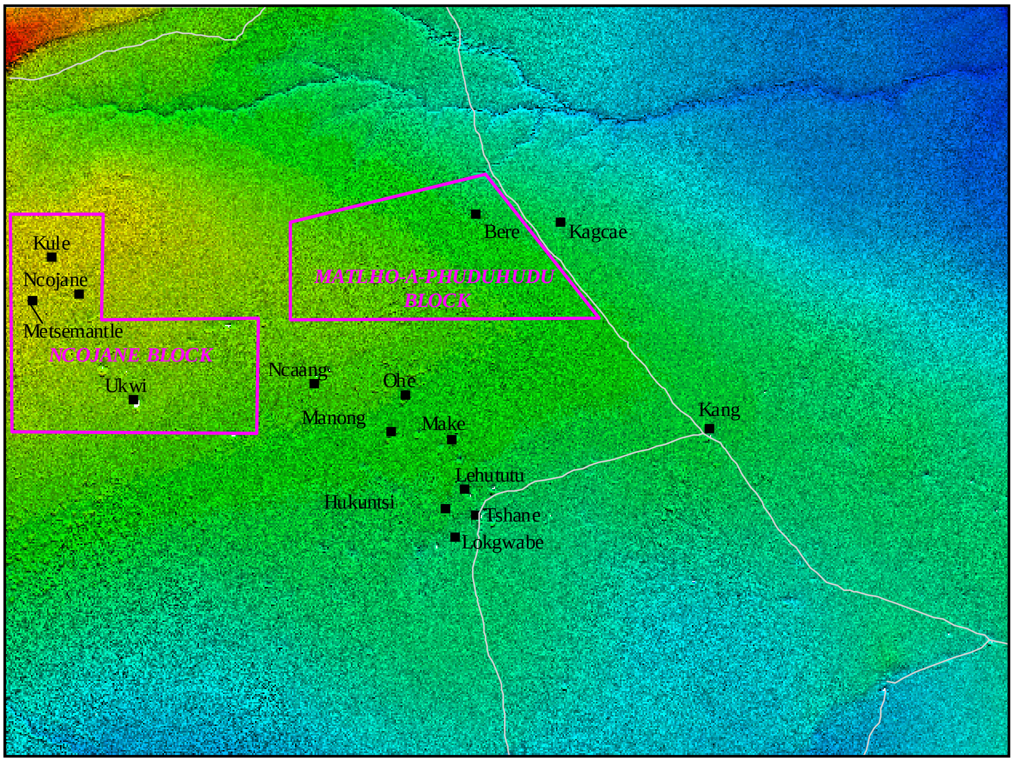
REPUBLIC OF BOTSWANA

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

Matsheng Groundwater Development Project

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



FINAL REPORT
VOLUME 4
HYDROCHEMISTRY & ENVIRONMENTAL ISOTOPES
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PREFACE

This report **Volume 4, Hydrochemistry and Environmental Isotopes** contains a hydrochemical analysis of the project area aquifers with particular focus on the two main aquifers of the project area which are the Ntane and Otshe Sandstones. An evaluation of the compliance to the drinking water specifications of Botswana (BOS 32:2000) is also contained in this report. In addition to this, recharge assessment in the project area based on chemistry, stable and radioactive isotopes is also presented in this report.

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 A and B)
Volume 3C	Downhole Geophysical Logging Report
Volume 4	**Hydrochemistry and Environmental Isotopes**
Volume 5	Groundwater Modelling
Volume 6	Preliminary Wellfield Design and Cost Estimates

SUMMARY

Hydrochemistry data collated from existing studies and data collected during the current project indicates that from a water quality perspective, both the Ntane and Otshe Sandstone Aquifers can yield potable groundwater though the geographic extent of the potable aquifers limited.

Recharge area(s) of the Ntane sandstone aquifer are not clearly defined from the water quality data as there is little indication of hydrochemical evolution in this aquifer. Although the groundwater gradient is mainly 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. Available data seem to confirm that recharge has to take place in several areas which may be expected due to the semi-confined to unconfined nature of this aquifer.

Groundwater flow in the Otshe Aquifer is mainly from west to east with a northwest to southeast component in the southern part of the Ncojane block. Hydrochemical evolution in the Otshe sandstone aquifer mainly takes place in these two directions and recharge seems to take place in the west and northwestern parts of the area Recharge or seepage along faults from overlying aquifers may also take place in confined parts of the aquifer (Faults **F6** and **F7**) and may introduce saline water from the overlying Mosolotsane/Kule (Kwetla) Formations into the Otshe aquifer. To the east of these faults the Otshe aquifer is found at greater depth with hydrochemical evolution reaching the highly saline stage.

The oxygen-18 and deuterium content is fairly uniform in the Otshe aquifer with a slight decrease towards the western part of the study area. Mean residence times calculated from ^{14}C data for Otshe aquifer indicates that the recharge water is more >11 000 years old. Ground water with the highest ^{14}C content and the lowest chloride content occurs in the western and northern parts of the area indicating that these are the most likely recharge areas zones for this aquifer.

For the Ntane aquifer, ^{14}C data indicates that the groundwater is of Holocene origin (age <11 000 years). Low chloride and relatively high ^{14}C indicate that localised 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.

Recharge estimates for the Ntane aquifer based on the CMB and D offset methods give values of less than 1 to 18 mm/yr with a mean of 6 mm/yr. Based on ^{14}C data, recharge values of 1 to 6 mm/yr were obtained which covers the range obtained by the other two methods.

For the Otshe, the CMB method is uncertain due to the old age of the groundwater and the likelihood of chloride uptake in the aquifer. Never the less assuming the present day chloride input, the borehole with the lowest chloride content gives a recharge value of 38 mm/yr 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.

The D-offset method of recharge determination was not applied to the Ecca, since the small δD difference is very susceptible to the actual rain input values.

Recharge estimates based on ^{14}C method yields fairly consistent values in the range of 0.7 to 1.4 mm/yr for the confined model. ^{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. Values in this range were used the numerical model.

The old age of the groundwater and its low replenishment rates necessitates great caution in its exploitation.

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, Charles Hill and Ghanzi. WRC also thank Charles Hill, 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, M.r N. Mbuli, Mr K. Setimela, Mr T. Setloboko representing the Department of Water Affairs; Mr Keakantse,from Ghanzi/Charles Hill 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 later 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 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 else not mentioned here 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
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 AND PROJECT AREA BACKGROUND

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. The 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 comprised of the Matsheng villages (Hukuntsi, Tshane, Lehututu and Lokgwabe), as well as some “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.

1.2 GEOLOGICAL AND HYDROGEOLOGICAL BACKGROUND

1.2.1 GEOLOGICAL BACKGROUND

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. The geology of the project area is inferred mainly based on interpretations 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 1.1** and the regional stratigraphy is summarised in **Table 1.1**.

Table 1.1 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		Dykes and sills
Carboniferous to Cretaceous	Karoo	Stormberg Lava	Layered basalt
		Lebung	Massive sandstone to sandstone/mudstone
		Ecca	Interlayered sandstone, siltstone, mudstone/shale with carbonaceous mudstone and coals seams
		Dwyka	Tillite, mudstone and siltstone
Late Proterozoic		Nama	Conglomerate, sandstones and siltstones
Mid to 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

1.2.2 HYDROGEOLOGICAL BACKGROUND

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 is given below with a more detailed analysis given in **Volume 2, Hydrogeological Report**.

1.2.2.1 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 the 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. The aquifer has variable yields, ranging from 3 to 54 m^3/hr. 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 (**Figure 1.3**). 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. 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.

1.2.2.2 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 to 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 are 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 represent a threat to Otshe aquifer if boreholes are not properly constructed.

Groundwater flow in the Ecca (Otshe) aquifer is primarily from the west to east with a northwesterly to southeasterly component (Group 1 lineament direction) in the southern part of the of the Ncojane Block (**Figure 1.4**). Several faults and lineaments inferred from aeromagnetic and remote sensing data interpretation during the Inception Phase (Faults F4, F5, F6, & F6). 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 groundwater flow direction running parallel to their orientation. 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.

1.2.2.3 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.

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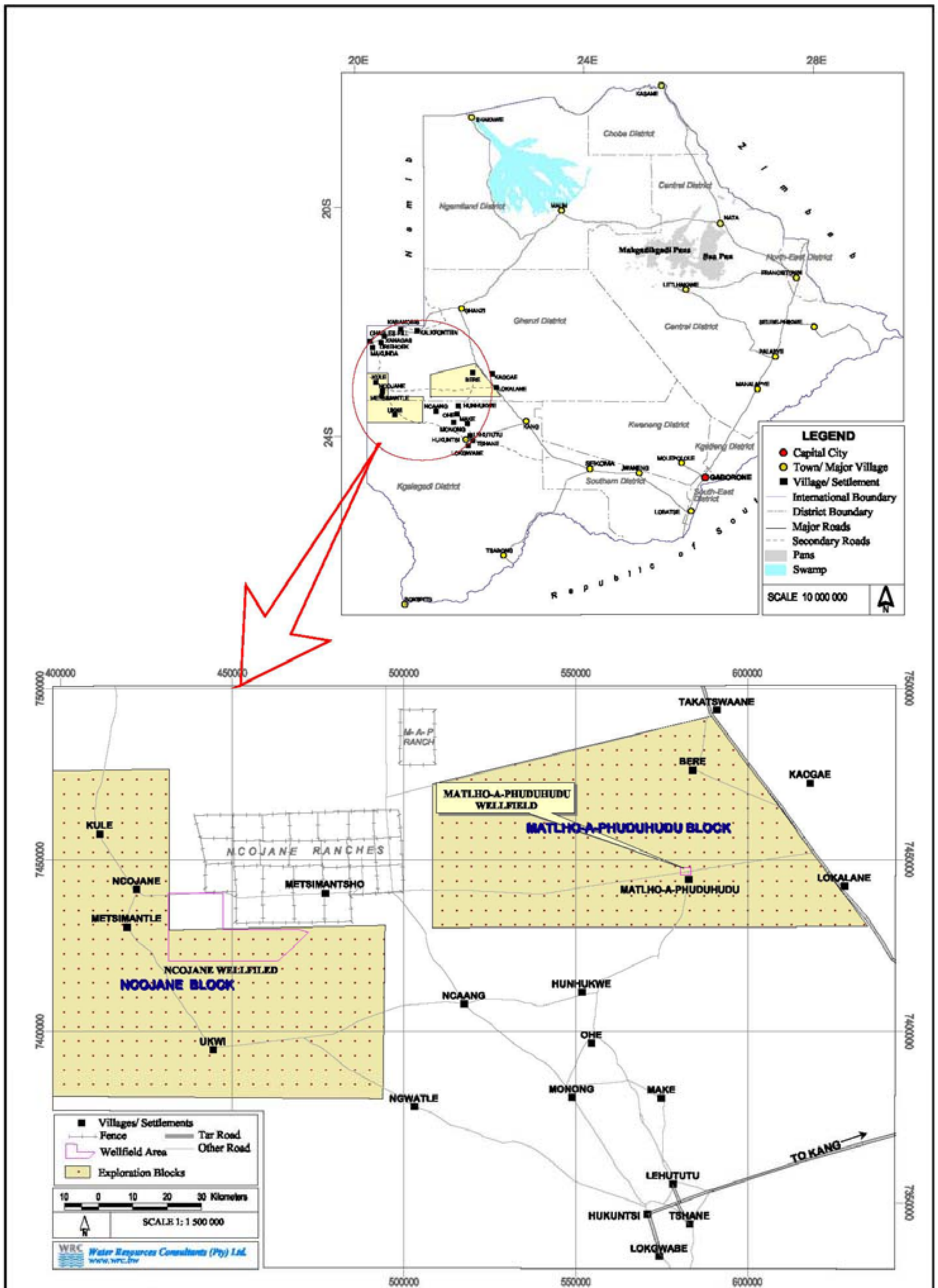
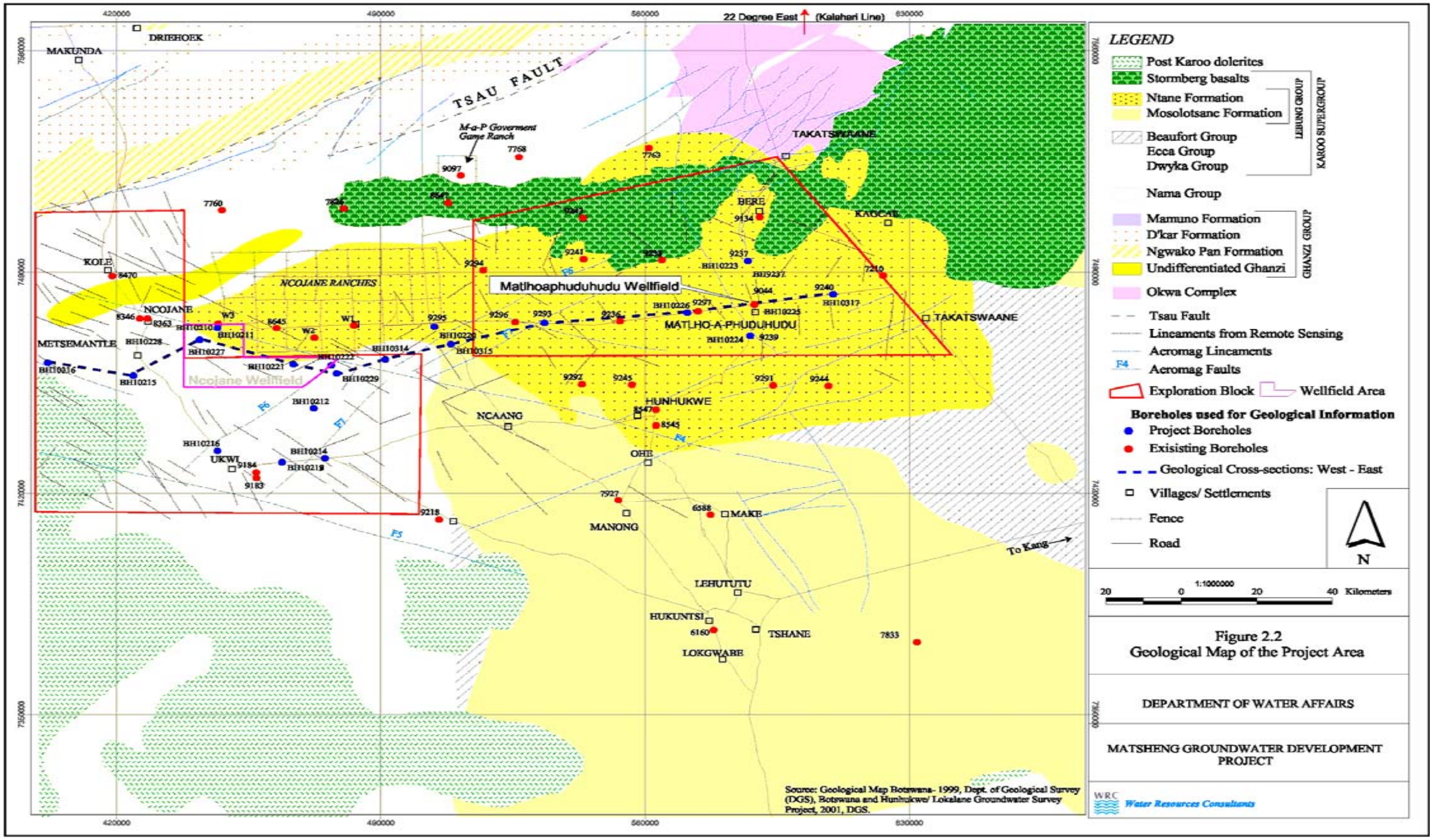


Figure 1.1 : Project Area Location Map

Figure 1.1 Project Area Location Map



Source: Geological Map Botswana- 1999, Dept. of Geological Survey (DGS), Botswana and Hunhukwe/ Lokalane Groundwater Survey Project, 2001, DGS.

