDS <= 450 (mg/L)
- TDS: 450 - 1000 (mg/L)
- TDS:1000 - 2000 (mg/L)
- TDS >=2000 (mg/L)
- Yield > 50 cubic meter/ hr
- Yield : 30 - 50 cubic meter/ hr
- Yield < 30 cubic meter/ hr

(Yield data not available for all BH)

- Private Borehole

T10, Private Boreholes Without Numbers

SCALE 1: 175,000

Coordinate System: UTM Zone 34S

Datum: Cape, Spheroid: Clarke 1880

3 0 3 6 Kilometers

N

Source: Geological Map Botswana- 1999, Dept. of Geological Survey (DGS), Hunhukwe/ Lokalane Groundwater Survey Project, 2001, DGS.

Figure 6.1:

Detailed Geophysical Survey Plan

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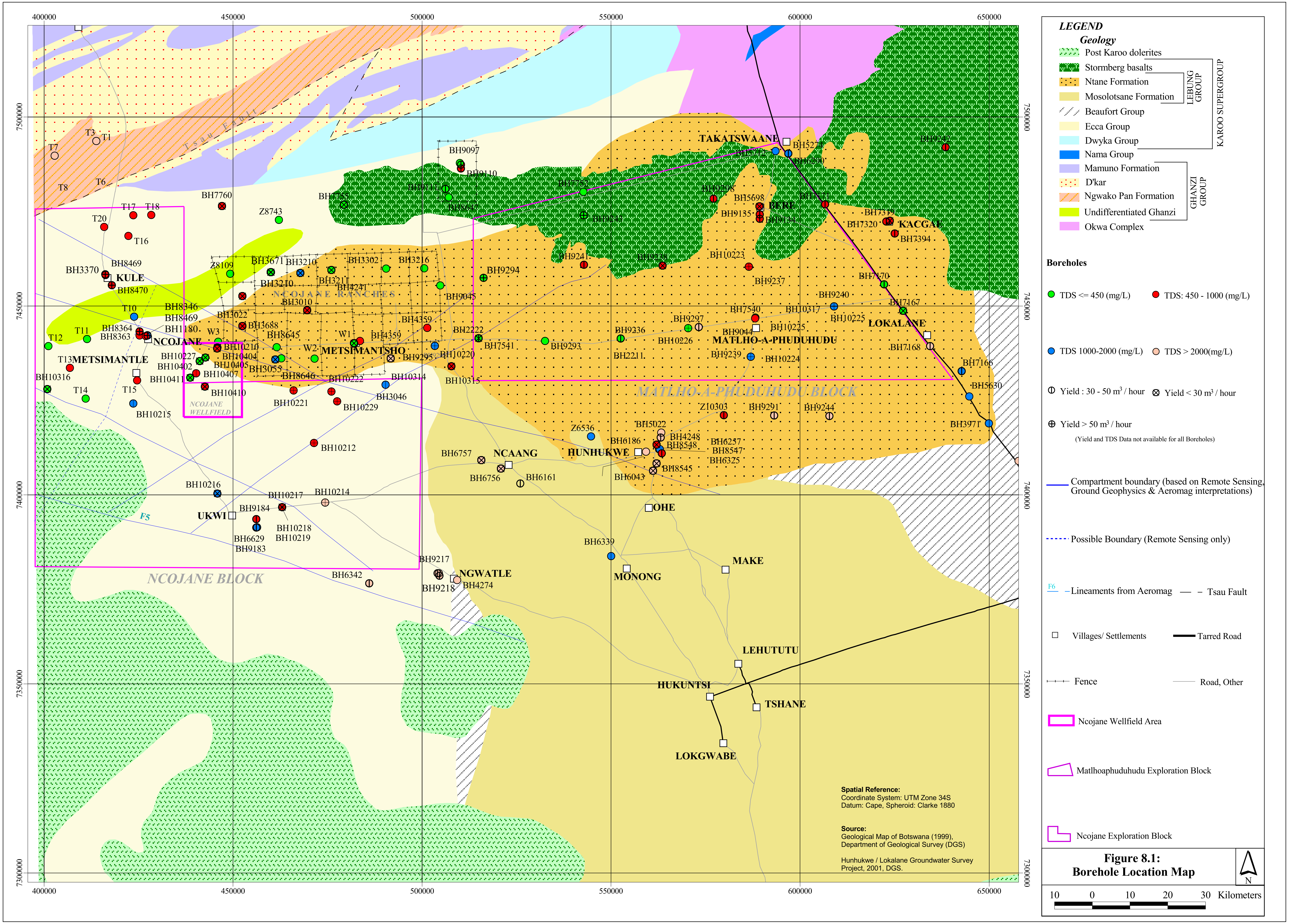
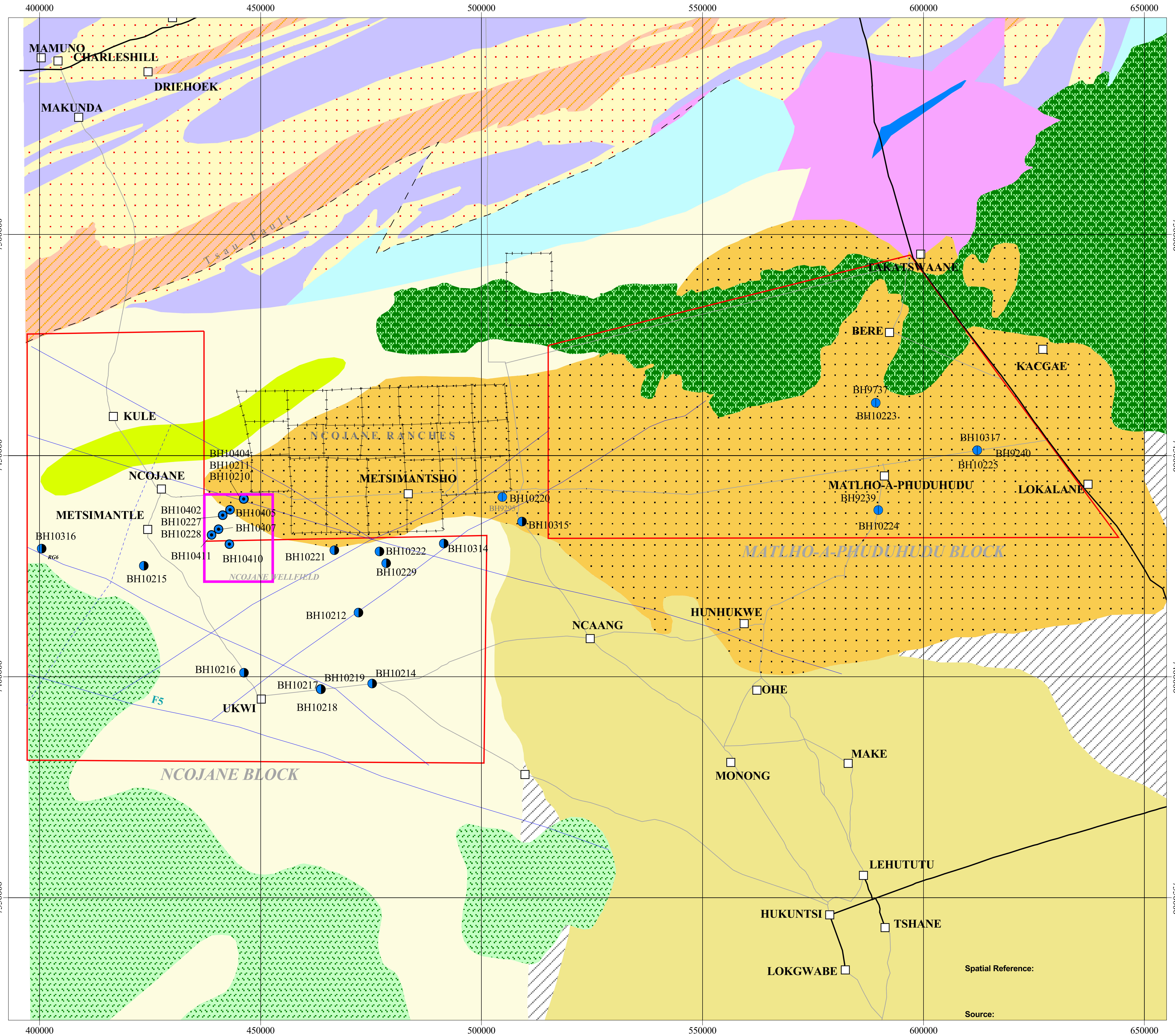


Figure 8.1:
Borehole Location Map



LEGEND

Geology

- Post Karoo dolerites
- Stormberg basalts
- Ntane Formation
- Mosolotsane Formation
- Beaufort Group
- Ecca Group
- Dwyka Group
- Nama Group
- Mamuno Formation
- D'kar
- Ngwako Pan Formation
- Undifferentiated Ghanzi
- Okwa Complex

LEBUNG GROUP

KAROO SUPERGROUP

GHANZI GROUP

Borehole

- Production Borehole
- Exploration Borehole
- Monitoring Borehole
- Compartment boundary (based on Remote Sensing, Ground Geophysics & Aeromag interpretations)
- Possible Boundary (Remote Sensing only)
- F6 Lineaments from Aeromag
- Tsau Fault
- Villages/ Settlements
- Tarred Road
- Fence
- Road, Other
- Ncojane Wellfield Area
- Matlhoaphuduhudu Exploration Block
- Ncojane Exploration Block

Table 1: TDS and Yield for Production Boreholes

Borehole	Easting	Northing	TDS	Yield	Legend
BH10402	441130	7435358	442	53	**Production**
BH10404	445760	7438700	538	64	**Production**
BH10405	442666	7436299	416	78	**Production**
BH10407	440170	7432108	461	51	**Production**
BH10410	442531	7428629	442	74	**Production**
BH10411	438640	7431014	550	44	**Production**