Figure 1.2 Geological Map of the Project Area

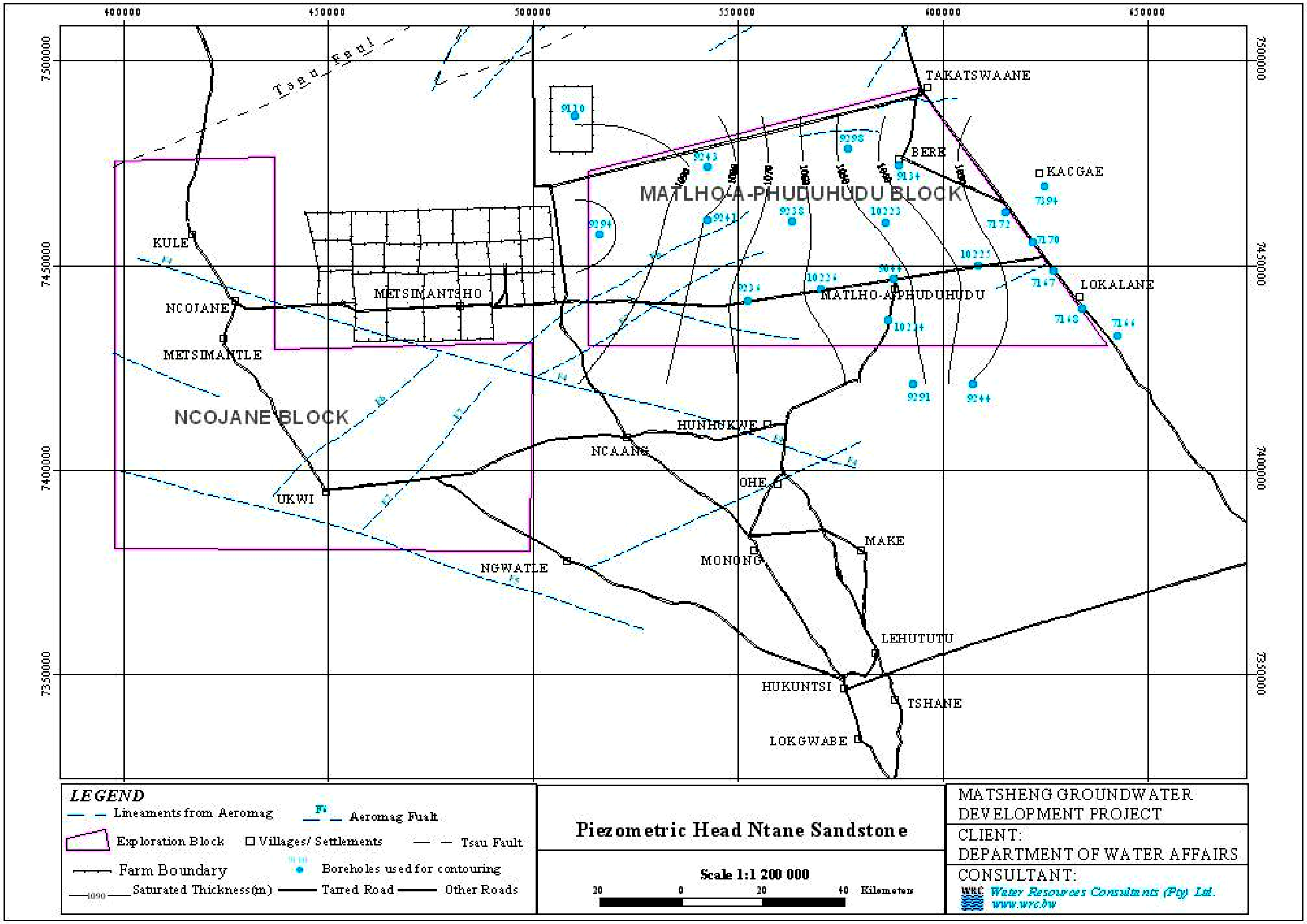


Figure 1.3 Piezometric Head Ntane Sandstone

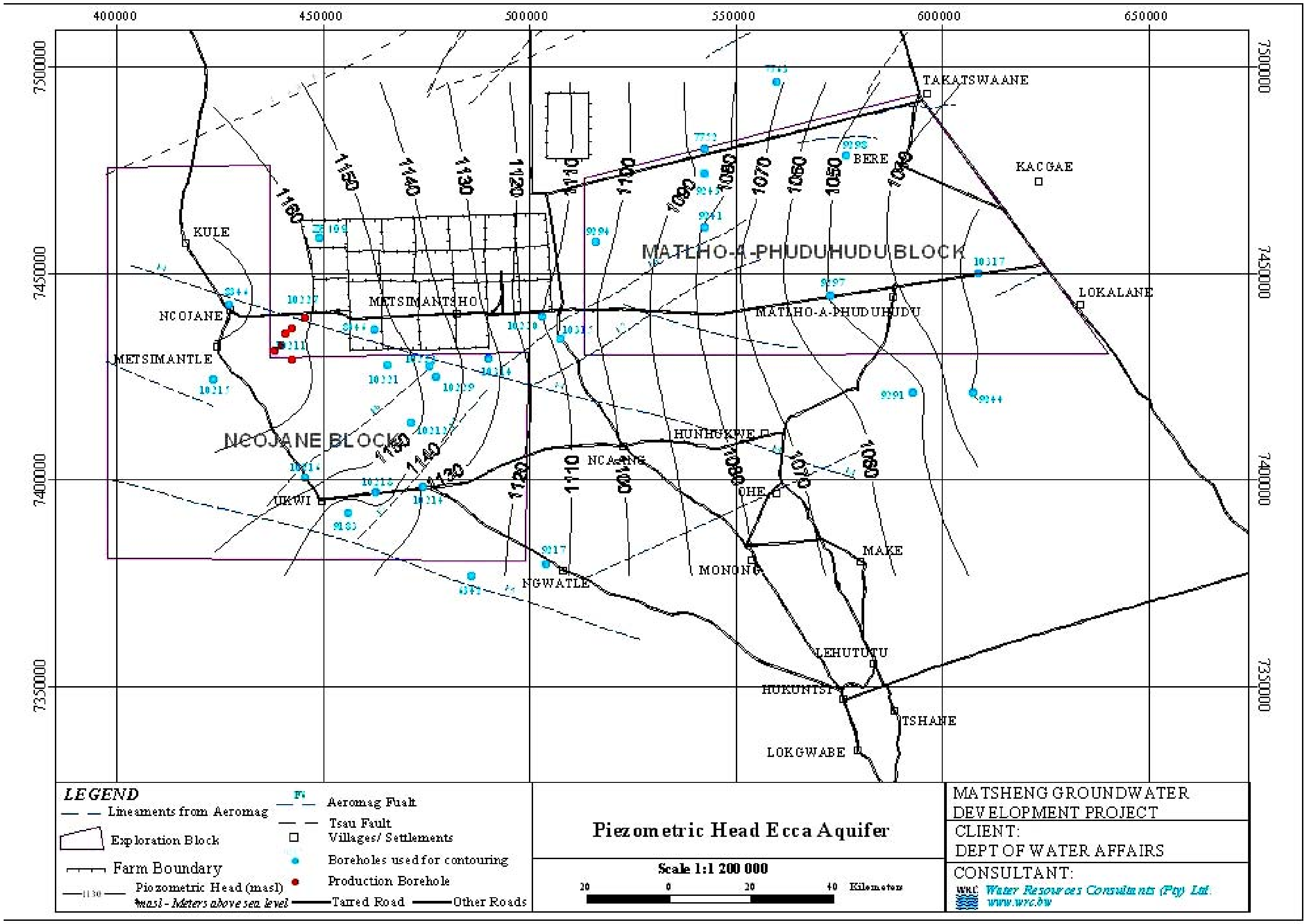


Figure 1.4 Piezometric Head Ecca Aquifer

2 HYDROCHEMISTRY RESULTS

2.1 OVERVIEW

In groundwater development, the available resource does not only depend on the 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.

The main aquifers in the project area are developed in the Ntane and the Otshe sandstones. The hydrochemistry and isotope result 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 aquifer is limited to the eastern part of the Matlho-a-Phuduhudu block where it forms an aquifer while most of the data for the Otshe pertains to western part of the Ncojane block where it forms the main aquifer

Information on the groundwater chemistry and isotopes for the project area was collated from existing reports and DWA data, as well as analysis of 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 laboratories in Stellenbosch and Pretoria.

In this Report an analysis of the groundwater quality and isotope data is presented with the following objectives;

- Interpret the hydrochemistry in terms of the conceptual hydrogeology
- To understand the relationships and mechanisms that control the availability of usable groundwater
- 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 based on the Botswana Drinking Water Specifications (BOS 32:2000)
- Present a conceptual understanding of the recharge dynamics of the project area with an aim of delineating actively recharging areas or areas which are close to active recharge zones
- Present an estimate of recharge quantities based on chemistry and isotope results

2.2 HYDROCHEMISTRY OF THE NTANE SANDSTONE AQUIFER

The hydrochemical data for the Ntane sandstone are sparse as a total of only 15 boreholes had reliable analytical data. Nevertheless, these were used to determine whether any noteworthy trends could be observed in the aquifer and also to compare the hydrochemistry with that of the other aquifers.

2.2.1 SALINITY (ELECTRICAL CONDUCTIVITY)

Water level data indicates that the groundwater in the Ntane aquifer flows in an easterly direction which implies that the recharge needs to enter the aquifer from the west or northwest (**Figure 1.3**). In general, the salinity in the aquifer increases along the flow path but this is clearly not the case in the boreholes representing the Ntane aquifer (**Figure 2.1**). Higher levels approaching the BOS 32:2000 Class II limit for EC of 1500 µS/cm are present in the north and south and to some extent also in the west of the area under discussion. In the east relatively low values occur which are within the BOS 32:2000 Class I limit for EC of 700 µS/cm and these low salinity areas could indicate that recharge is entering the aquifer in the east in addition to the expected recharge areas in the west.

2.2.2 SODIUM

As in the case of the EC, the highest sodium concentrations occur in the north and south of the areas with analytical data (**Figure 2.2**). In the east and southwest of this area the sodium values are well within the BOS 32:2000 Class I limit for sodium of 100 mg/L. Apart from these observations no general trend can be discerned.

2.2.3 CALCIUM

In the case of calcium, there is a general trend of decreasing calcium values from west to east, i.e. along the presumed flow path of the groundwater (**Figure 2.3**). The calcium concentration is often highest in newly recharged water and provided the aquifer material has a cation exchange capacity, the calcium concentration will decrease along the flow path of the groundwater as calcium in solution is exchanged for sodium derived from the aquifer matrix. Further investigation is necessary to confirm whether this actually occurs in the Ntane aquifer. The calcium levels are generally low with the highest value at 67 mg/L.

2.2.4 MAGNESIUM

The magnesium levels are slightly lower in the west than in the east of the area (**Figure 2.4**). No definite trend is visible. For all boreholes both calcium and magnesium are within the BOS 32:2000 Class I limits which are 80 mg/L and 30 mg/L respectively.

2.2.5 CHLORIDE

As for most of the parameters discussed above, the chloride concentrations are lowest in the east and west and do not show any definite trend (**Figure 2.5**). Only one borehole, at the southern end of the area with data, exceeds the BOS 32:2000 Class II limit of 200 mg/L for chloride. The chloride concentration in groundwater generally increases along the flow path and for that reason the recharge areas generally have the lowest chloride values. In case of the Ntane aquifer no definite trend is definite trend is discernable in the chloride distribution.

2.2.6 SULPHATE

Sulphate concentrations are low and the lowest values occur in the east and west with higher values in the south (**Figure 3.6**).

2.2.7 FLUORIDE

The fluoride concentration in the Ntane groundwater is very low and is within the BOS 32:2000 Class I limit of 0.7 mg/L. The spatial distribution of fluoride also does not show any significant development trend in the area for which results are available (**Figure 3.7**).

2.2.8 NITRATE

In the paragraphs above it was indicated that the groundwater level in the aquifer had an easterly gradient. The concentration of nitrate supports an easterly groundwater flow direction to certain extent. Despite the small number of points and some erratic values the nitrate concentration seems to increase in a (south) easterly direction (**Figure 2.8**). Considering the depth to the water table this is a noteworthy finding as it raises the question of the degree of confinement of the Ntane aquifer because all nitrogen sources would be found at the surface. During the project no attempt was made to determine the source of the nitrate and it would be important to investigate this further as the highest levels are (already) above 50% of the BOS 32:2000 drinking water limit (all Classes). The increasing levels imply that there must be more than one source along the flow path. The chances of any geological source of nitrogen occurring in the area are very slim and can be ruled out. The nitrogen source could be natural, e.g. nitrogen fixing vegetation and bacteria, or from anthropogenic and animal origin.

2.2.9 TOTAL ALKALINITY

The highest total alkalinity concentrations (expressed as $CaCO_3$) occur in the north and these decrease southeast wards but at the most southern borehole (No 9239) the alkalinity is again higher (**Figure 2.9**).

2.2.10 POTASSIUM

Potassium has its highest values in the north and these decrease in southward direction in a fairly consistent way (**Figure 2.10**). This may indicate a hydrochemical development pattern or could be the result of recharge processes in the north.

2.2.11 SODIUM PERCENTAGE (ME/L)

The sodium percentage (of the cations) is a useful parameter to follow the hydrochemical development in an aquifer as it generally increases along the flow path due to various processes contributing sodium to the groundwater. In the Ntane aquifer the sodium percentage, is at its highest in the central part of the area which may indicate that groundwater is recharged in the eastern and western parts (**Figure 2.11**). It could, however, also be related to the water of different quality being recharged in different parts of the aquifer, i.e. without any significant hydrochemical development taking place such as ion exchange.

2.2.12 SULPHATE PERCENTAGE (ME/L)

As sulphate concentrations are low the percentage of sulphate is generally also low with the lowest values occurring in the east and west (**Figure 2.12**). A slight decrease in a southerly direction can be noted in the central part and this may be due to the increasing concentrations of other anionic constituents.

2.2.13 TOTAL ALKALINITY PERCENTAGE

In recharge areas groundwater generally assumes a calcium-magnesium bicarbonate character and hence such water often has a high total alkalinity percentage. As the water undergoes ion exchange the alkalinity may increase further followed by a reduction during the salinisation phase. The high percentages in the east and west are interpreted as potential recharge areas with the central area a salinisation zone (**Figure 2.13**).

2.2.14 SODIUM/CHLORIDE IONIC RATIO

In the interior of the continents, recharge water has generally very low chloride concentrations. This is generally concentrated in the soil zone by evaporation and the dissolution of salt deposited during previous events which were not of sufficient magnitude to lead to groundwater recharge (**Figure 2.14**).

2.2.15 STIFF CHEMICAL COMPOSITION DIAGRAMS

The Stiff hydrochemical composition diagrams for the Ntane aquifer showing the absolute concentrations of the various parameters are given **Figure 2.15**. In these diagrams, the size of the figures gives an indication of the salinity of the water. All figures are drawn to the same scale. At the same time the three axes each for cations and anions give a clear indication of the relative compositions. It is evident that except for five boreholes, the salinity and composition of the groundwater at the various borehole locations is fairly similar with some minor deviations (**Figure 2.15**). The five boreholes are 5698, 9134 and 9135 in the north, 9241 in the west and 9239 in the south. The latter borehole has the highest salinity. Borehole 9237, and to a lesser extent 9044, 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 7172, 7170 and 9240 located in the east show a remarkable similarity in composition, including a very low chloride concentration.