Table 2: TDS and Yield for Project Boreholes

Borehole	Easting	Northing	Tds	Yield	Legend
BH9295	503305	7439434	1190	50	**Cleaned**
BH10220	503298	7439428	1144	Na	**Monitoring**
BH10210	445827	7439007	358	Na	**Monitoring**
BH10221	465933	7427586	822	12	**Exploration**
BH10222	475982	7427299	858	12	**Exploration**
BH10223	586358	7460350	809	Na	**Monitoring**
BH10227	441140	7435377	410	Na	**Monitoring**
BH10224	586902	7436518	1918	Na	**Monitoring**
BH10225	608914	7449809	358	Na	**Monitoring**
BH10215	423550	7424116	1437	37	**Exploration**
BH10228	441134	7435388	378	93	**Exploration**
BH10211	445818	7439004	480	70	**Exploration**
BH10216	445843	7400347	1200	51	**Exploration**
BH10226	570319	7444055	308	Na	**Monitoring**
BH10229	477486	7424731	864	20	**Exploration**
BH9237	586367	7460348	580	Na	**Cleaned**
BH10217	462926	7396725	7542	Na	**Monitoring**
BH10314	490310	7429080	1806	43	**Exploration**
BH10212	471357	7413720	793	25	**Exploration**
BH10315	507682	7433985	579	55	**Exploration**
BH10218	462941	7396727	939	Na	**Monitoring**
BH10316	400854	7427983	179	95	**Exploration**
BH10219	462945	7396707	794	95	**Exploration**
BH10317	608900	7449809	1694	Na	**Monitoring**
BH10214	474333	7397979	2016	3	**Exploration**

Units of Measure: TDS - mg/L and Tested Yield - Cubic Metres, EC - Micro Siemens / Centimeter

Figure 9.1: Location of Tested Boreholes

N

10 0 10 20 30 Kilometers

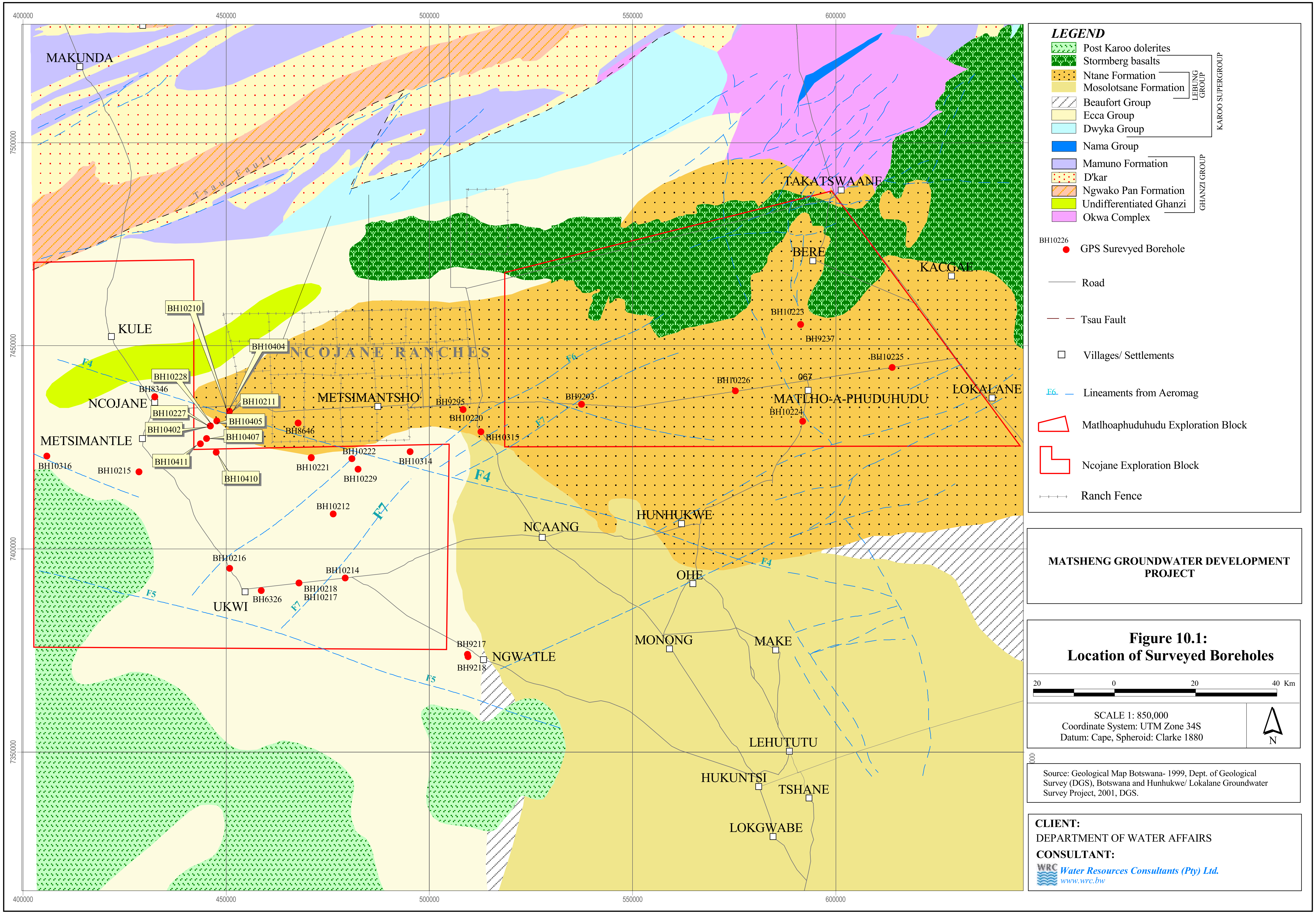
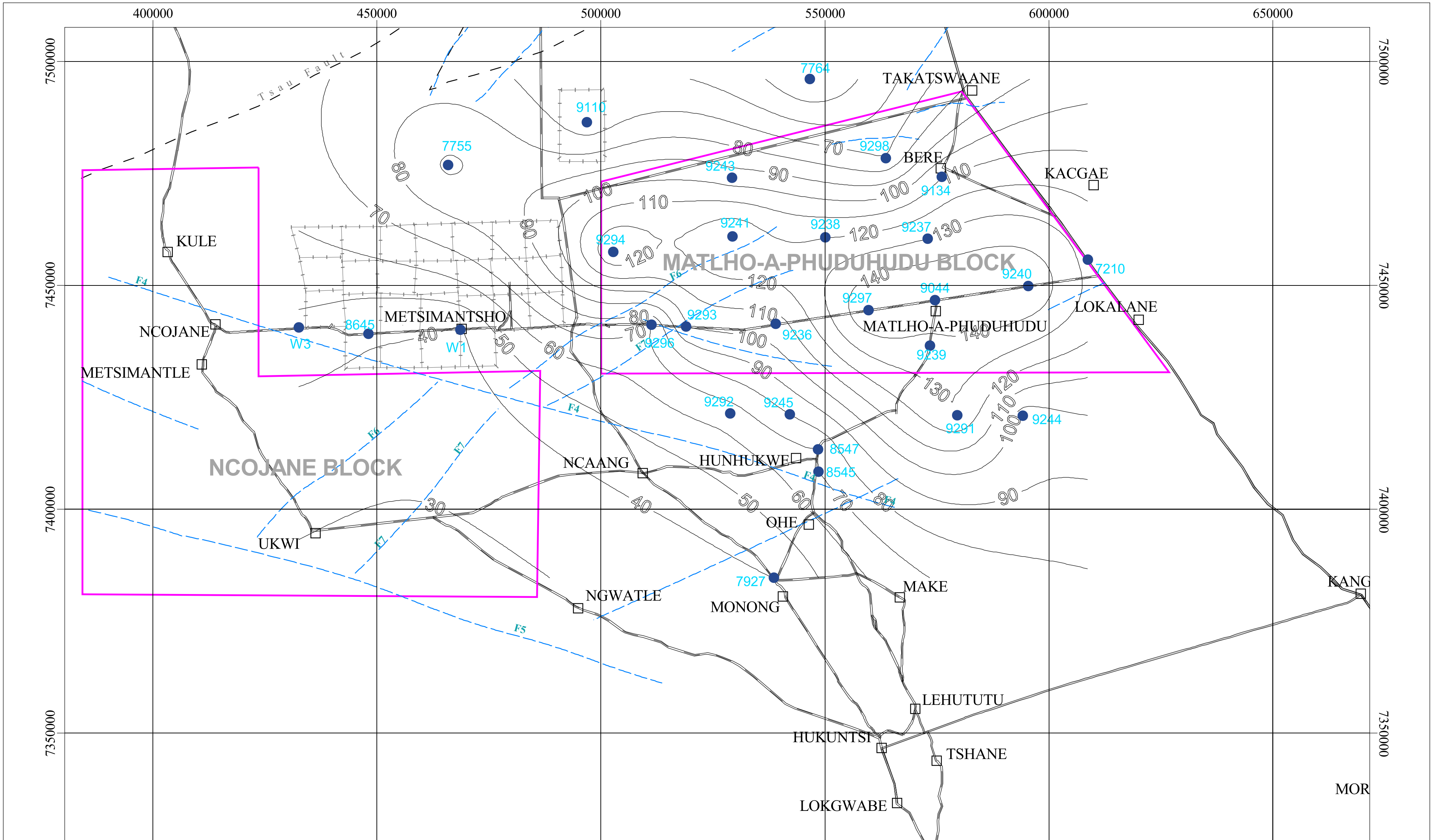


Figure 10.1: Location of Surveyed Boreholes



LEGEND

- Lineaments from Aeromag
- F6 Aeromag Fualt
- Exploration Block
- Villages/ Settlements
- Tsau Fault
- Farm Boundary
- 9292 Boreholes used for contouring
- 30 Depth(m)
- Tarred Road
- Other Roads