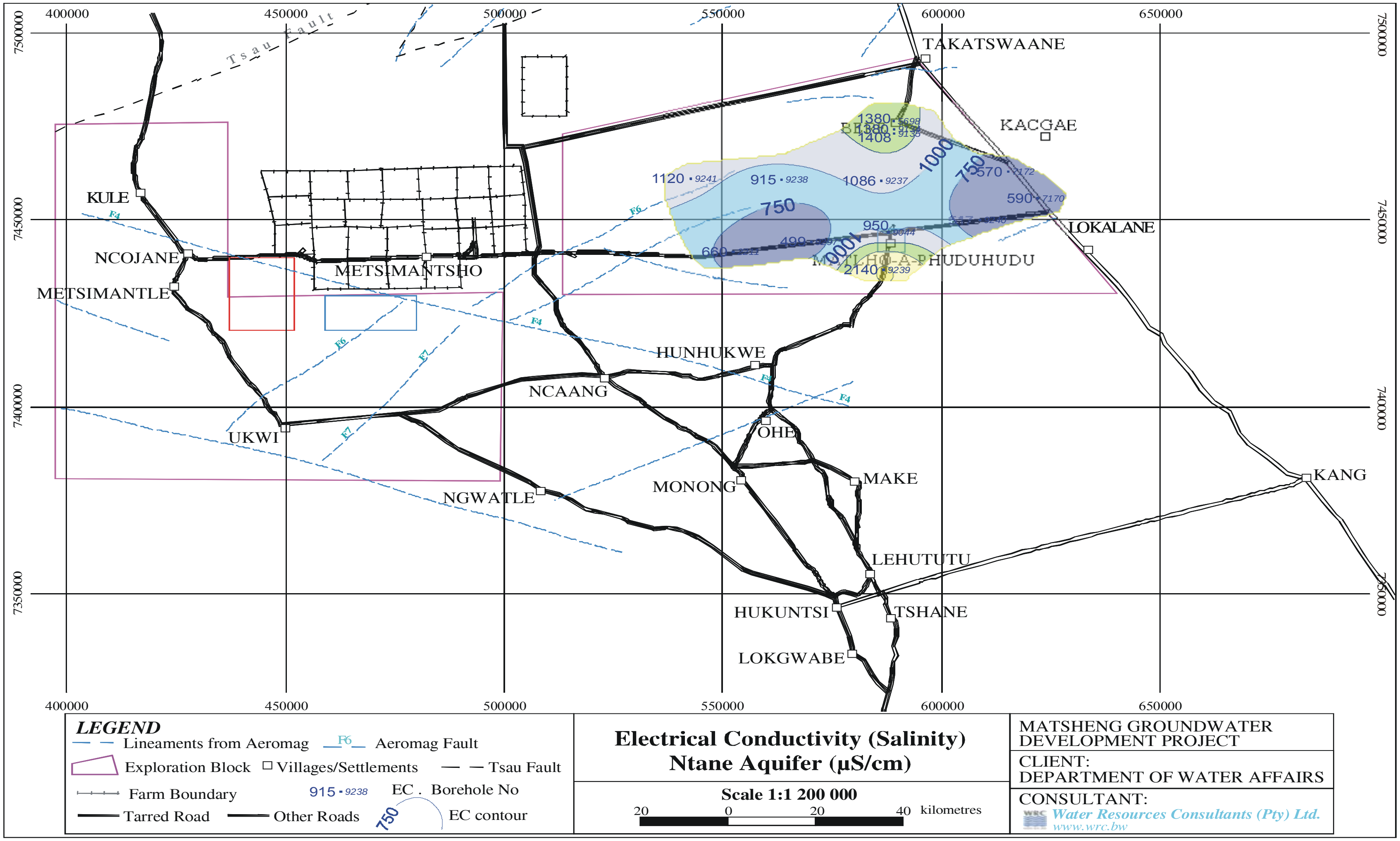


Figure 2.1 Electrical Conductivity (Salinity) Distribution, Ntane Aquifer

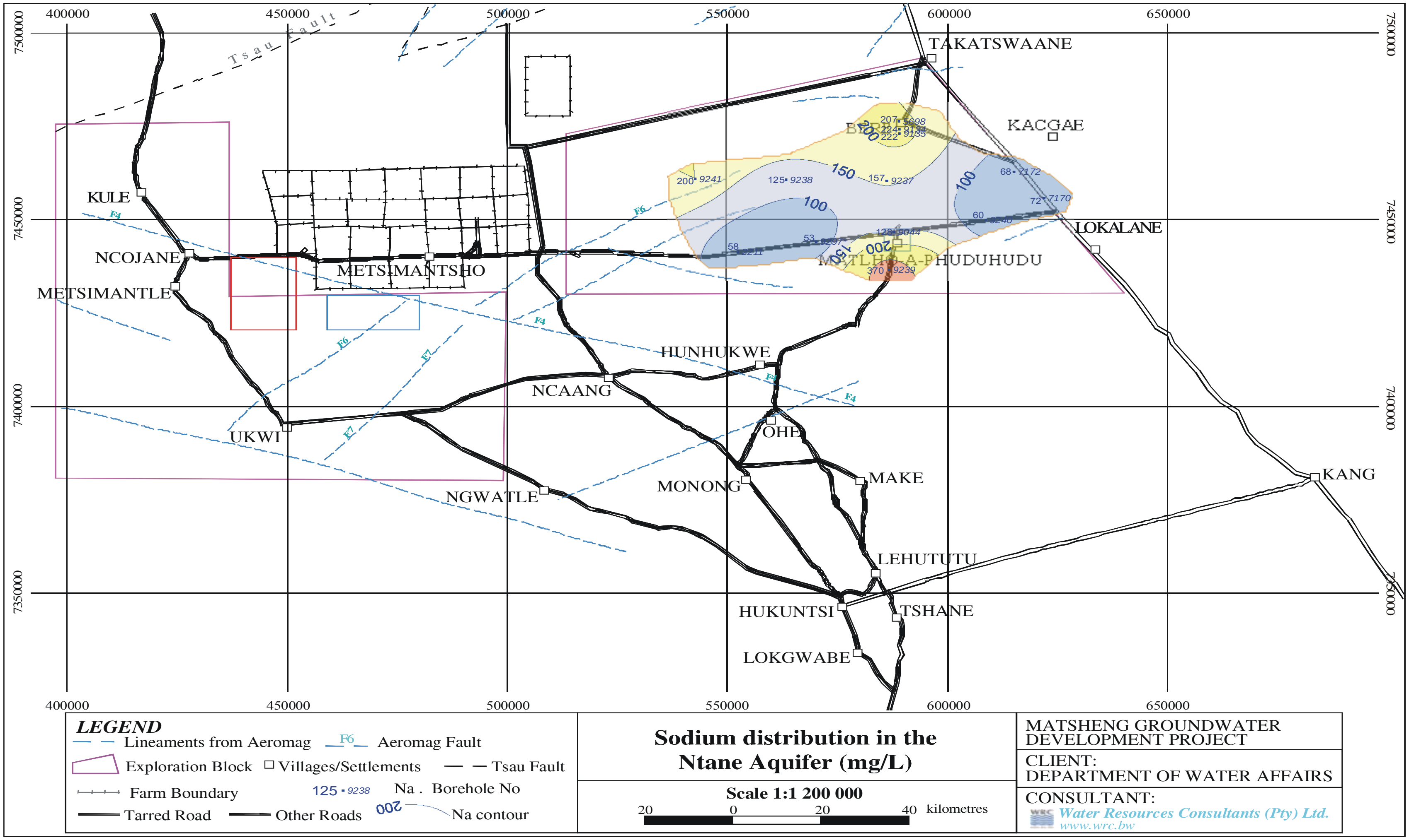


Figure 2.2 **Sodium Distribution, the Ntane Aquifer**

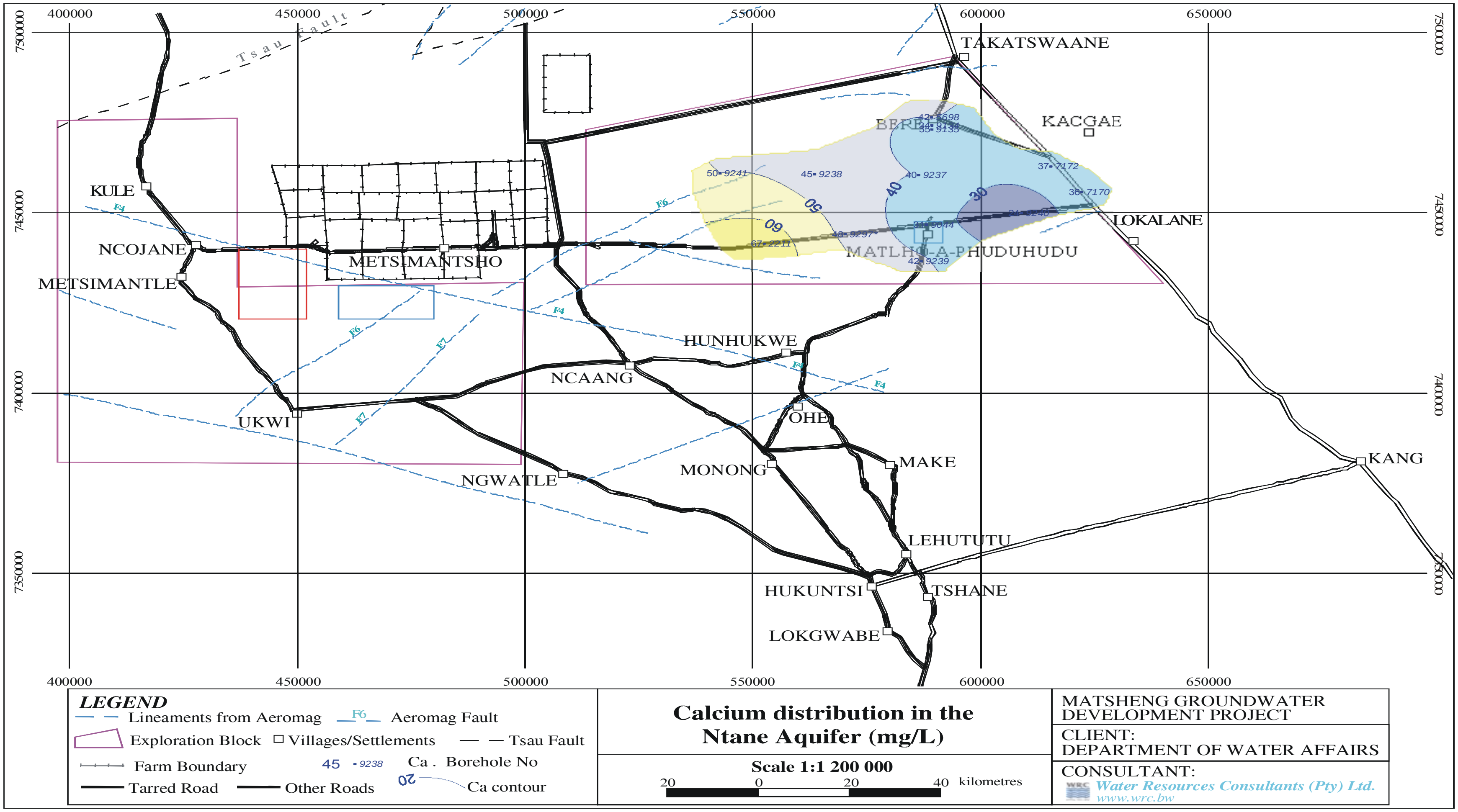


Figure 2.3 **Calcium Distribution, Ntane aquifer**

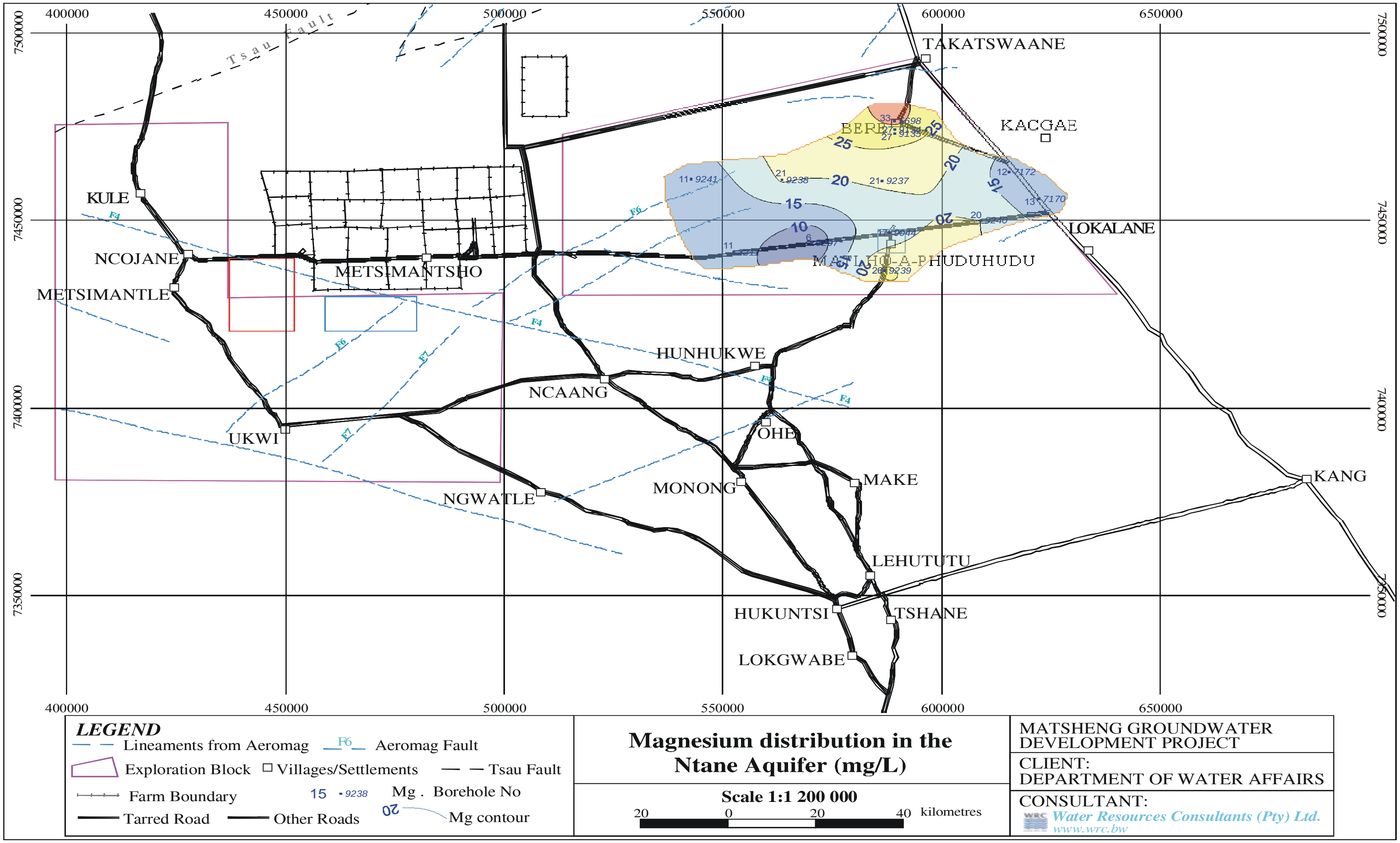


Figure 2.4 **Magnesium Distribution, Ntane aquifer**

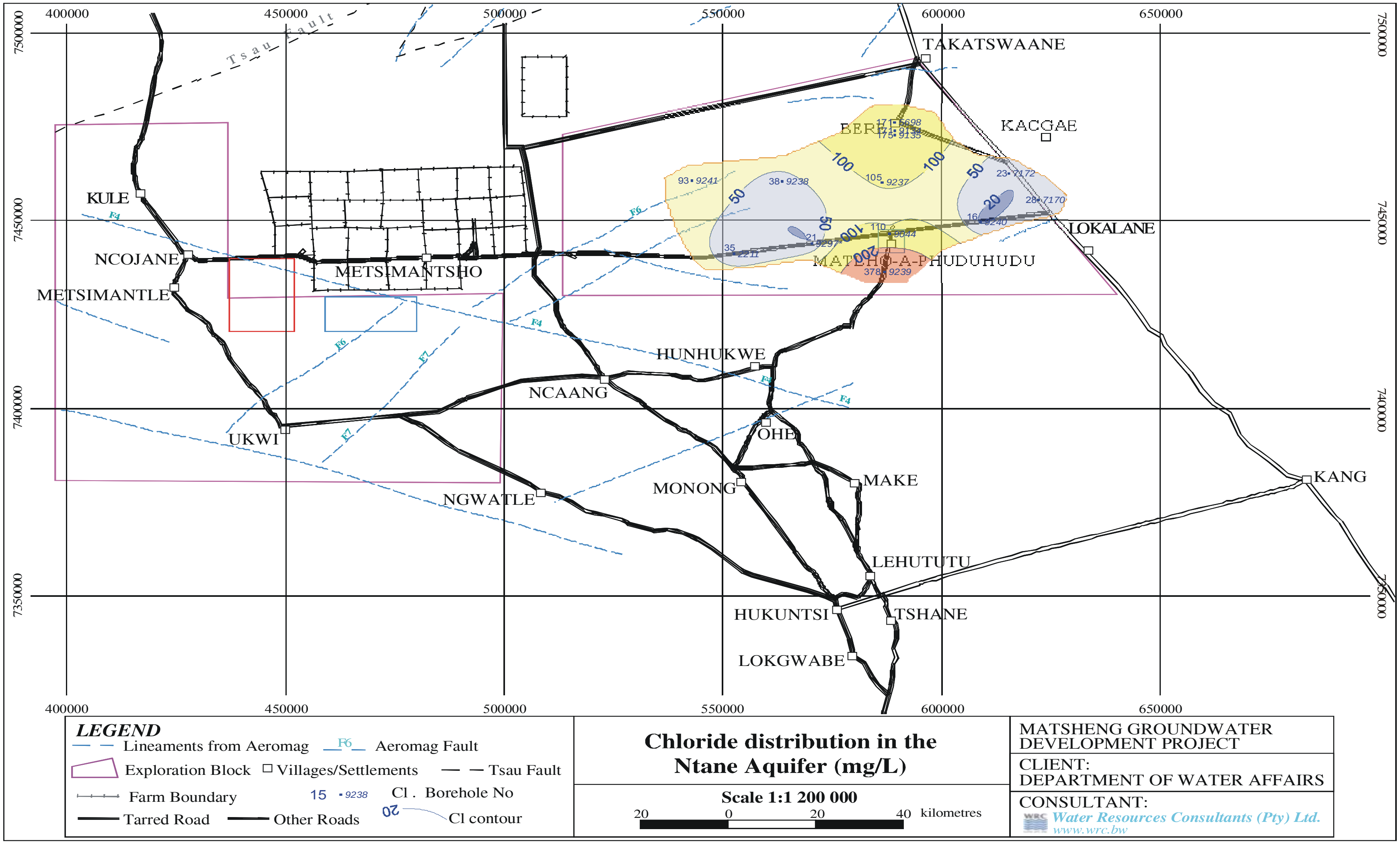


Figure 2.5 **Chloride Distribution, Ntane aquifer**

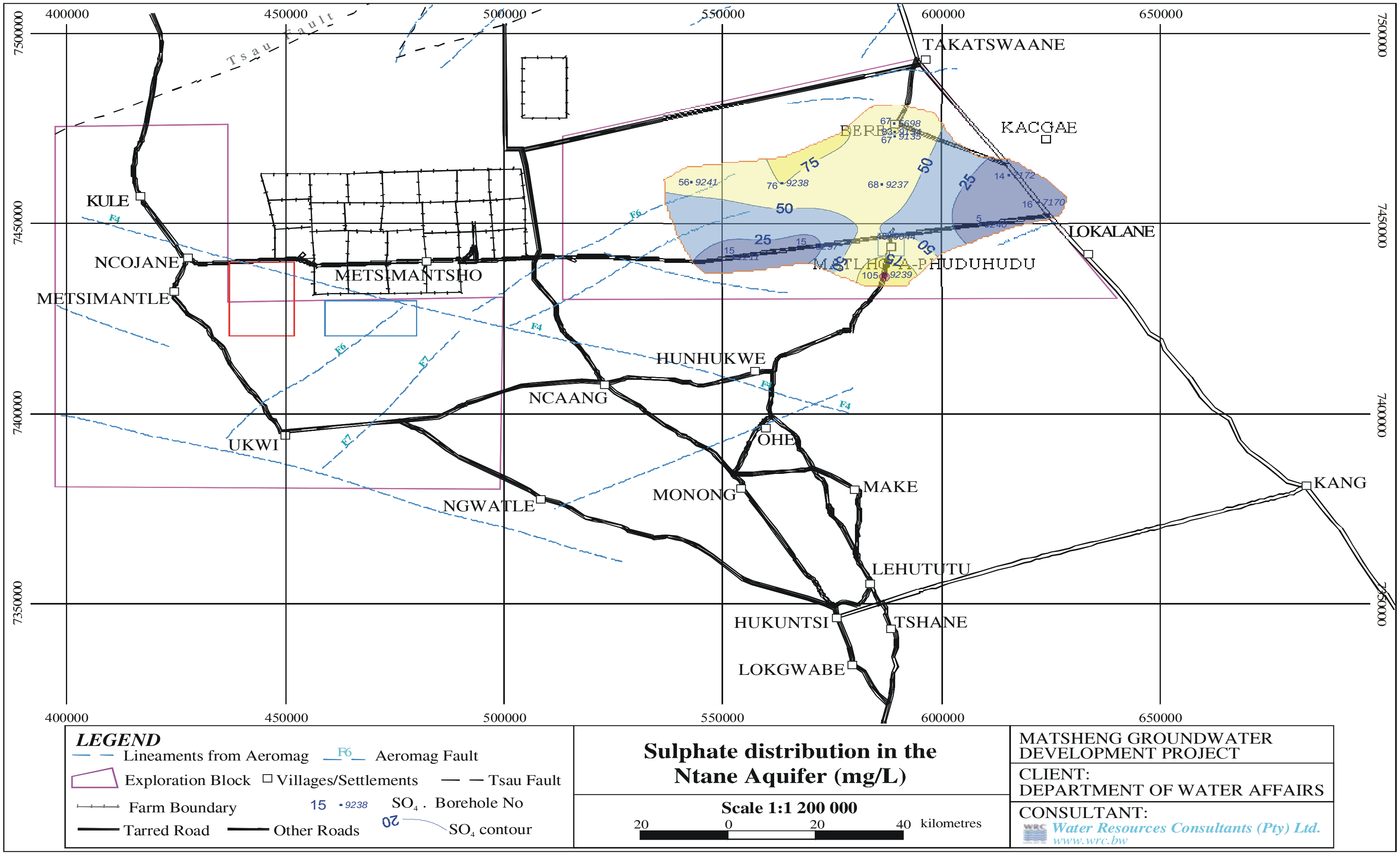


Figure 2.6 **Sulphate Distribution, Ntane aquifer**

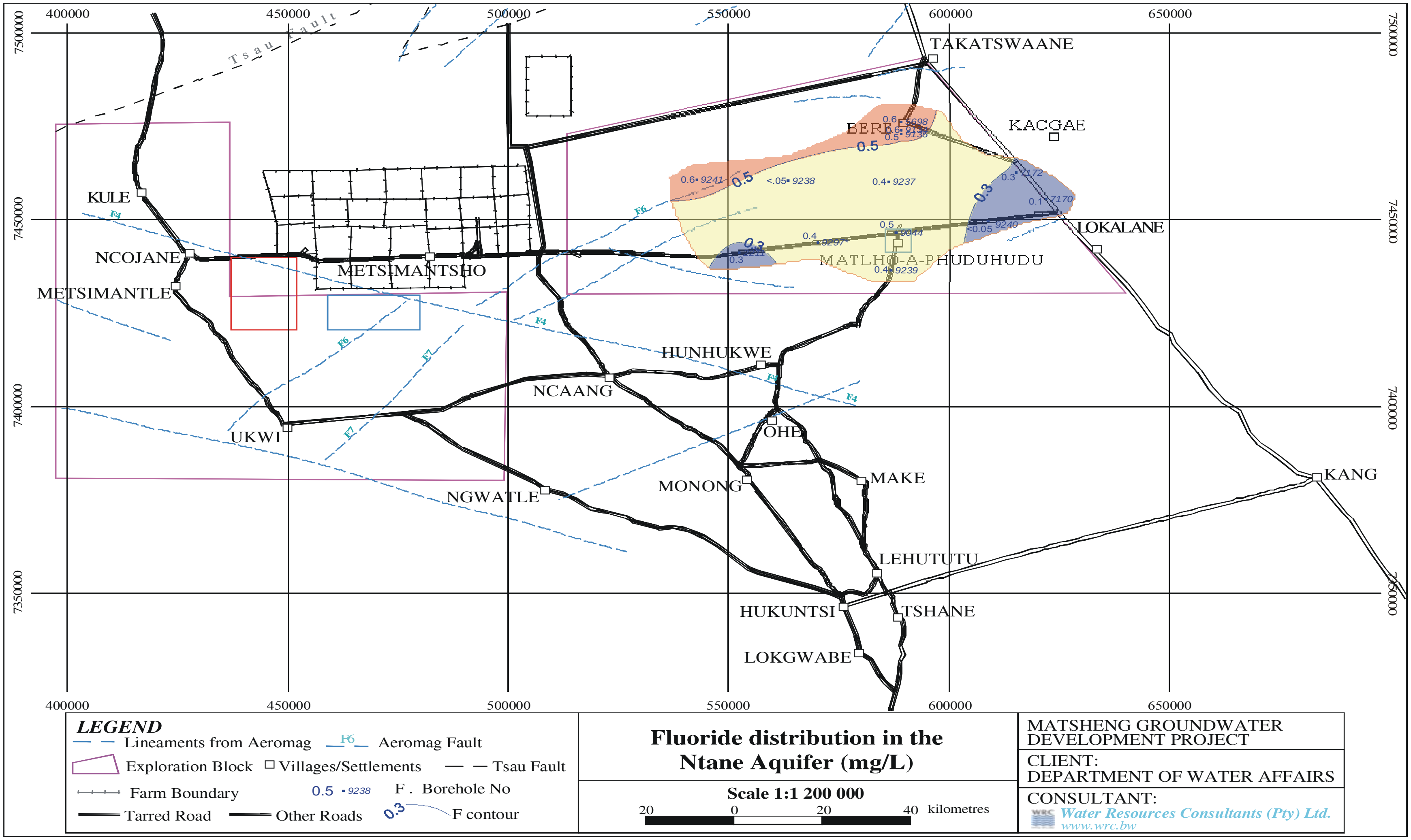


Figure 2.7 Fluoride Distribution, Ntane aquifer

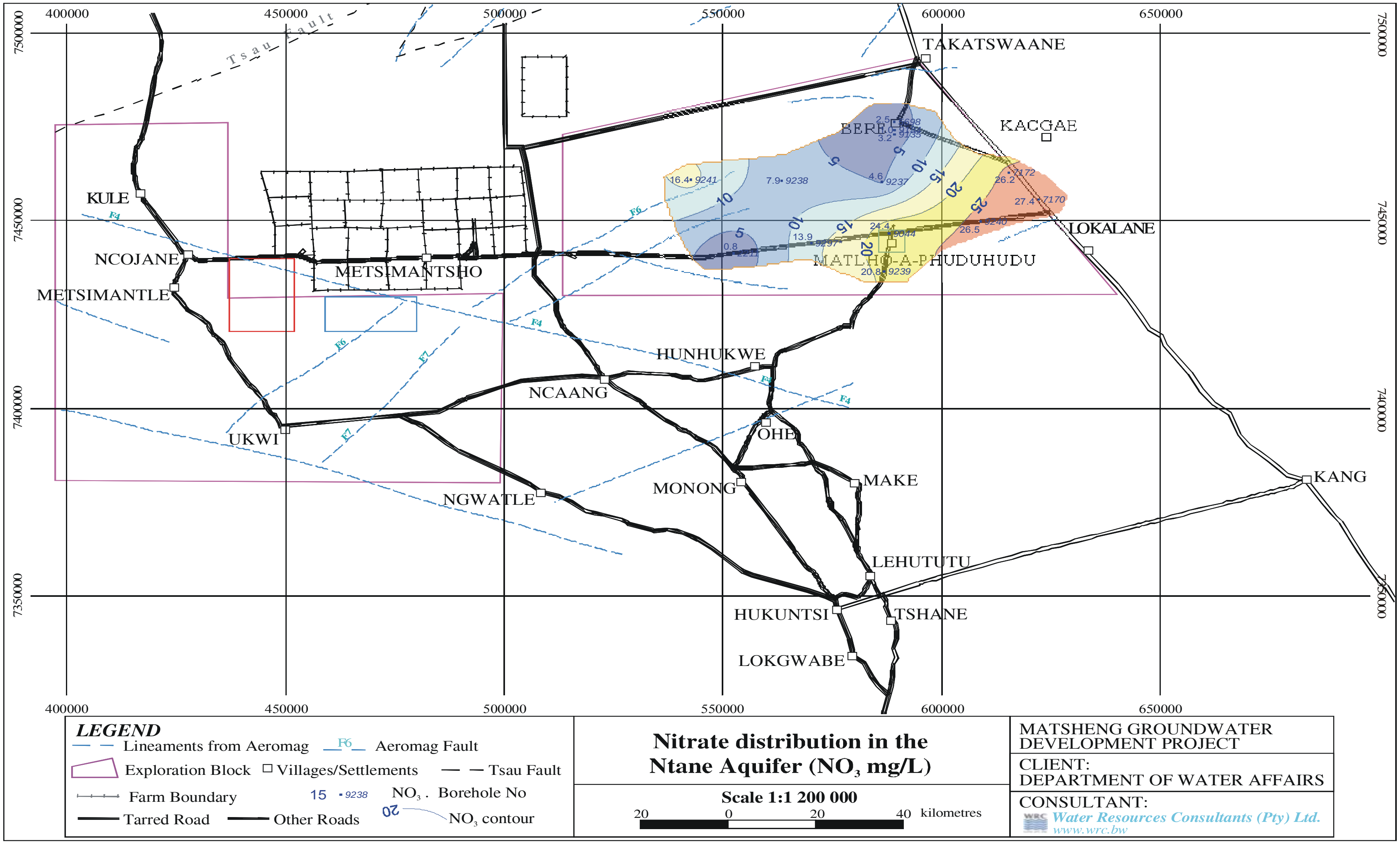


Figure 2.8 Nitrate distribution, Ntane aquifer

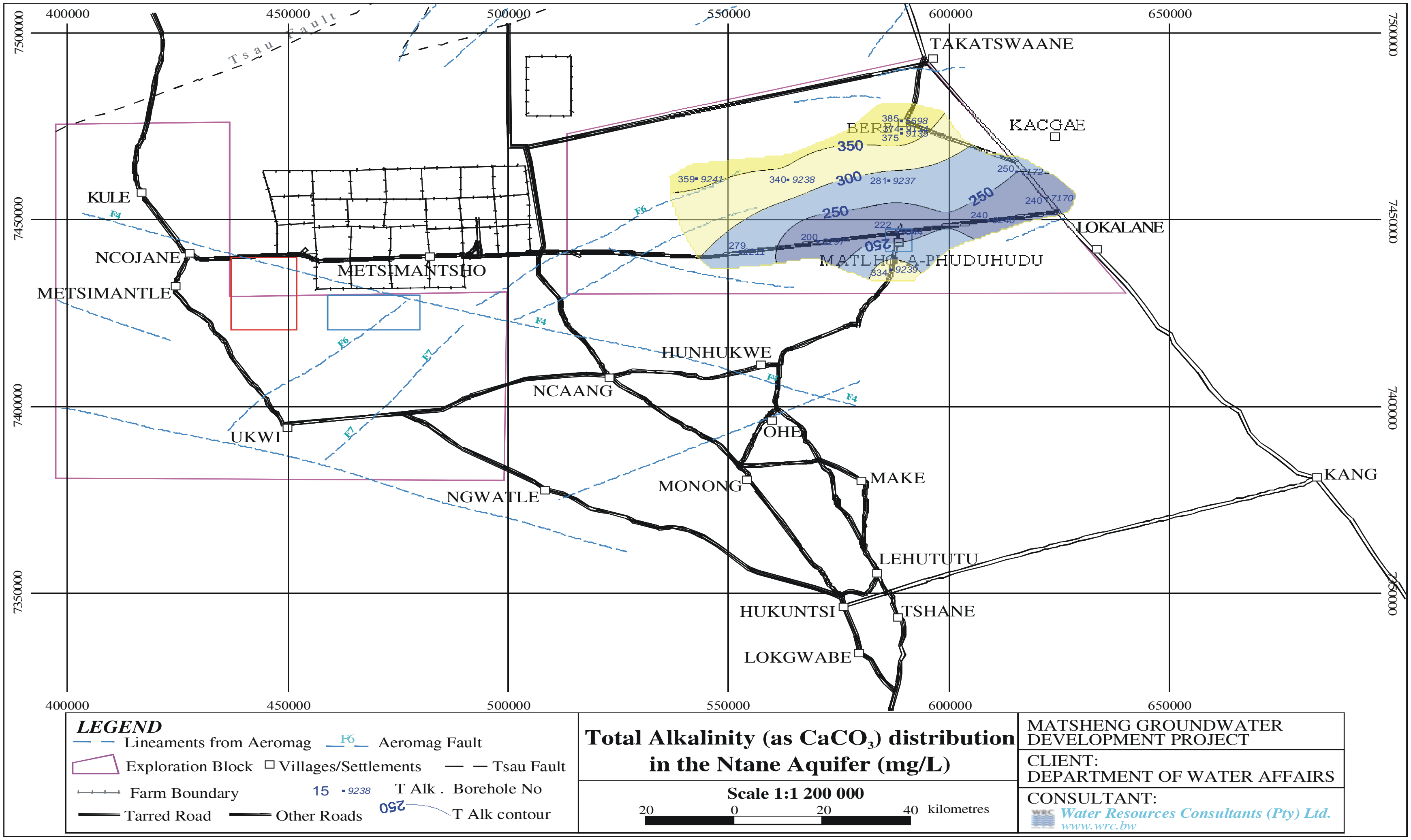


Figure 2.9 Total Alkalinity Distribution, Ntane Aquifer

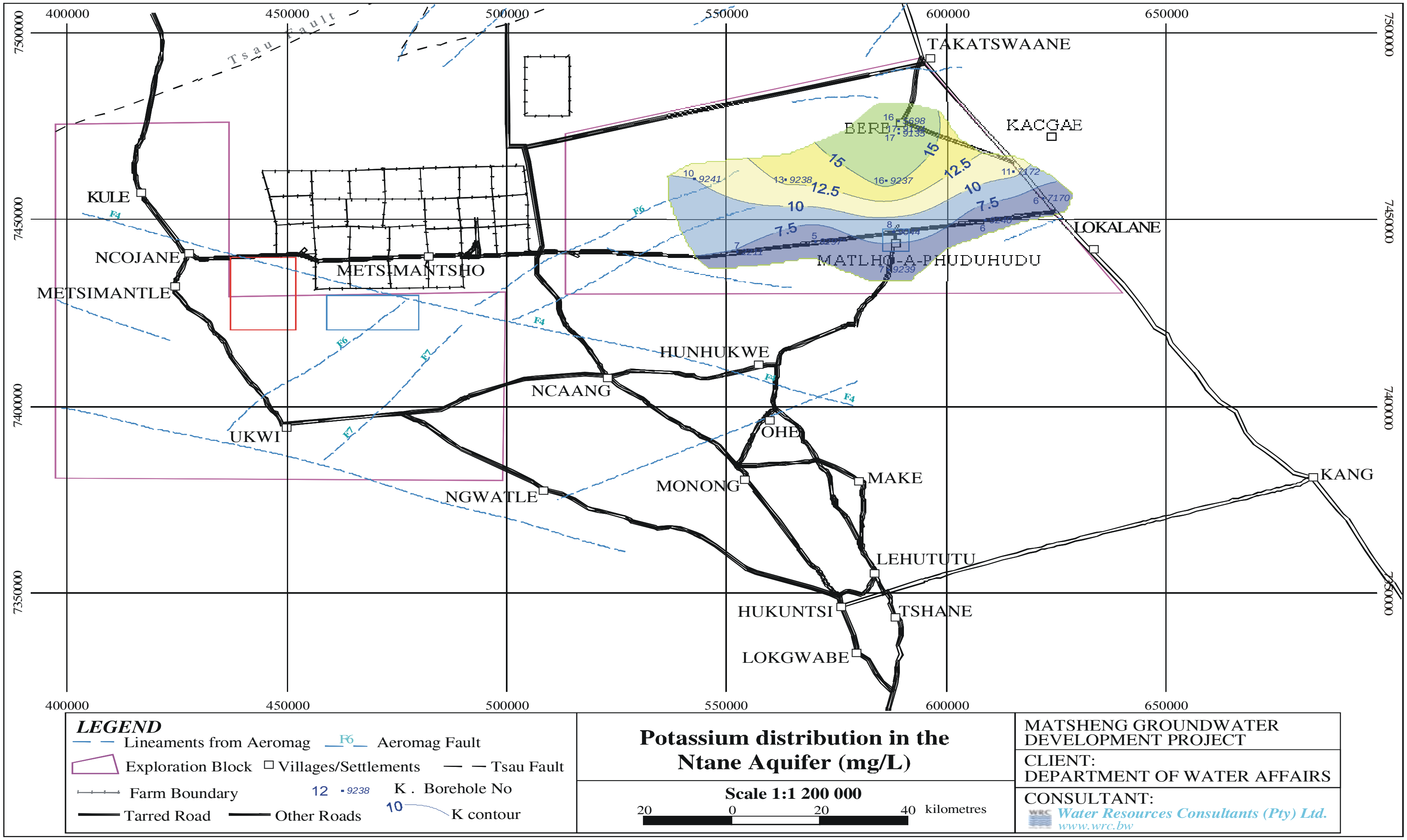


Figure 2.10 **Potassium Distribution, Ntane Aquifer**

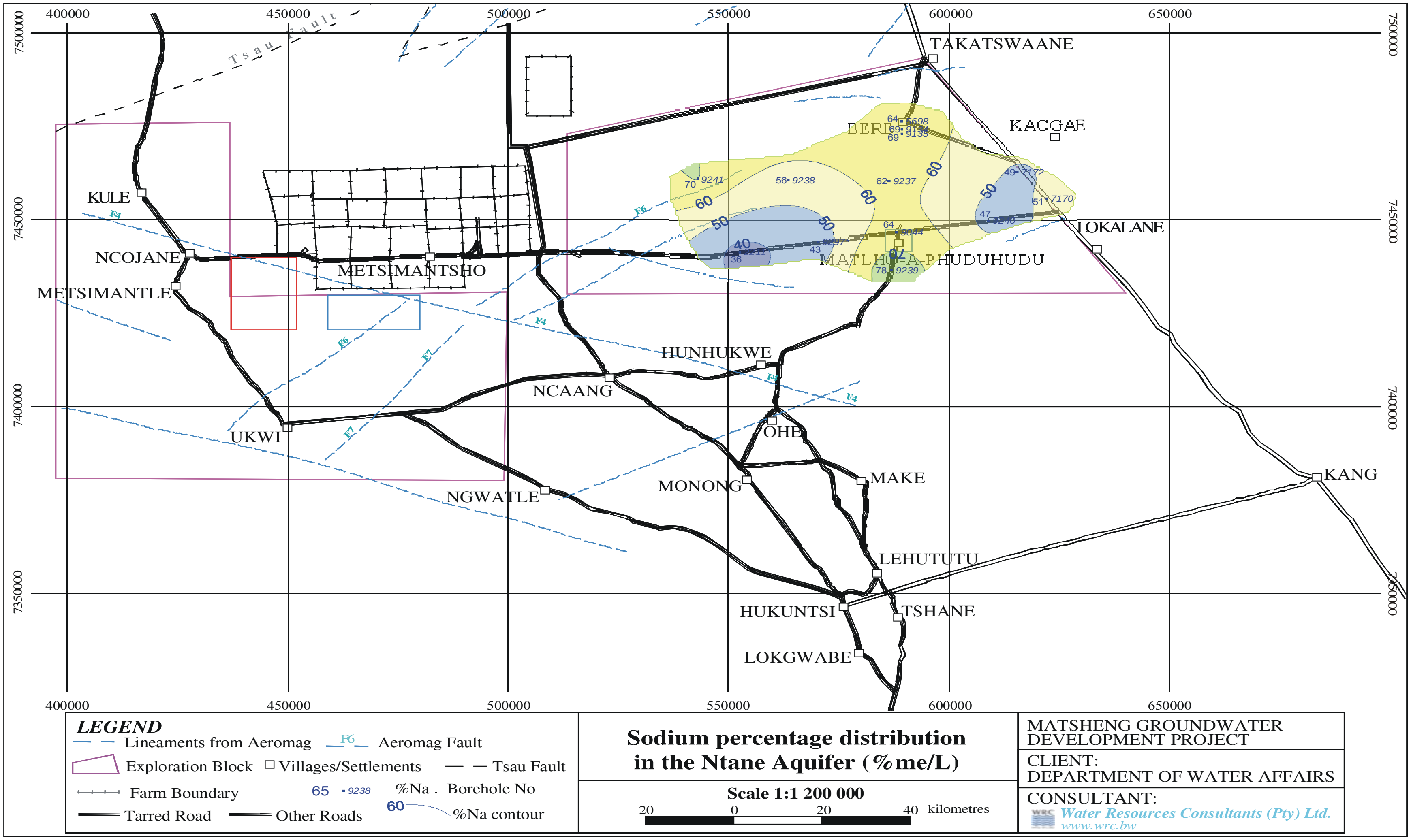


Figure 2.11 Sodium Percentage Distribution, Ntane Aquifer

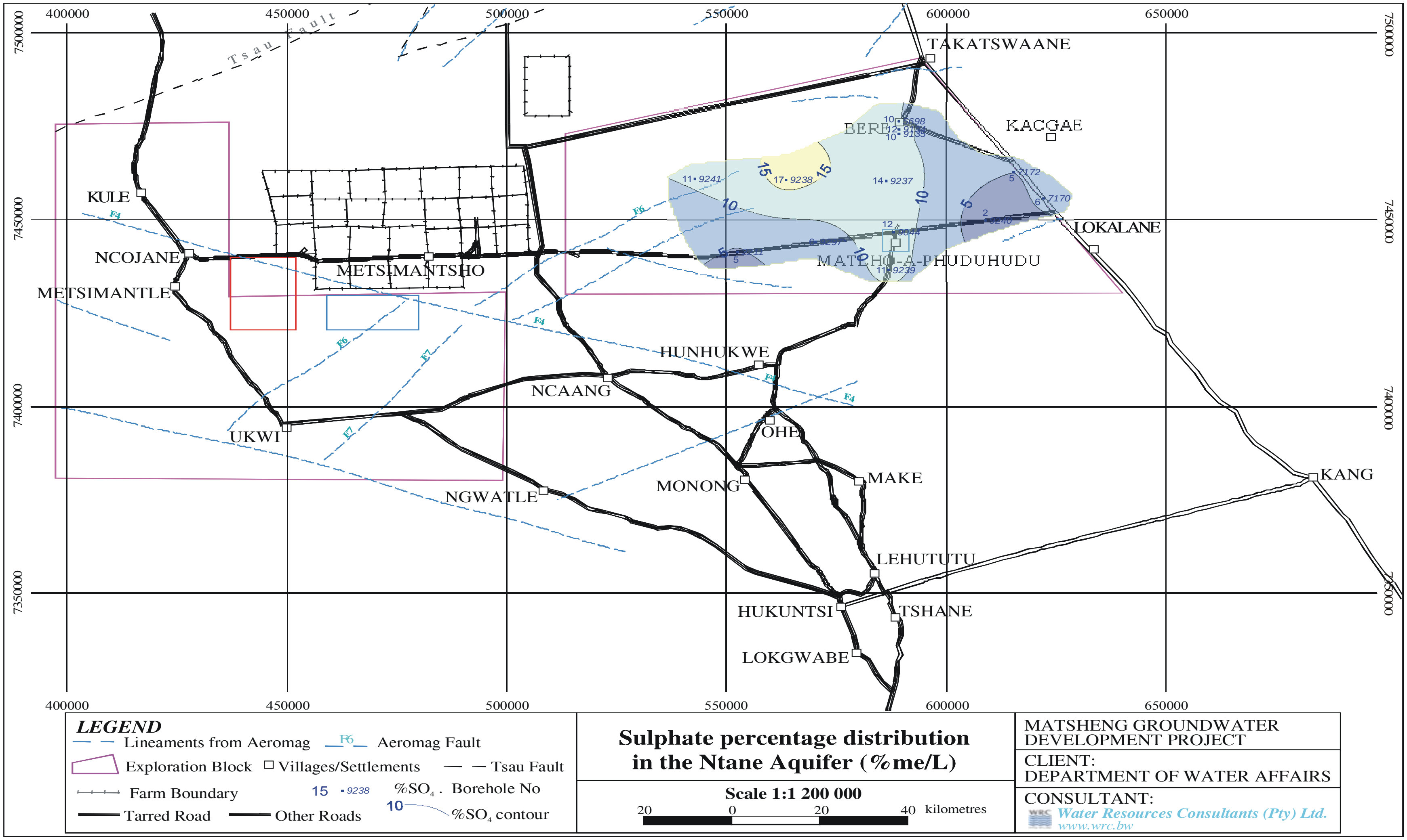


Figure 2.12 **Sulphate Percentage Distribution, Ntane Aquifer**

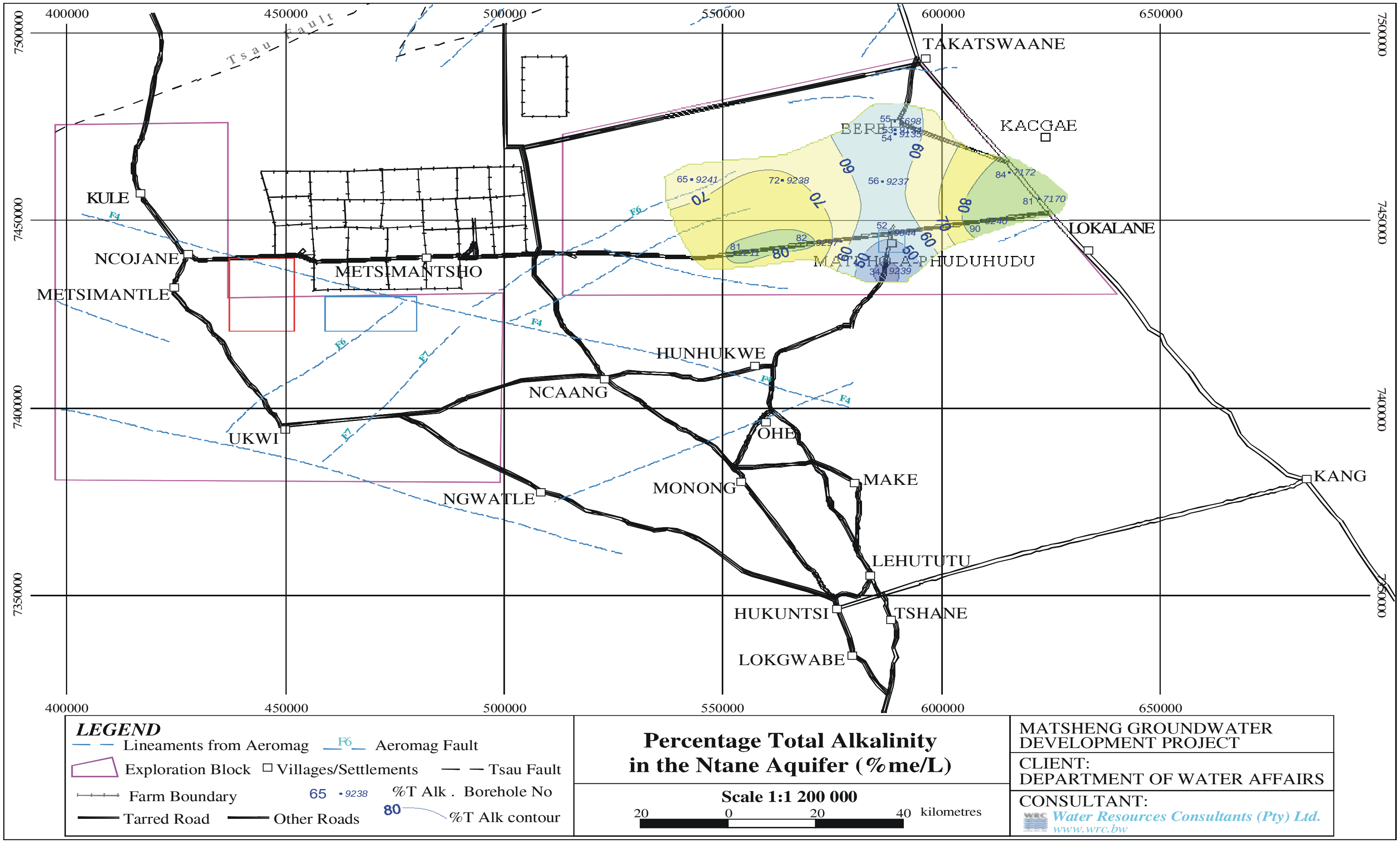


Figure 2.13 Distribution of the Total Alkalinity Percentage ,Ntane Aquifer

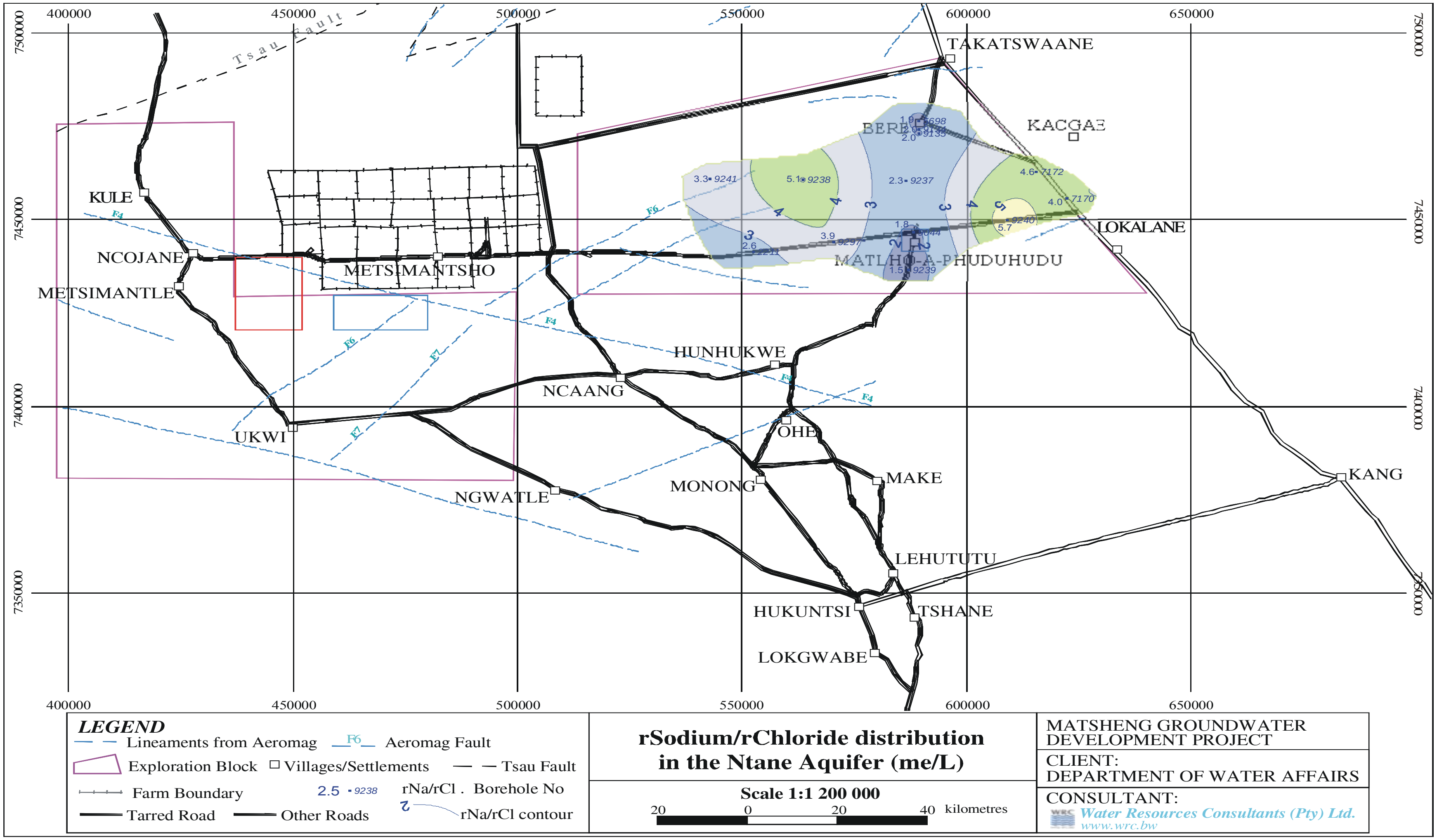


Figure 2.14 Sodium Vs Chloride Ionic Ratio Distribution, Ntane Aquifer

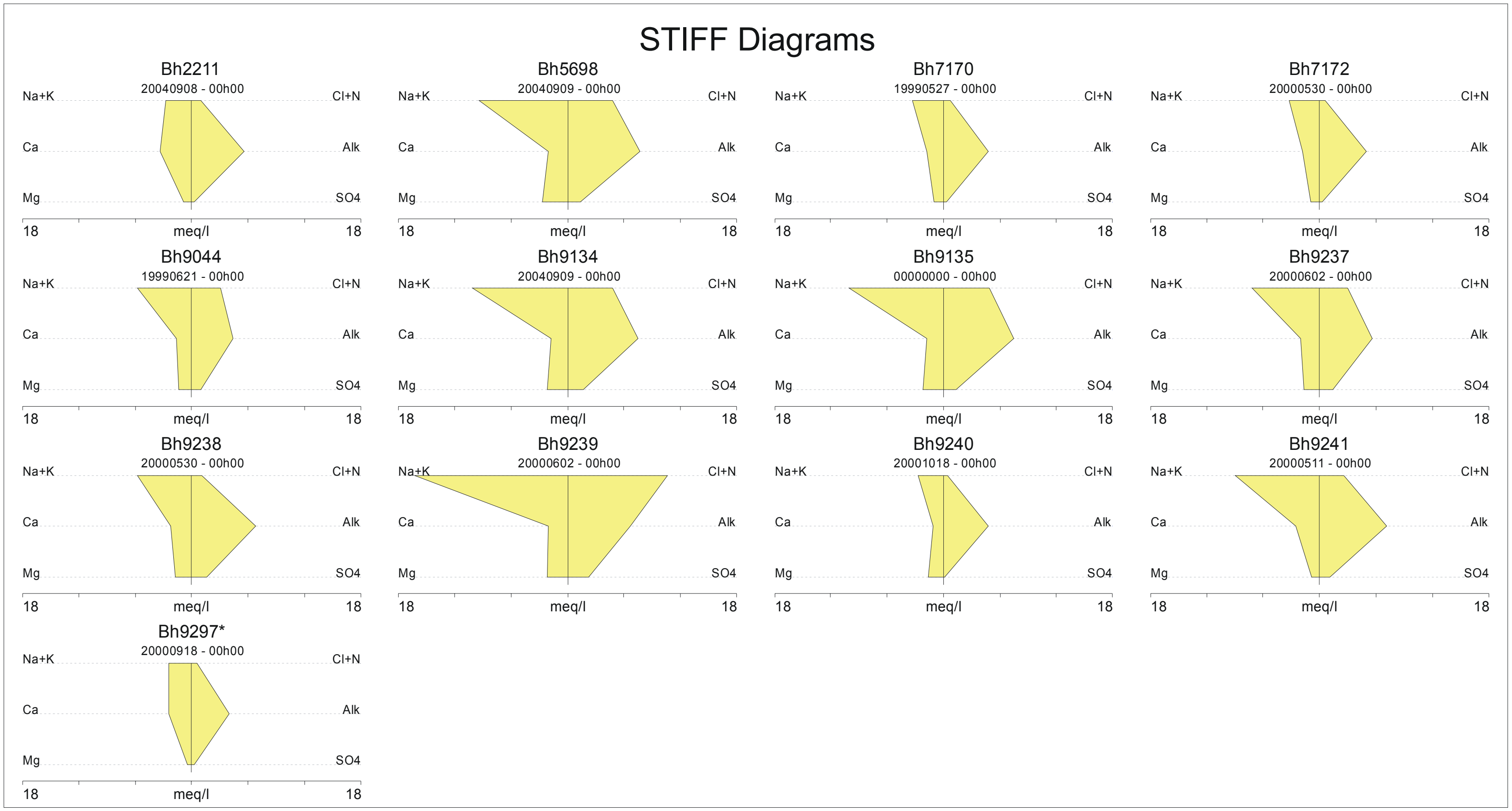


Figure 2.15 Stiff Chemical Composition Diagrams, Ntane Aquifer

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2.3 HYDROCHESTRY OF OTSHE (ECCA) AQUIFER

The Otshe aquifer is well represented with regard to boreholes with analytical data, particularly in the western part of the project area, with a total of 40 exploration and 6 production boreholes in the whole area. This means that hydrochemical trends in the Otshe aquifer can be identified with a high degree of confidence. Furthermore, as the Otshe is essentially a confined aquifer, a consistent hydrochemical evolution is expected along the flow path in the aquifer from recharge areas to discharge areas except for faults that may affect groundwater flow in the aquifer either by connecting it with overlying or underlying aquifers. The main piezometric gradient is from west to east and northwest to southeast which means that the hydrochemical evolution in the aquifer should take place in an eastward direction and southeasterly directions.

2.3.1 ELECTRICAL CONDUCTIVITY (SALINITY)

The lowest salinity occurs in the western, north-western, and far north-eastern parts of the aquifer while the highest salinity is found at Hunhukwe in the south of the project area (**Figure 2.16**). The overall distribution of salinity and the gradual increase follows the notion of groundwater flow in a southeasterly and easterly directions. However, it would seem that low salinity water is also entering the aquifer in the far northeast with increasing salinity towards Hunhukwe in the south. Several anomalies are noted, e.g. northwest as well as east of Ncojane (borehole 3055), and northwest of Ukwi. It is possibly that some of these anomalies may not relate to the aquifer as such but rather to conditions at the borehole itself, e.g. leakage from overlying saline aquifers. To the east of Ukwi (east of Faults F6 & F7) where the aquifer occurs at much deeper depths and water strikes are deeper, the salinity (EC) in the aquifer increases rapidly and eventually exceeds 8000µS/cm at Hunhukwe.