Figure 11.1
Depth to Top of Ntane Sandstone

Scale 1:1 200 000

20 0 20 40 Kilometers

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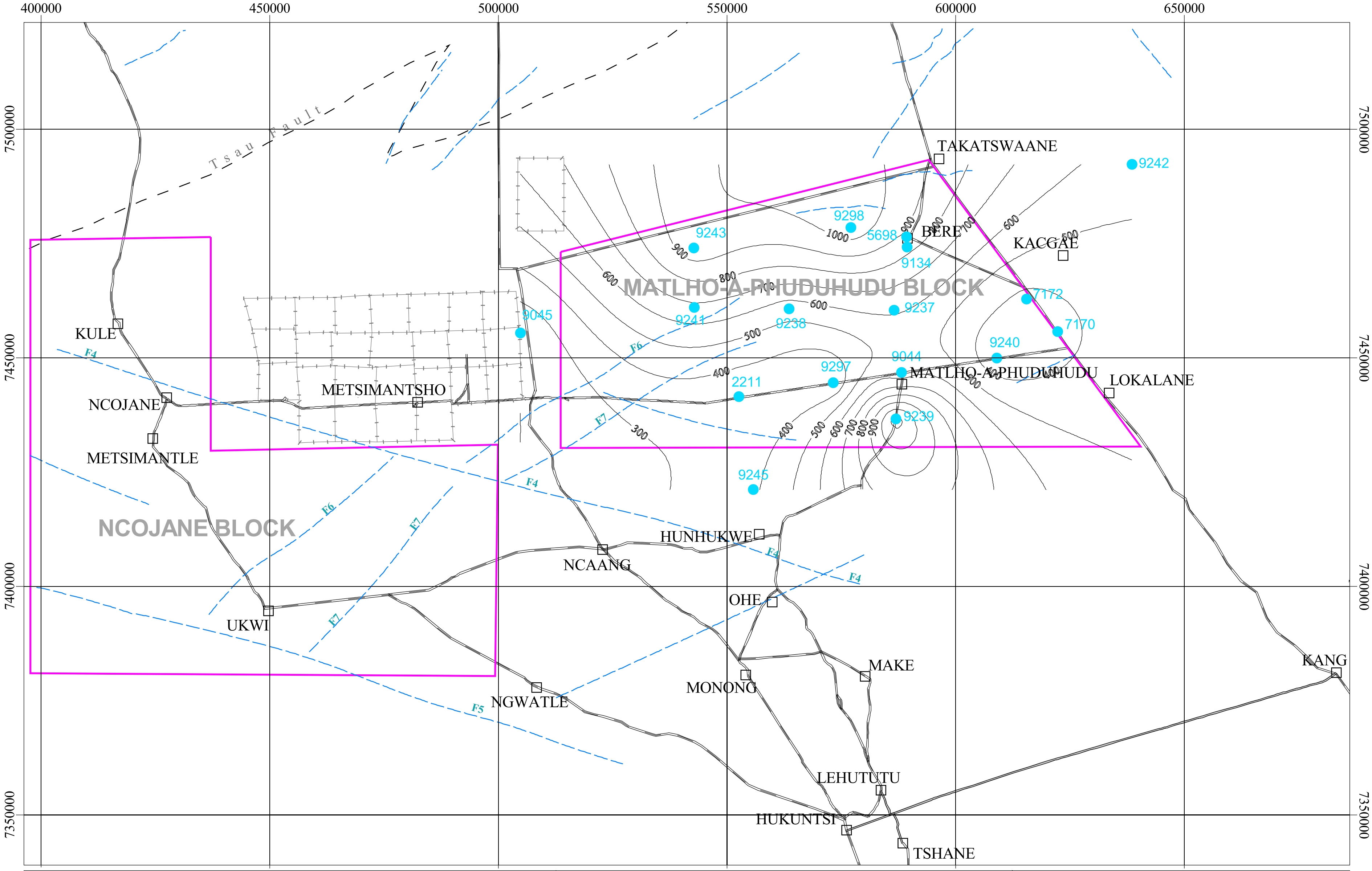

LEGEND

Lineaments from Aeromag
F6 Aeromag Fualt
Exploration Block
Villages/ Settlements
Tsau Fault
Farm Boundary
9243 Boreholes used for contouring
300 Saturated Thickness(m)
Tarred Road
Other Roads

Figure 11.11
TDS Distribution Ntane Aquifer

Scale 1:1 200 000

20 0 20 40 Kilometers

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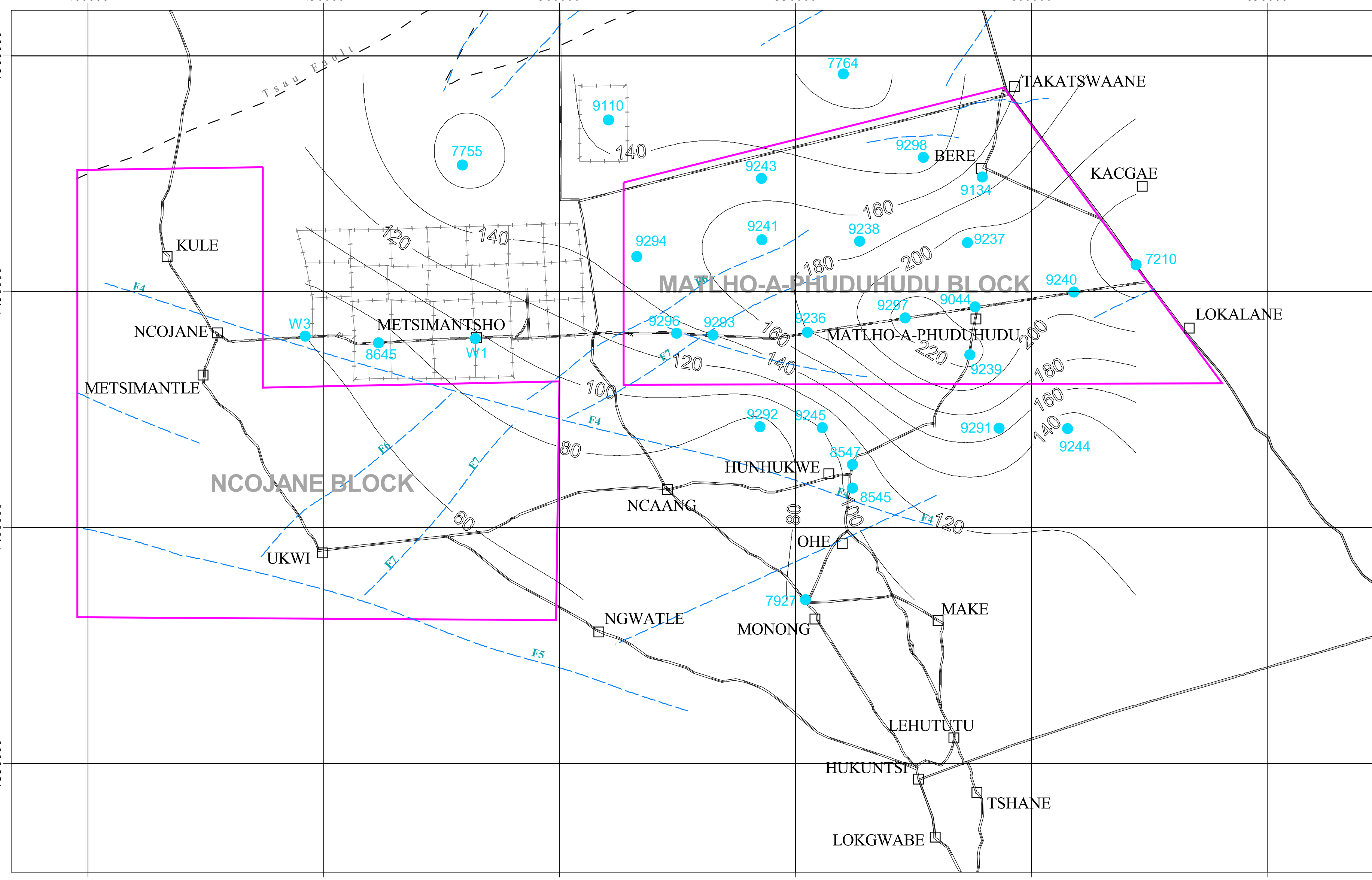

LEGEND

Lineaments from Aeromag

F6 Aeromag Fualt

Exploration Block

Villages/ Settlements

Tsau Fault

Farm Boundary

8645 Boreholes used for contouring

60 Depth(m)

Tarred Road

Other Roads

Figure 11.2:
Depth To Bottom of Ntane Sandstone

Scale 1:1 200 000

20 0 20 40 Kilometers

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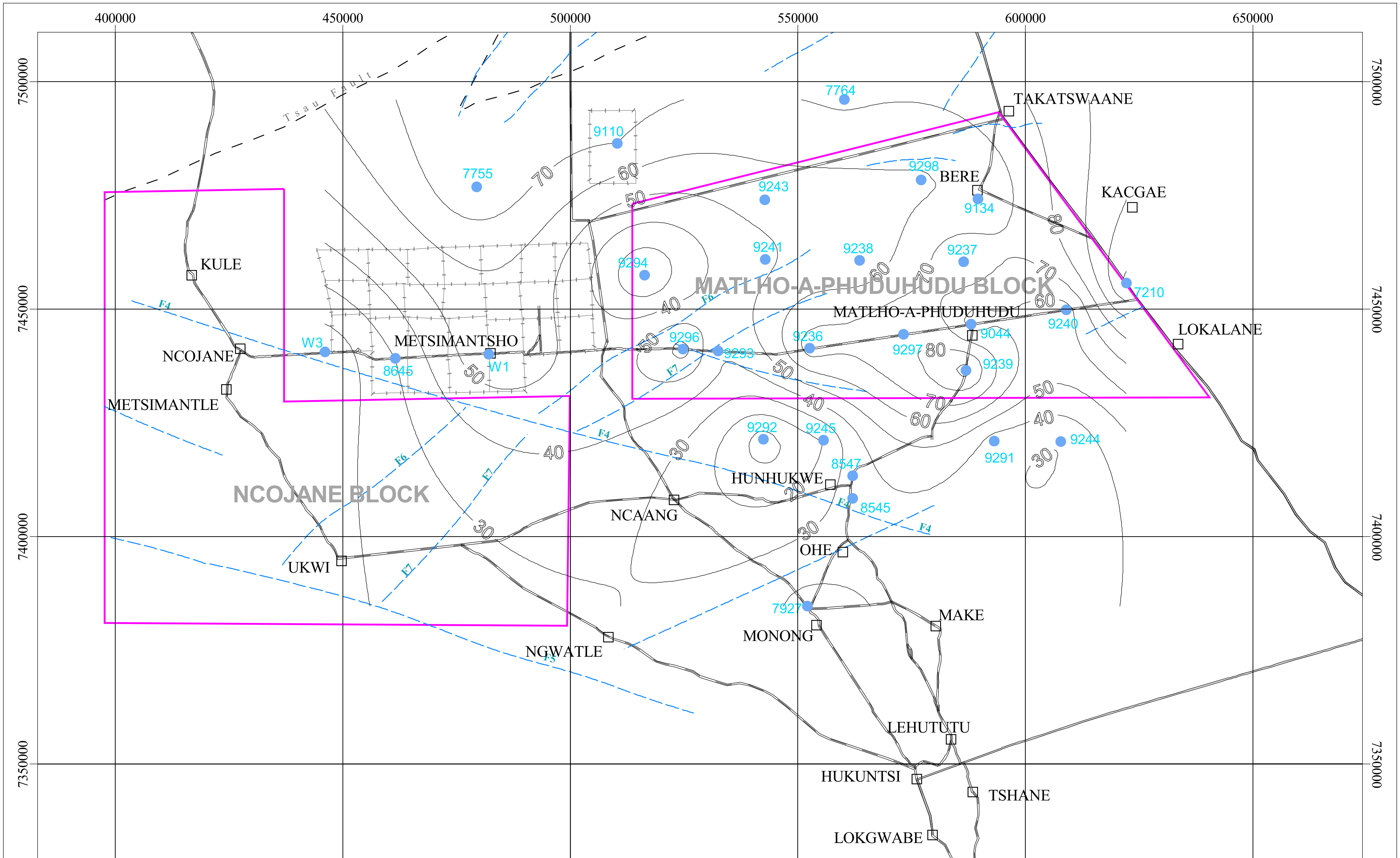

LEGEND

Lineaments from Aeromag — F6 Aeromag Fualt

Exploration Block — Villages/ Settlements — Tsau Fault

Farm Boundary — 9110 Boreholes used for contouring

30 Thickness(m) — Tarred Road — Other Roads

Figure 11.3:
Thickness of the Ntane Sandstone

Scale 1:1 200 000

20 0 20 40 Kilometers

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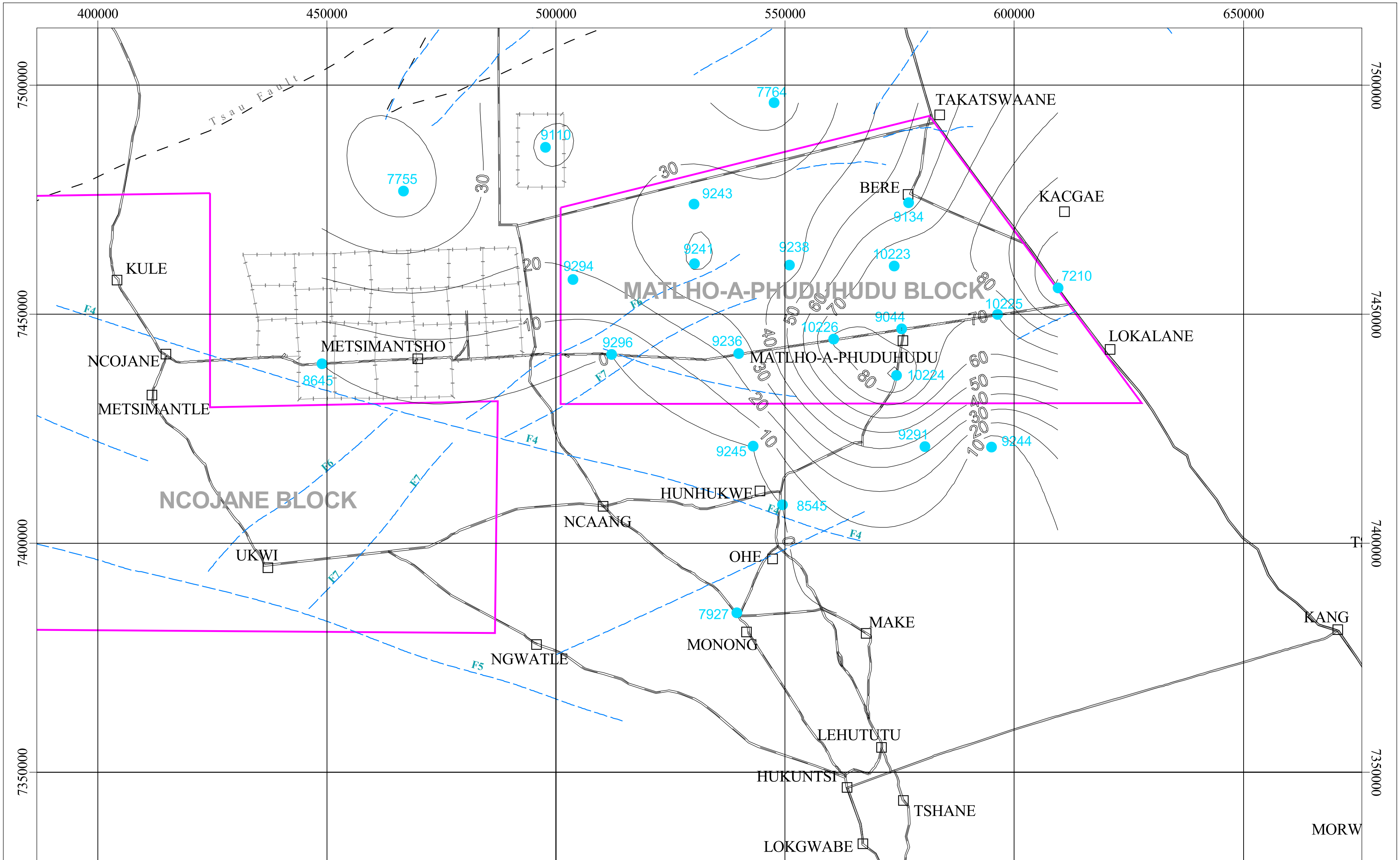

LEGEND

- Lineaments from Aeromag
- F6 Aeromag Fualt
- Exploration Block
- Villages/ Settlements
- Tsau Fault
- Farm Boundary
- 9110 Boreholes used for contouring
- 10 Saturated Thickness(m)
- Tarred Road
- Other Roads

Figure 11.4
Saturated Thickness of Ntane Sandstone

Scale 1:1 200 000

20 0 20 40 Kilometers

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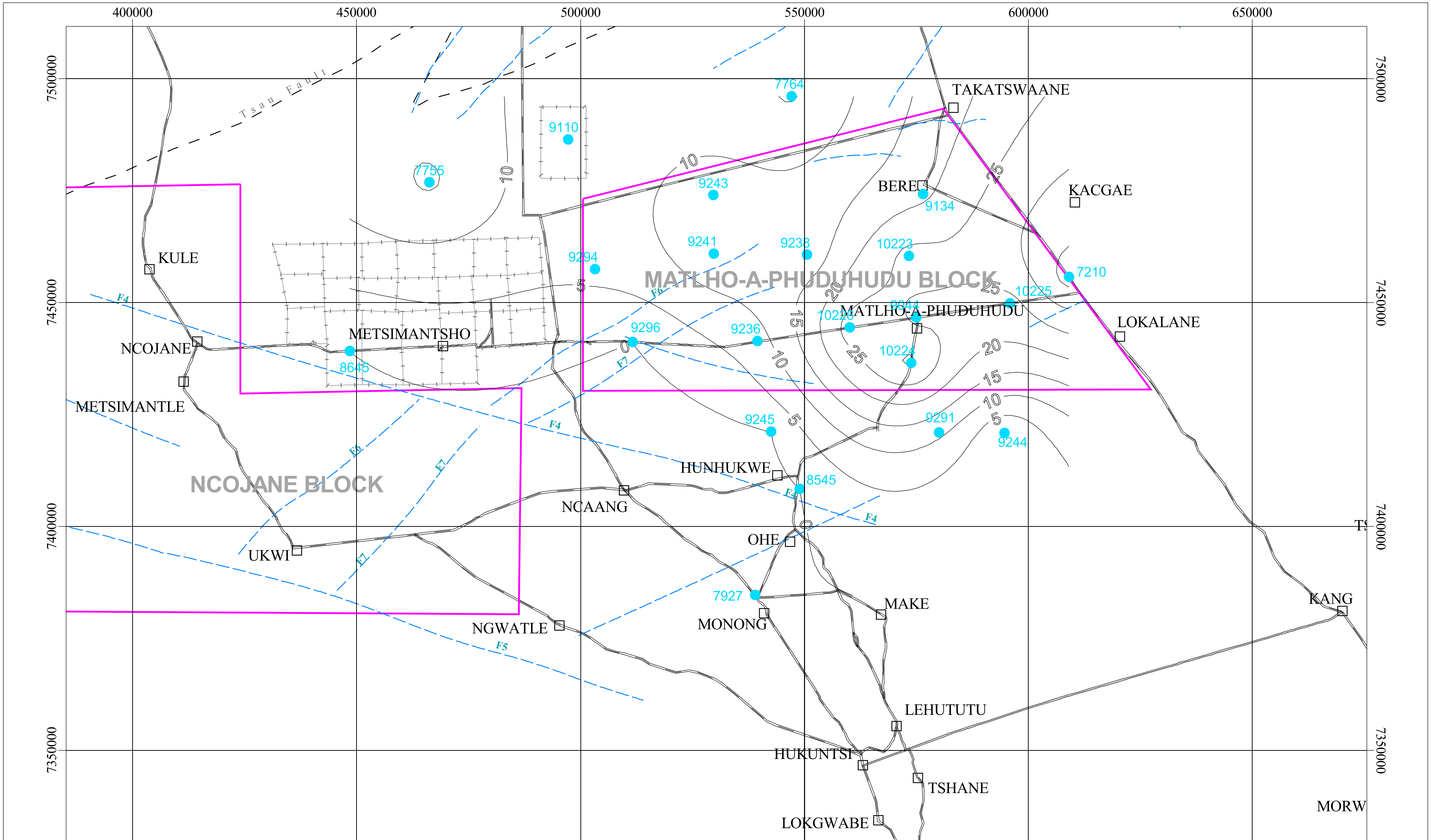