2.3.2 SODIUM

The sodium concentration in the Otshe aquifer is low in the west, northwest, and east of the project area and increases eastward, southward and southwest wards towards Hunhukwe where it exceeds 1500 mg/L (**Figure 2.17**). As was the case in the salinity, sodium anomalies exist northwest and east (borehole 3055) of Ncojane, as well as at Ukwi (borehole 10216). This is again attributed to borehole construction rather than the aquifer it's self. Overall sodium follows the distribution of EC very closely. In the Ncojane wellfield where the new production boreholes were drilled the sodium concentration is at or just above the BOS 32:2000 Class I limit of 100 mg/L for Class I.

2.3.3 CALCIUM

The calcium concentration in the Otshe aquifer is generally low to very low but it is highest in the west and northwest of the project area. The main anomalies are found at Ncojane and also some distance further east at borehole 3055 (**Figure 2.8**). In a large area to the east and northeast of Ukwi calcium is very low (<5 mg/L) but further east where the aquifer is much deeper the calcium increases somewhat and reaches 44 mg/L at the saline borehole (8545) at Hunhukwe. The decrease in calcium is ascribed to the exchange of calcium ions in solution with sodium ions from the rock matrix.

2.3.4 MAGNESIUM

The distribution of magnesium is very similar to that of calcium and generally its concentrations are lower than that of calcium (**Figure 2.19**). The only exception is at borehole 3055 where the magnesium reaches 61 mg/L. Magnesium in solution is also subject to ion exchange with sodium from the rock matrix hence the large degree of similarity with calcium. However, despite the fact that both these elements are so-called alkaline earth metals, many magnesium salts are considerably more soluble than the corresponding calcium salts, e.g. magnesium sulphate compared to calcium sulphate or gypsum which is sparingly soluble in water.

2.3.5 CHLORIDE

Chloride concentrations in the groundwater generally increase with residence time, i.e. along the flow path. In a confined aquifer this process is better defined and consistent patterns develop. In the Otshe this is fairly well defined. Water with very low chloride enters the aquifer from the northwest as well as from the west and the extreme east of the project area (**Figure 2.20**). From the west the chloride concentration increases relatively rapidly in an easterly and south-easterly direction and it exceeds 1500 mg/L at Hunhukwe. From the eastern extreme of the area, the chloride similarly increases in a south-westerly direction until reaching Hunhukwe. It is expected that the “age” of the groundwater will increase in an easterly and south-easterly direction. Comparing the chloride contours with the ^{14}C distribution it is evident that the groundwater “age” in the Otshe aquifer increases as the chloride concentration in creases. It is also evident that the groundwater in the aquifer has a very high ^{14}C age of the order of 20 000 to 30 000 years.

2.3.6 SULPHATE

Similar to chloride, sulphate is present in rainwater. It also originates from sulphates minerals such as gypsum. In a well-aerated aquifer without organic materials, sulphate may also serve as a conservative tracer similar to chloride. The occurrence of higher levels in a confined aquifer may be ascribed to oxidation-reduction reactions, particularly to the oxidation of pyrites occurring in the geological material, e.g. in the confining mudstones and shale. The sulphate concentration increases from very low levels (<10 mg/L) in the northwest to about 1500 mg/L in the southeast at Hunhukwe (**Figure 2.21**).

2.3.7 FLUORIDE

Fluoride concentrations in groundwater are dependent on a number of chemical equilibria controlling the solubility of the fluoride ion and its complexes. The most important one is the fluorite (CaF_2) equilibrium. This implies that the fluoride concentration is highly dependent on the calcium content of the water. As the calcium concentration decreases the fluoride concentration will increase. To some extent this is modified by the ionic strength of the water because at higher salinity conditions a higher fluoride concentration is possible for a given calcium concentration. It is evident that the fluoride concentration is low at the western, northern, and eastern edge of the area but increases rapidly along the flow path in the aquifer (**Figure 2.22**). Comparison with the calcium concentration shows that in most of the area where fluoride exceeds 1 mg/L the calcium concentration is less than 15 mg/L.

2.3.8 NITRATE

Only in exceptional cases does nitrate in groundwater originate from the aquifer matrix. Nitrate is derived from natural processes (e.g. nitrogen fixing by leguminous vegetation) or anthropogenic sources at the surface and enters the water in the recharge area or at pollution point sources (e.g. on-site sanitation systems). In a confined aquifer such as the Otshe, nitrate will be derived from the recharge area and considering the residence time of the water in the aquifer, an anthropogenic source is generally excluded. In general, Kalahari groundwater has naturally low but persistent nitrate concentration which will also affect the Otshe aquifer due to the recharge via the overlying Kalahari beds. It is evident that the nitrate disappears relatively quickly in the Otshe aquifer and this is ascribed to natural denitrification (**Figure 2.23**). In the vicinity of Ncojane significant concentrations of nitrate occur. It should be established whether this is derived from on-site sanitation and seepage thorough poorly constructed boreholes.

2.3.9 TOTAL ALKALINITY

The total alkalinity of the groundwater in the recharge areas (west and northwest) are of the order of 150 to 200 mg/L (**Figure2.24**). This increases along the flow path due to cation exchange involving shale or mudstone surfaces removing calcium from solution and releasing sodium into solution. At the same time calcium carbonate, and possibly gypsum, is dissolved from the sandstone matrix due to the change in ionic equilibria (JICA, 2002). This calcium is also exchanged for sodium as the water moves along the flow path. This process increases the pH and alkalinity of the water until chemical equilibrium is reached for the particular conditions in the aquifer.

2.3.10 POTASSIUM