LEGEND

Lineaments from Aeromag
F6 Aeromag Fualt
Exploration Block
Villages/ Settlements
Tsau Fault
Farm Boundary
9110 Boreholes used for contouring
5 Exploitable Thickness(m)
Tarred Road
Other Roads

Figure 11.6:
Exploitable Saturated Thickness
Ntane Sandstone

Scale 1:1 200 000

20 0 20 40 Kilometers

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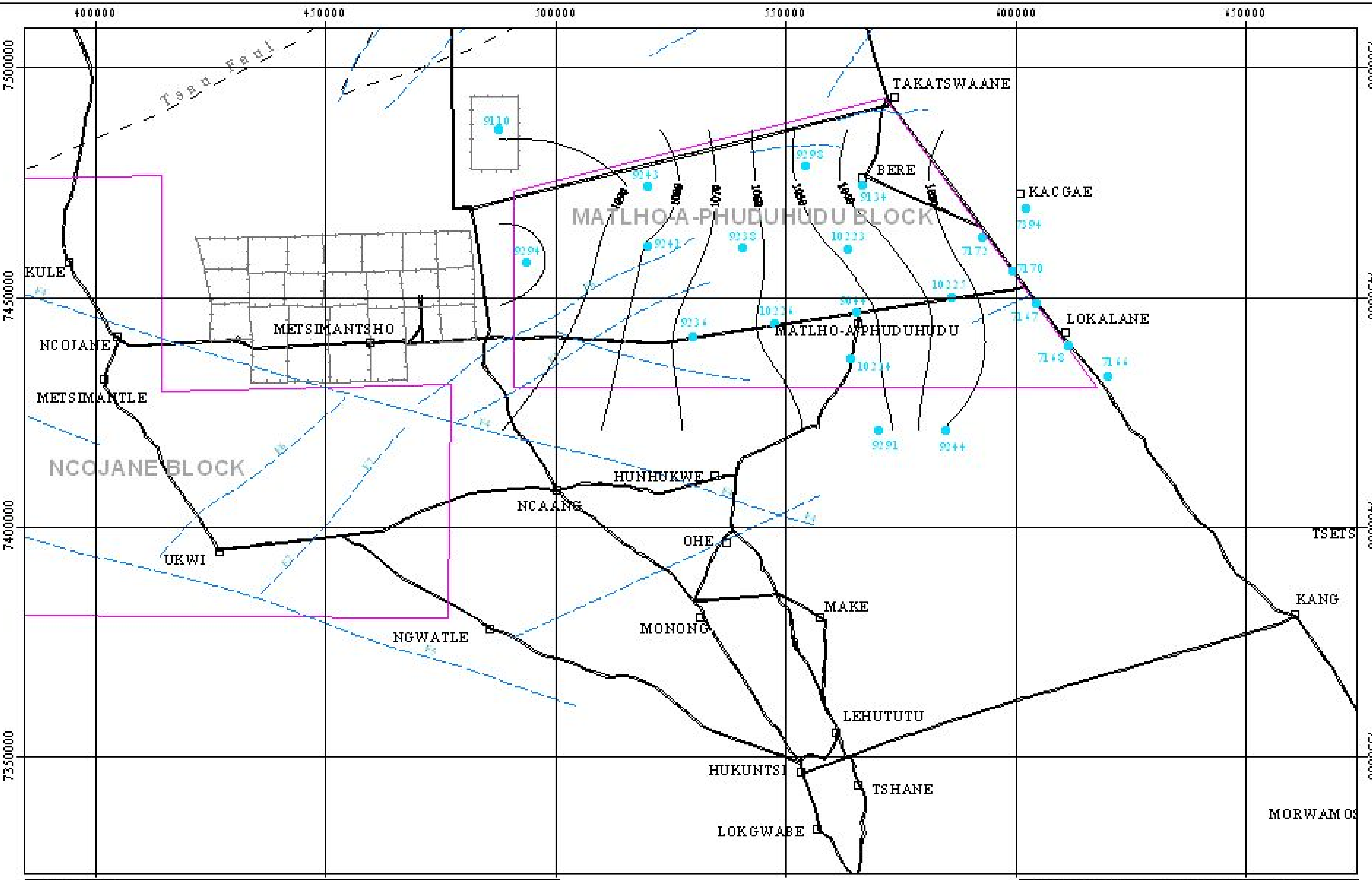


LEGEND	**Figure 11.7:**	MATSHENG GROUNDWATER DEVELOPMENT PROJECT
Lineaments from Aeromag; Aeromag Fualt	**Piezometric Head Ntane Sandstone**	CLIENT:
Exploration Block; Villages/ Settlements; Tsau Fault		DEPARTMENT OF WATER AFFAIRS
Farm Boundary; Boreholes used for contouring	**Scale 1:1 200 000**	CONSULTANT:
Saturated Thickness (m); Tarred Road; Other Roads	20 0 20 40 Kilometers	Water Resources Consultants (Pty) Ltd. www.wrc.bw

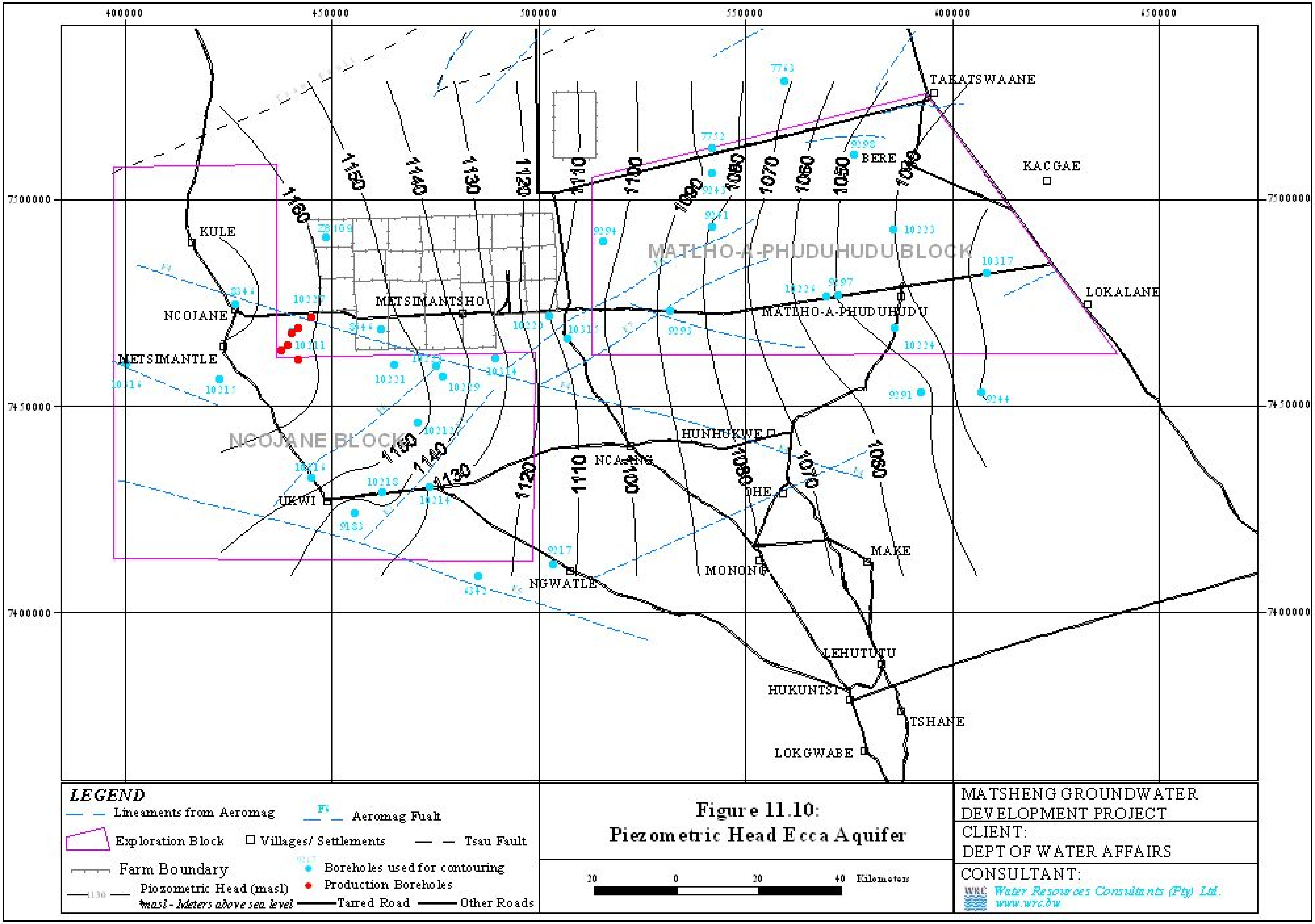
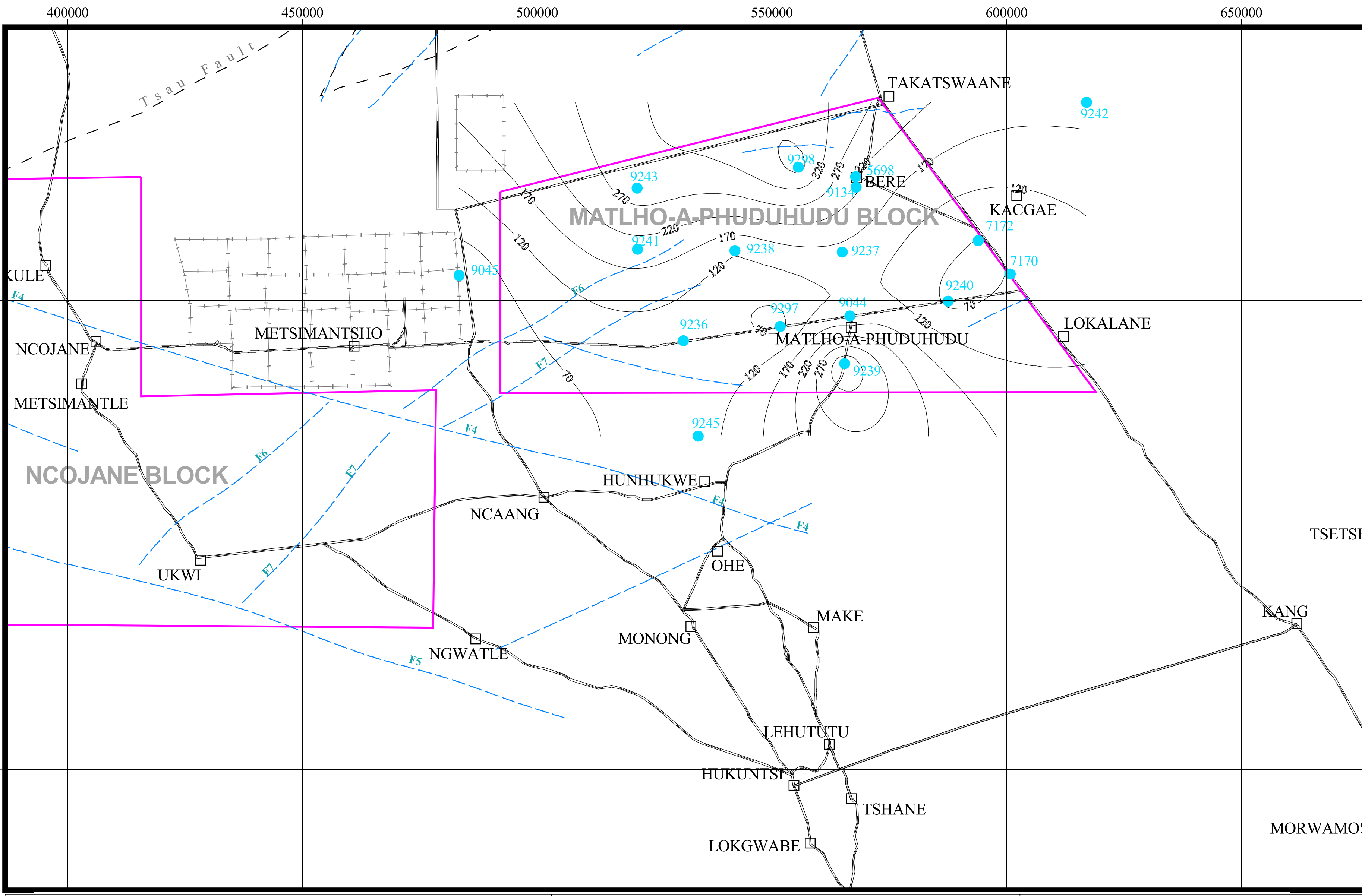