The potassium concentration in groundwater is generally very low, however, in groundwater from the Kalahari sediments it is often slightly elevated (Kirchner & Tredoux, 1975). Potassium may also serve as a very useful indicator of pollution derived from on-site sanitation, from waste disposal sites, and similar pollution sources. However, potassium itself is not a pollutant. Potassium undergoes fixation where the clay mineral Illite is present, e.g. in mudstones and shales. Therefore, the potassium concentration in solution can be reduced along the flow path. In the Otshe aquifer the potassium concentration does not vary over a wide range (**Figure 2.25**). An extreme value occurs only at borehole 3055 which was previously noted for other anomalies. It is concluded that this concentration does not fit the Otshe aquifer at this point and the water is possibly not derived from this aquifer. If it actually came from the aquifer, there could be a pollution point source at or near the borehole.

2.3.11 SODIUM PERCENTAGE (ME/L)

The hydrochemical evolution of groundwater in aquifers 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 exist. 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. In the Otshe aquifer the recharge water has a sodium percentage ranging between 40 and 50 per cent but as hydrochemical evolution takes place it rapidly increases to 90 per cent and higher (**Figure 2.26**).

2.3.12 SULPHATE PERCENTAGE

The sulphate percentage indicates the importance of this constituent in the context of a particular aquifer. It is evident that the sulphate concentration is very low in the recharge area and as set out above, the initial concentration is derived from rainwater and soil processes. The contour diagram shows that the sulphate increases significantly along the flow path which implies that sulphate is derived from the aquifer material (**Figure 2.27**). For the Otshe it would mean dissolution of gypsum as well as oxidation of pyrite to sulphate. Sulphate may also be generated due to the denitrification process when sulphur bacteria are involved.

2.3.13 TOTAL ALKALINITY PERCENTAGE

Whereas the relative sodium concentration increases during the hydrochemical evolution of groundwater the relative bicarbonate concentration decreases. Therefore, the initial bicarbonate concentration can exceed 70 percent while the final concentration could be below 25 percent. This generally occurs despite the increase in total alkalinity due to the ion exchange process as described above. In the case of the Otshe aquifer the percentage total alkalinity decreases from 60 to 80 in the recharge areas to 20 in the discharge area (**Figure 2.28**).

2.3.14 SODIUM VS CHLORIDE IONIC RATIO

As mentioned above the chloride concentration generally serves as a conservative tracer. In contrast sodium is subject to various processes during hydrochemical evolution in an aquifer. Using chloride as a baseline, the changes in sodium concentration along the flow path in the aquifer can be evaluated. It can be expected that in the recharge area the ionic ratio between sodium and chloride should be approximately unity. As additional sodium is added in the evolution process the ionic ratio should change with sodium exceeding chloride. In the Otshe aquifer the ratio generally exceeds unity, i.e. the sodium concentration is much higher than the chloride concentration (**Figure 2.29**). This is also the case in the recharge areas with the possible exception of the area northwest of Ncojane. In the north and east the sodium is at least five times higher than the chloride. Along the flow path this ratio decreases and in the "discharge area" it is between 1 and 2. This implies that despite the increase in the sodium concentration the chloride concentration increased even faster in the aquifer.