Figure 11.10: Piezometric Head Ecca Aquifer



LEGEND

Lineaments from Aeromag — F6 Aeromag Fualt

Exploration Block — Villages/ Settlements — Tsau Fault

Farm Boundary — 9245 Boreholes used for contouring

120 Saturated Thickness(m) — Tarred Road — Other Roads

Figure 11.12:
Sodium Distribution Ntane Sandstone

Scale 1:1 200 000

20 0 20 40 Kilometers

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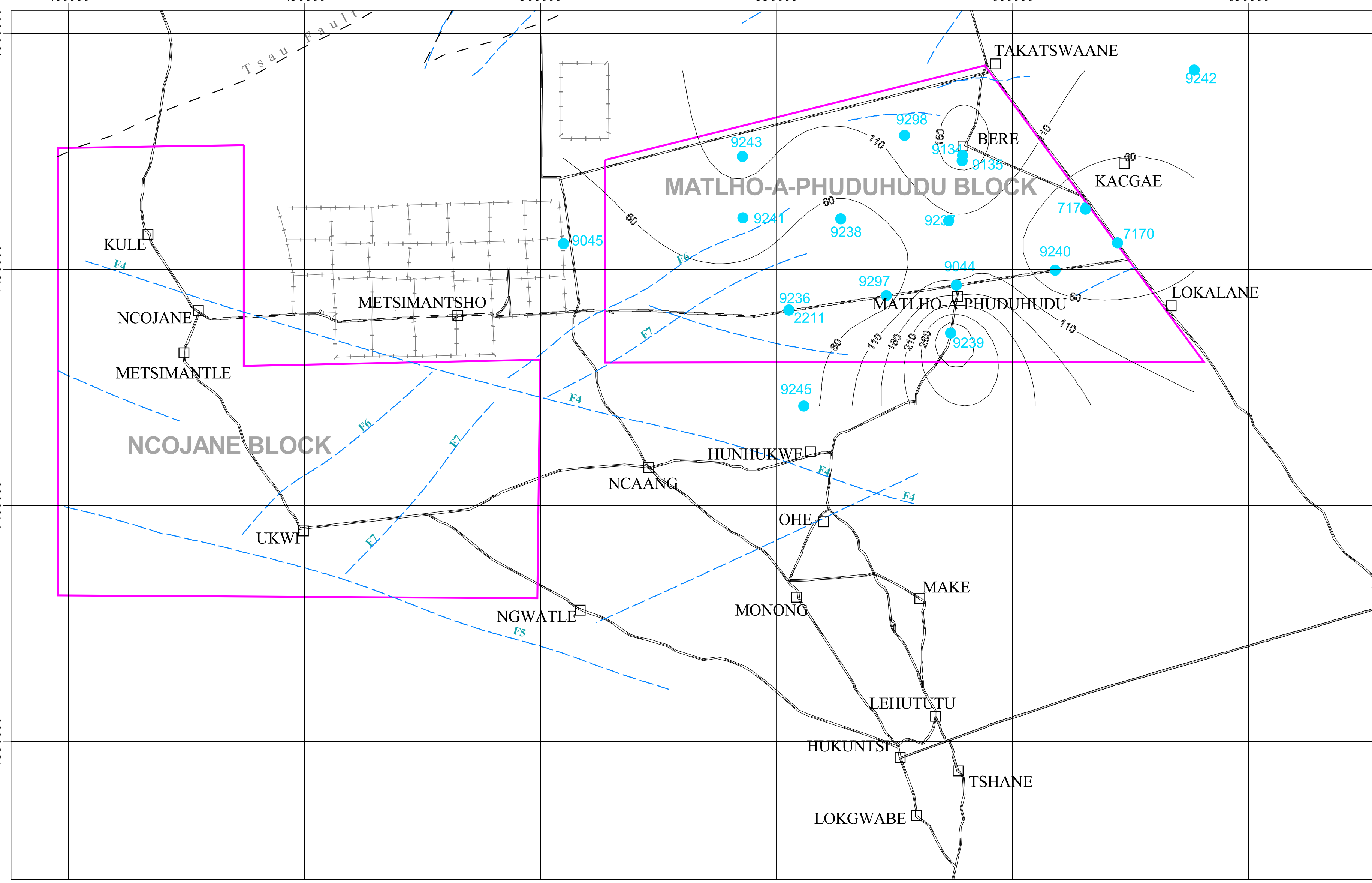

Figure 11.13:
Chloride Distribution Ntane Aquifer

Scale 1:1 200 000

20 0 20 40 Kilometers

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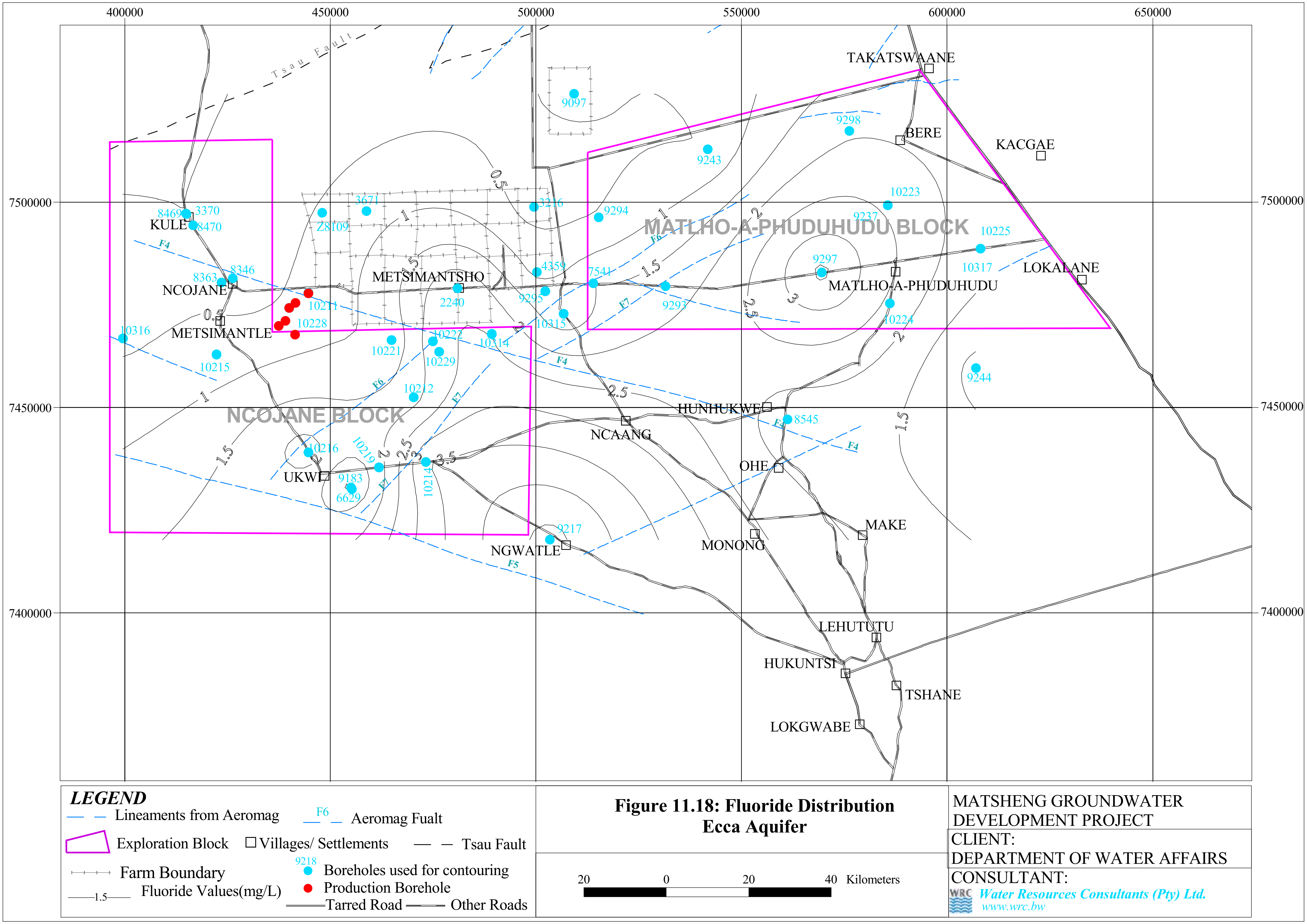

Figure 11.18: Fluoride Distribution Ecca Aquifer

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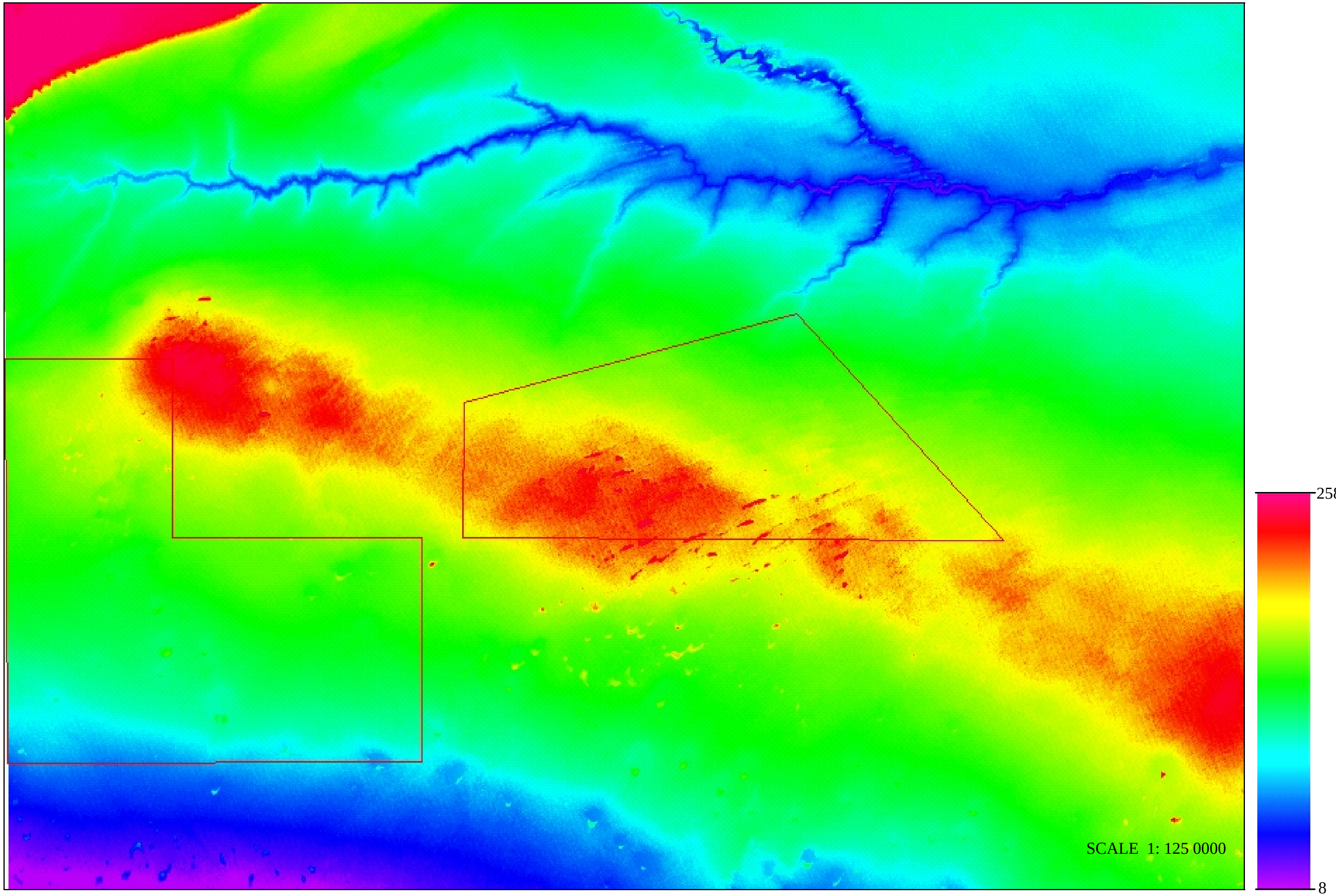
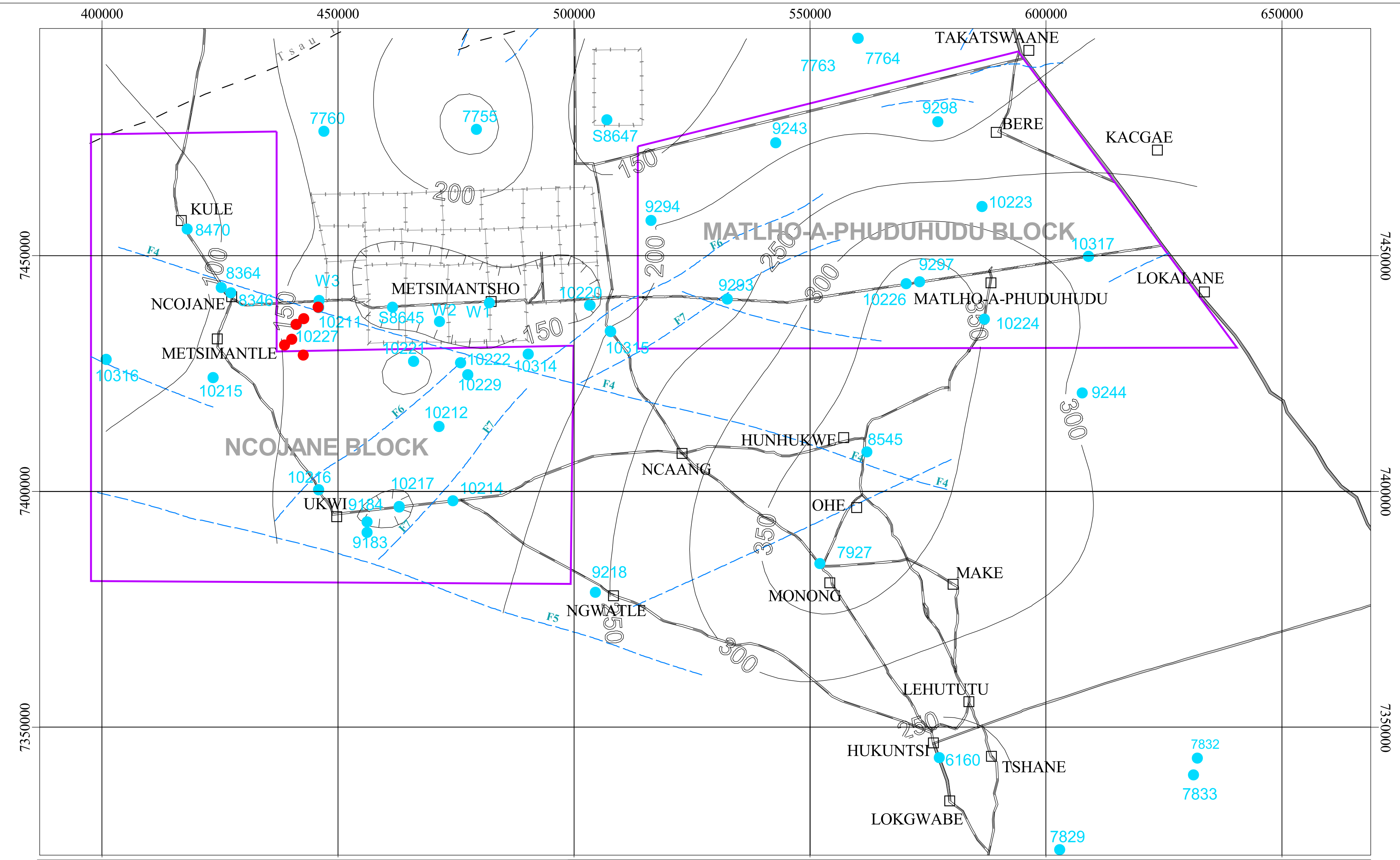