2.3.15 STIFF CHEMICAL COMPOSITION DIAGRAMS

As explained above the Stiff hydrochemical composition diagrams show the absolute concentrations of the various parameters and the size of the figures gives an indication of the salinity of the water. All figures on one page are drawn to the same scale. At the same time the three axes each for cations and anions give a clear indication of the relative compositions of cations and anions (**Figure 2.30 part 1** and **Figure 2.31 Part 2**).

2.3.16 PRODUCTION BOREHOLES

The six new production boreholes at Ncojane are of good quality and at three of these only the hardness exceeds the BOS 32:2000 Class I limit. At the other three boreholes the salinity slightly exceeds the limit with sodium and chloride exceeding the specifications. All boreholes comply with Class II specifications.

The Stiff chemical composition diagrams for the production boreholes at Ncojane indicate the degree of similarity of the water quality at these boreholes (**Figure 2.32**)

2.3.17 SUMMARY

Anomalies in the hydrochemical distribution patterns in a confined aquifer warrant closer examination. If a structural feature, e.g. a fault has not been identified in the area, either the classification of the borehole may be incorrect, i.e. it may be linked to another aquifer, or the casing could be leaking, or the analytical data may be incorrect. In the case of the Otshe aquifer, it is evident that it is overlain by mudstones with more saline water which may be contaminating the better quality Otshe aquifer. Similarly, the saline water may be up-coning from the underlying Kobe aquifer.

Salinisation of a confined aquifer with time has been observed in neighbouring Namibia, possibly aggravated due to over abstraction and stressing of the aquifer (JICA, 2002). Special care needs to be exercised in areas where faults are known to exist, potentially linking the aquifer with others of inferior water quality as well as borehole construction.

In this context, water chemistry anomalies, such as was found at borehole 3055, need to be investigated to identify the reasons for the difference in composition. Initially, the borehole should be re-sampled to confirm the hydrochemical results. Furthermore, once it is certain that the classification of the aquifer, the placement of the screens etc are correct; the borehole should be inspected with a borehole camera and logged with down-the-hole logging equipment including hydrochemical logging.