Figure 5.9: First Order Trend Surface from Topographic Surface



LEGEND

Lineaments from Aeromag — F6 Aeromag Fualt

Exploration Block — Villages/ Settlements — Tsau Fault

Farm Boundary — 7755 Boreholes used for contouring

150 Depth(m) — Production Boreholes

Tarred Road — Other Roads

Figure 11.9: Depth to Top of Ecca

20 0 20 40 Kilometers

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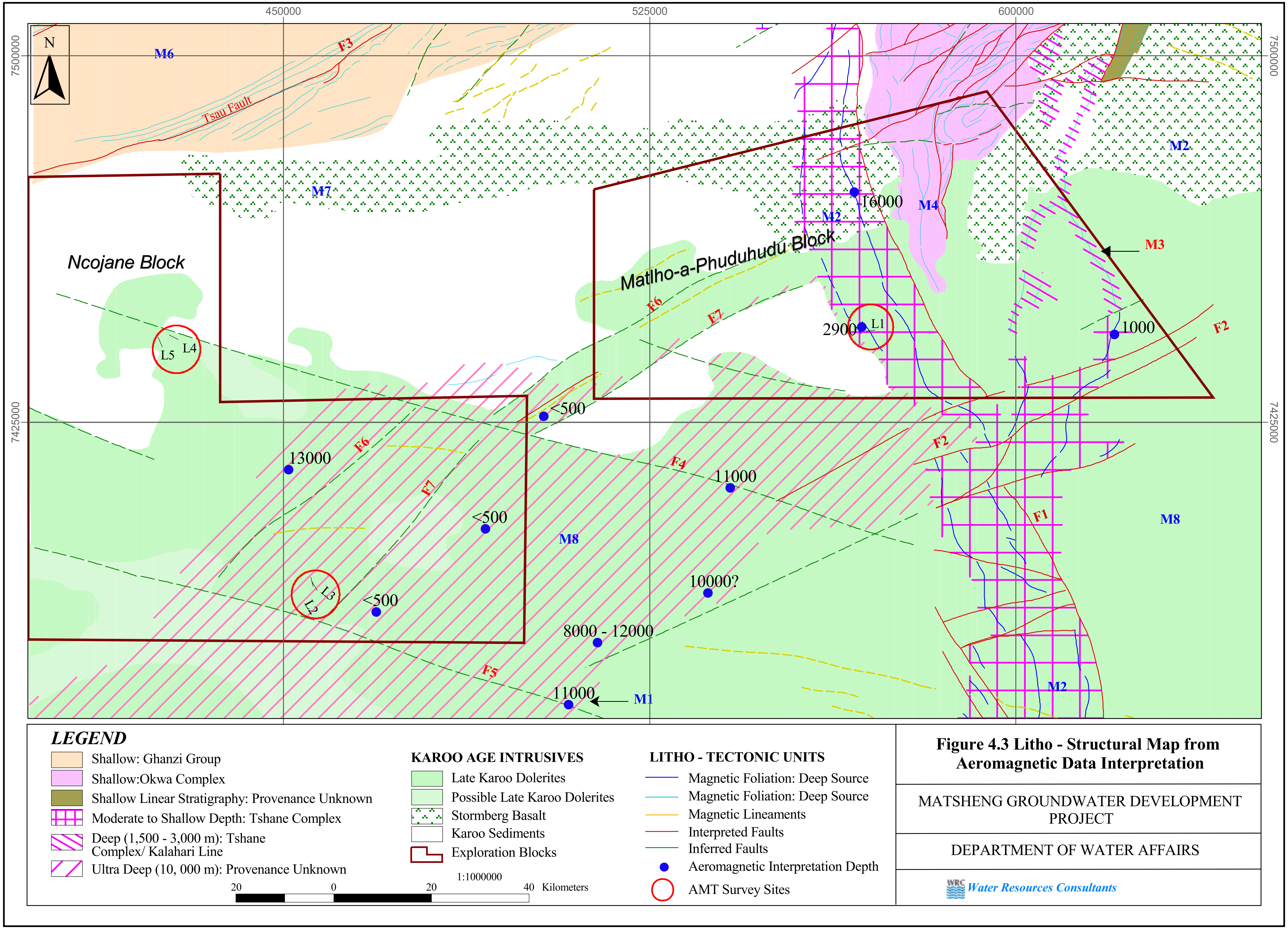

Figure 4.3 Litho - Structural Map from Aeromagnetic Data Interpretation

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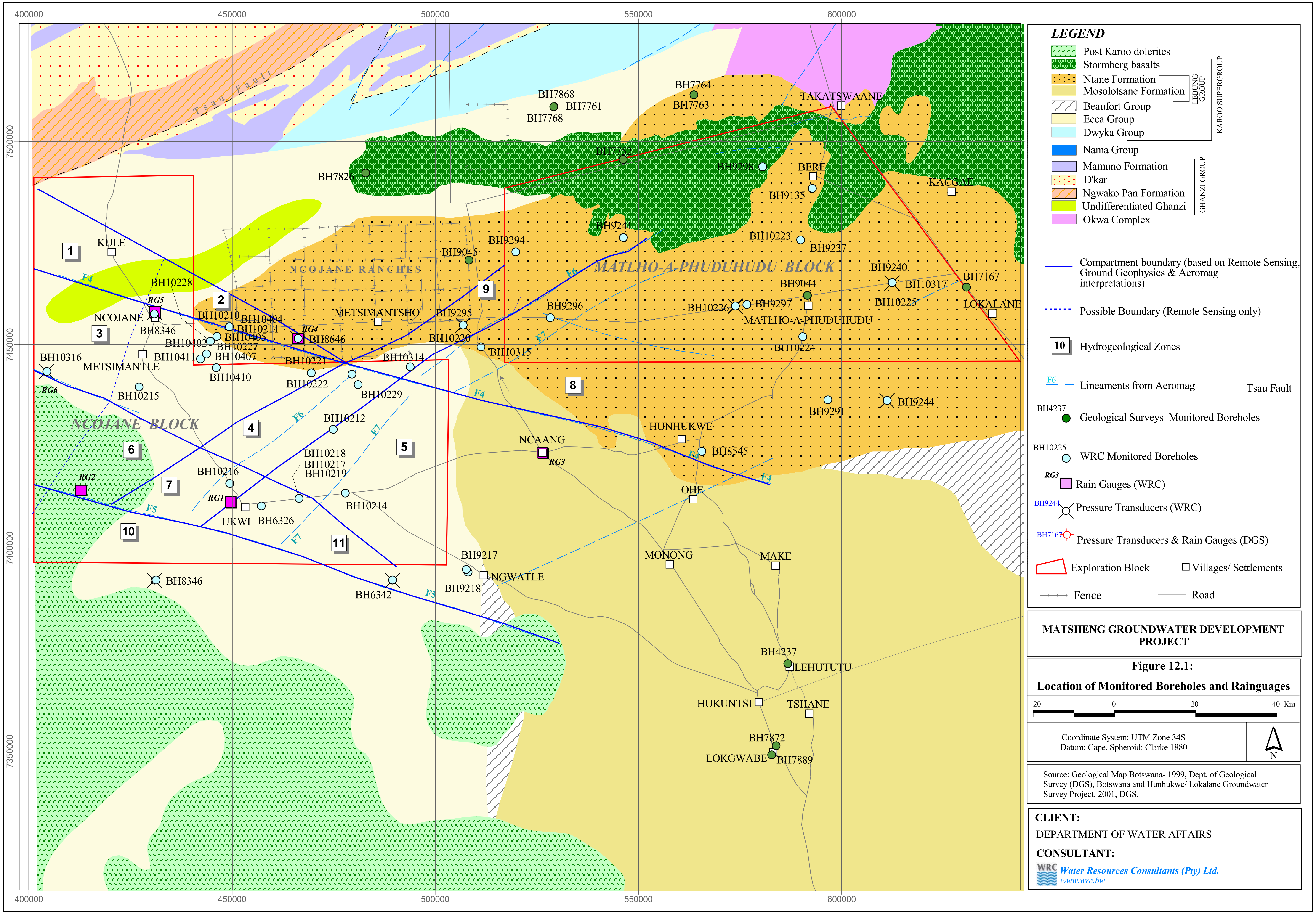

Figure 12.1:

Location of Monitored Boreholes and Rainguages

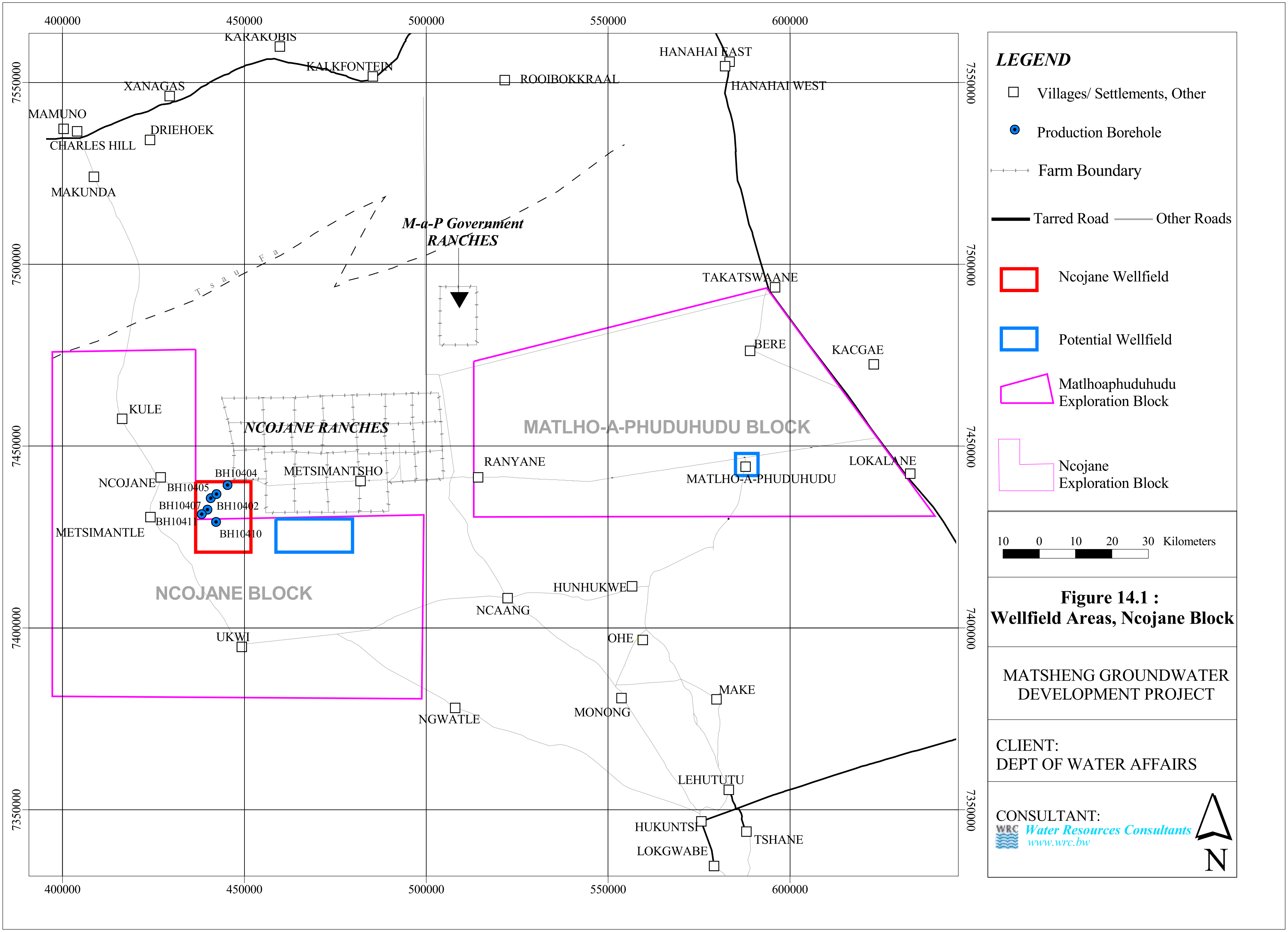

Figure 14.1 : Wellfield Areas, Ncojane Block

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