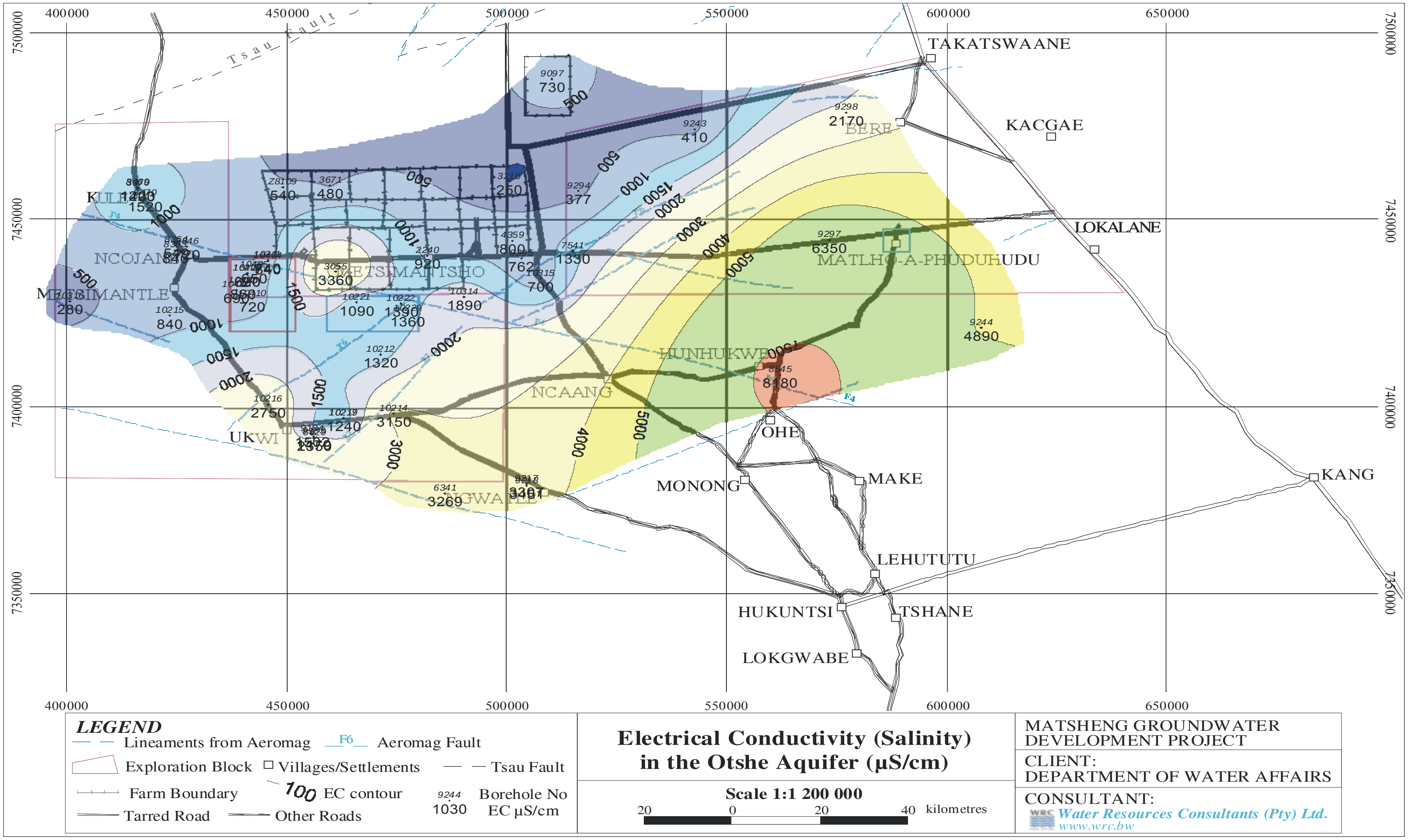

Figure 2.16 Electrical Conductivity (salinity) Distribution, Otshe aquifer

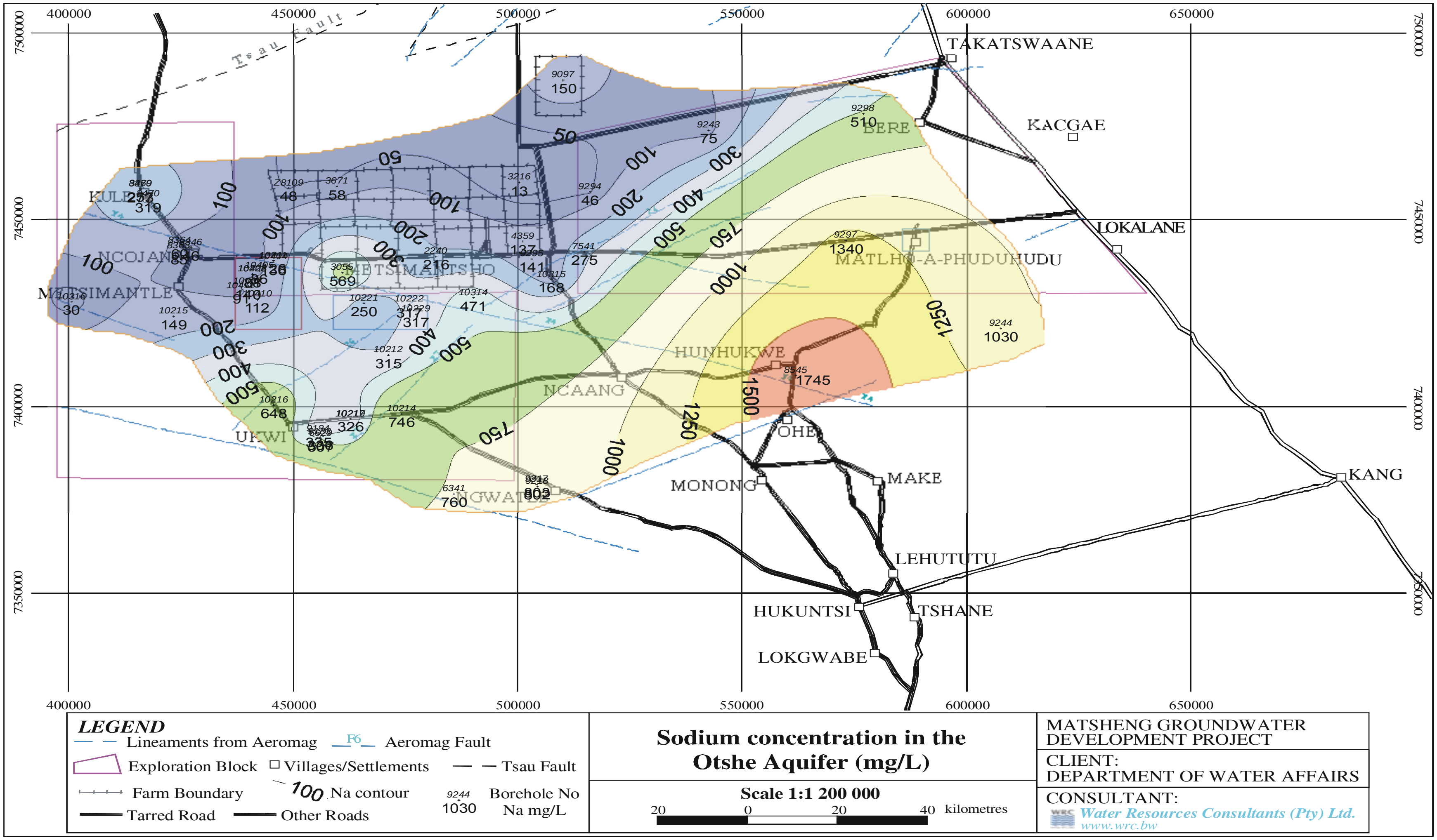

Figure 2.17 Sodium Distribution, Otshe aquifer

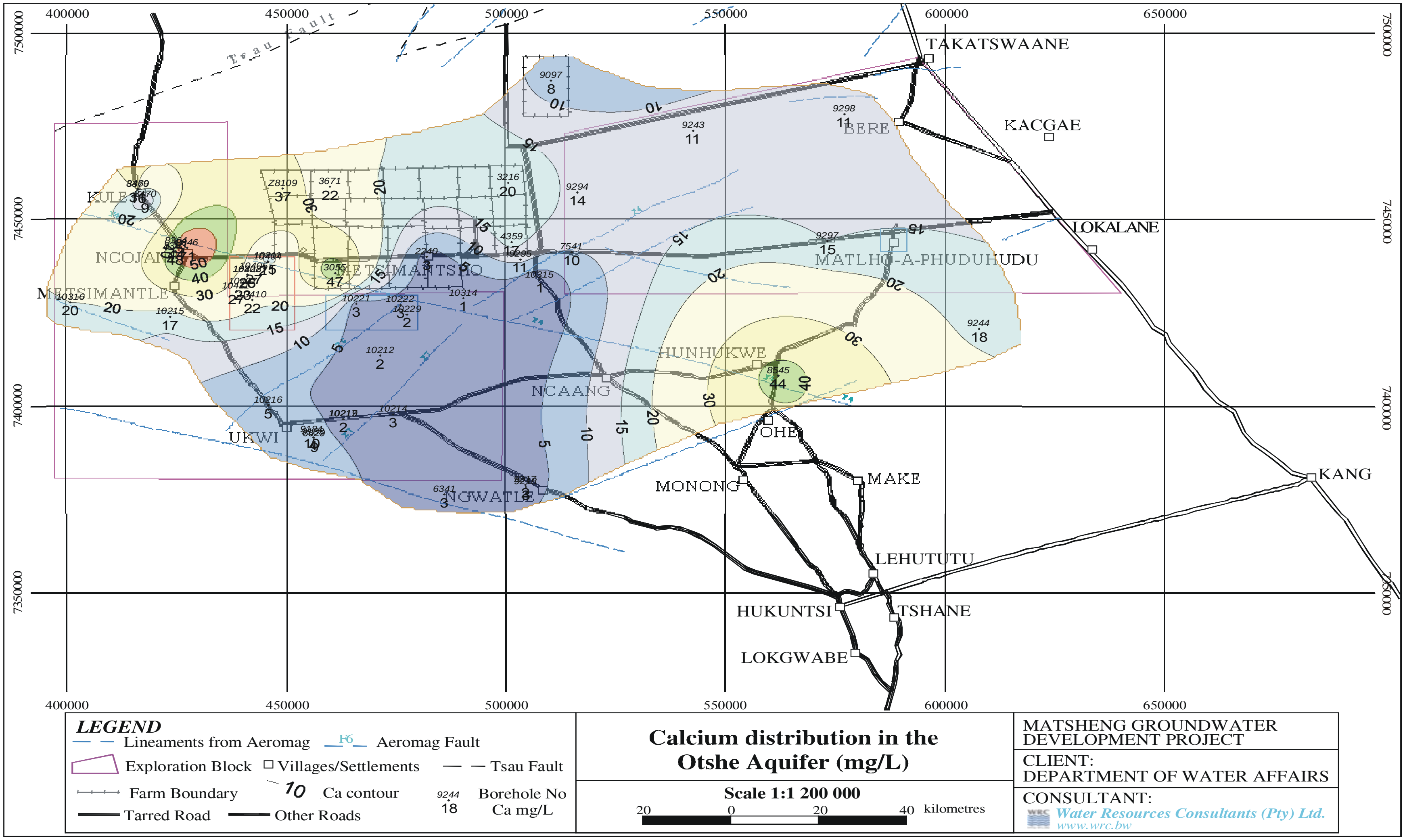

Figure 2.18 Calcium Distribution, Otshe aquifer

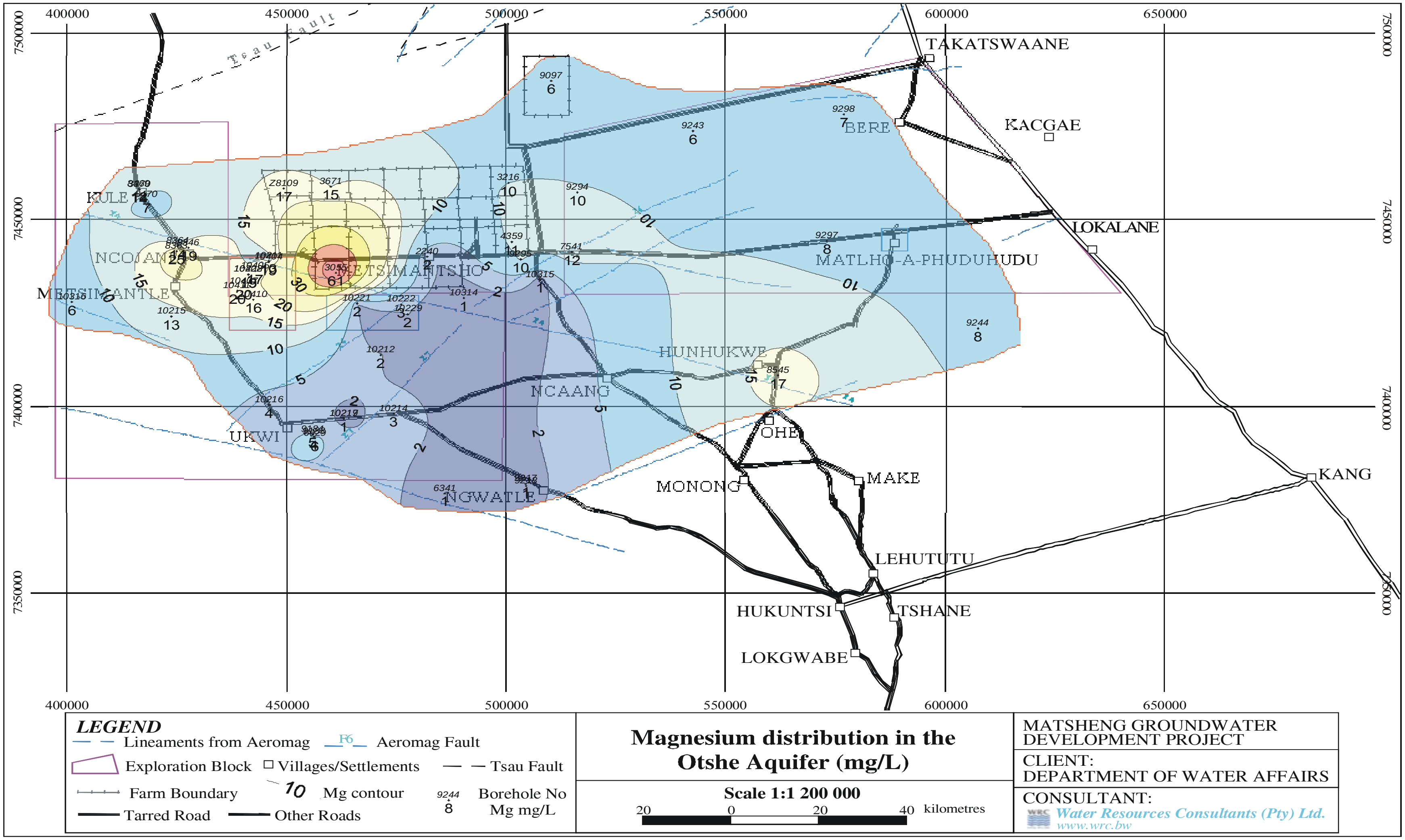

Figure 2.19 Magnesium Distribution, Otshe aquifer

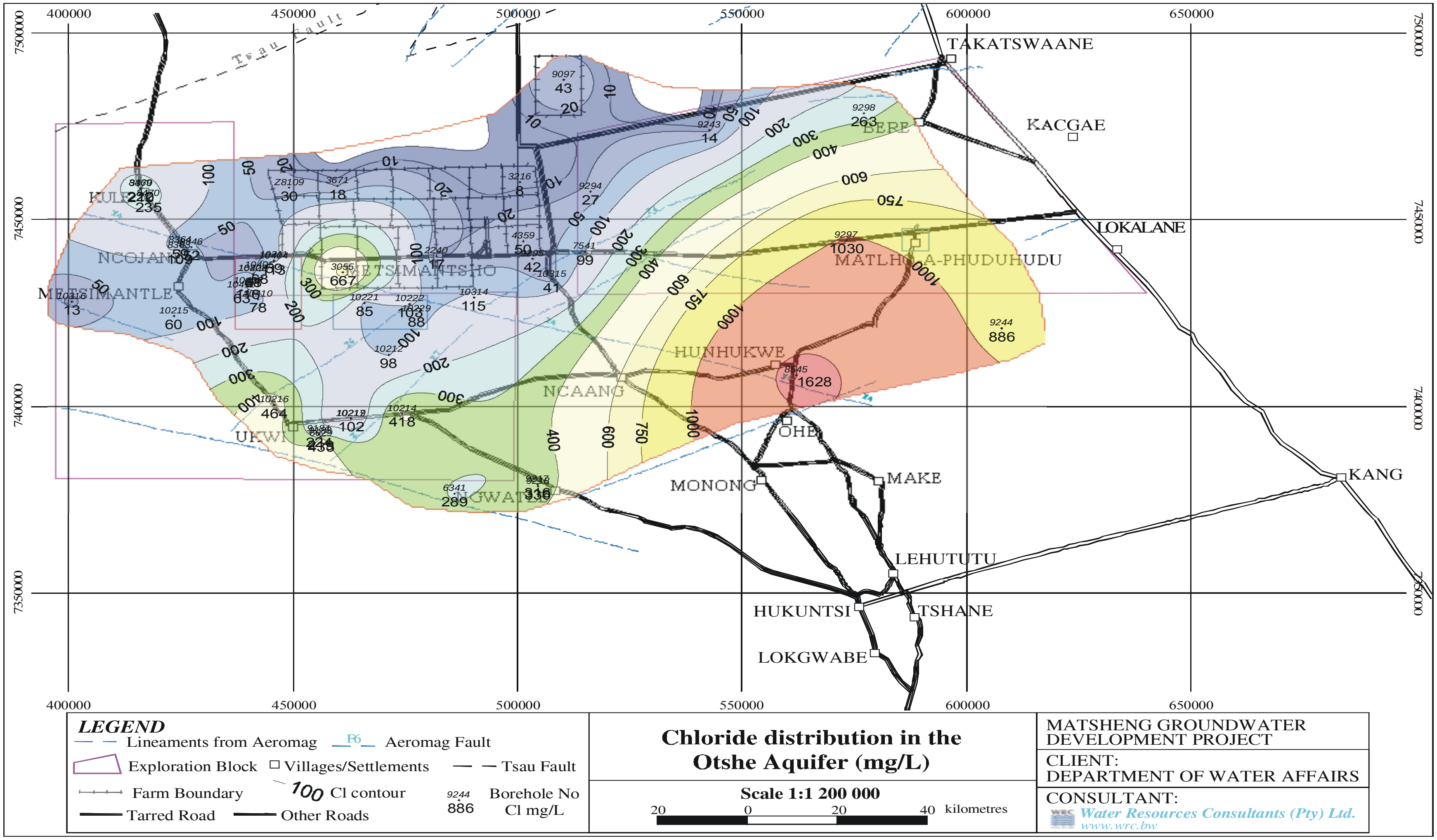

Figure 2.20 Chloride Distribution, Otshe aquifer

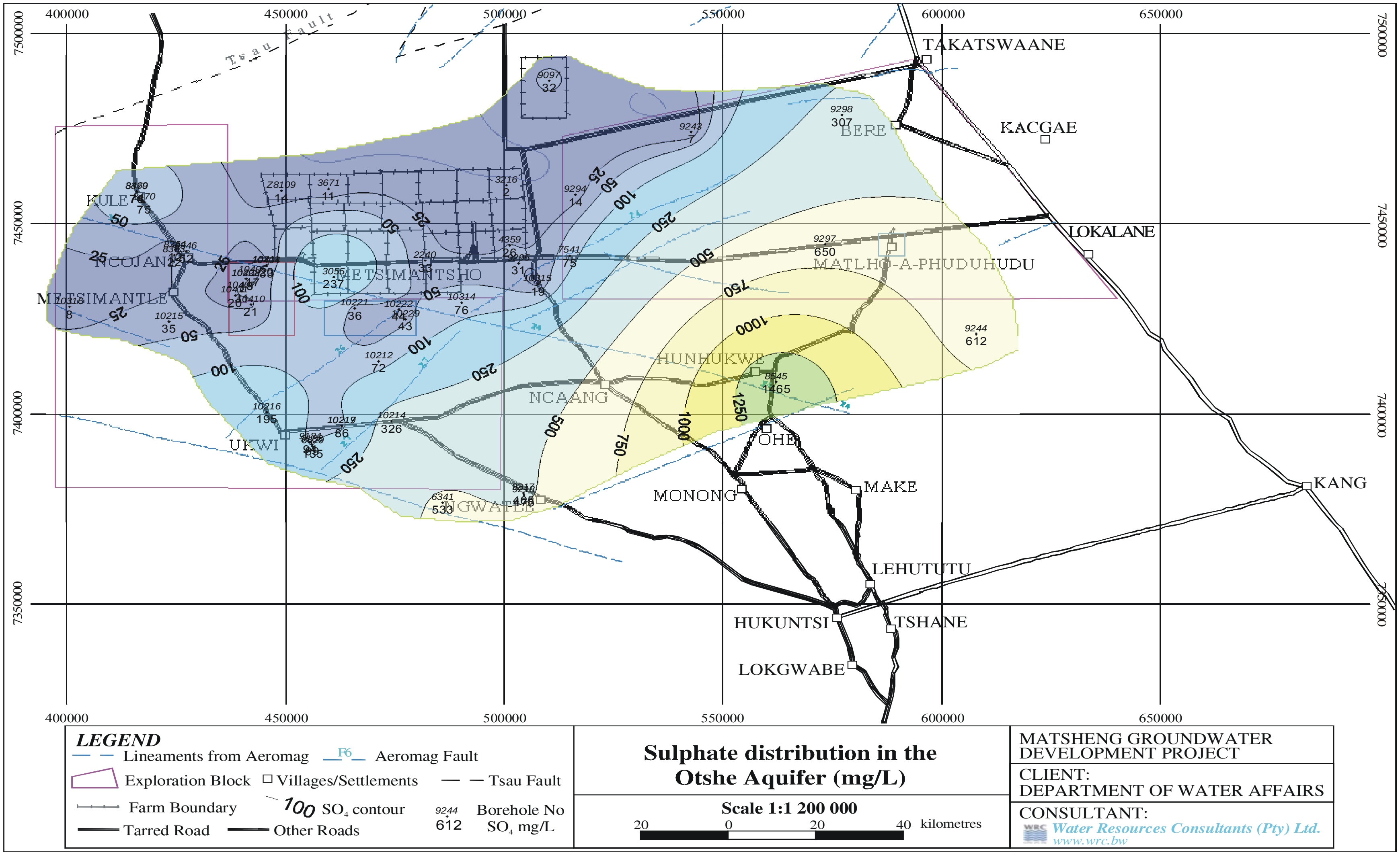

Figure 2.21 Sulphate Distribution, Otshe aquifer

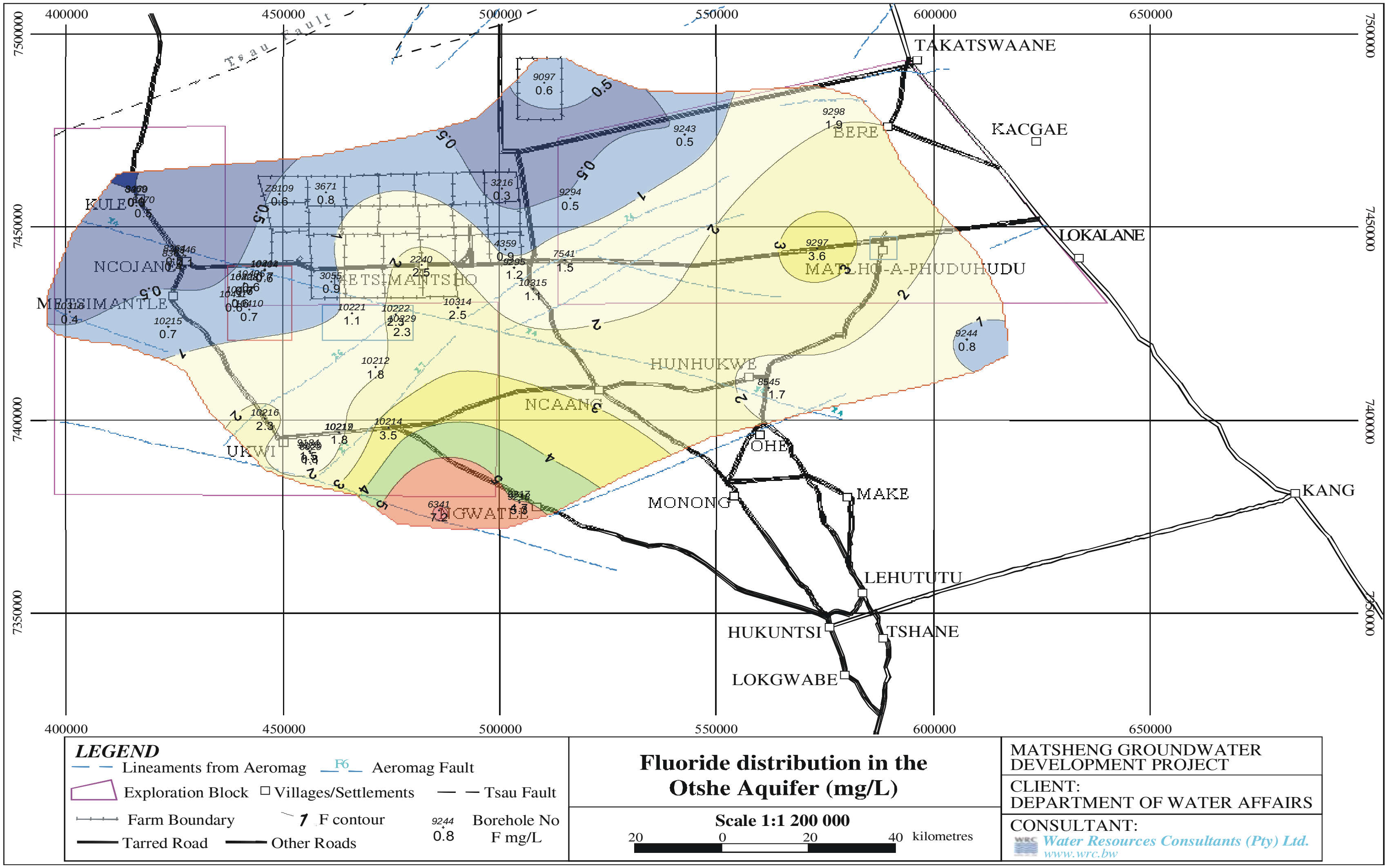

Figure 2.22 Fluoride Distribution, Otshe aquifer

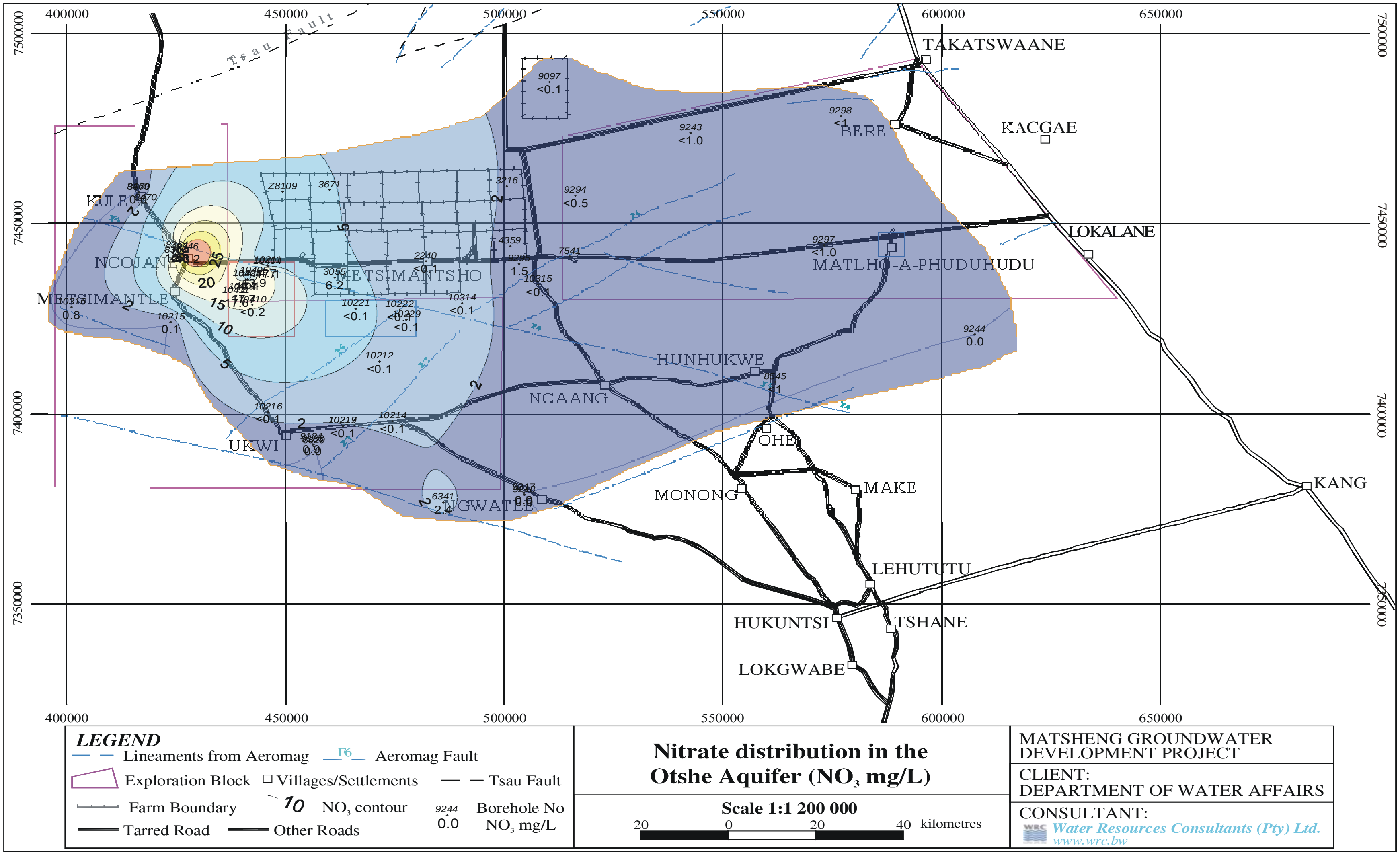

Figure 2.23 Nitrate Distribution, Otshe aquifer

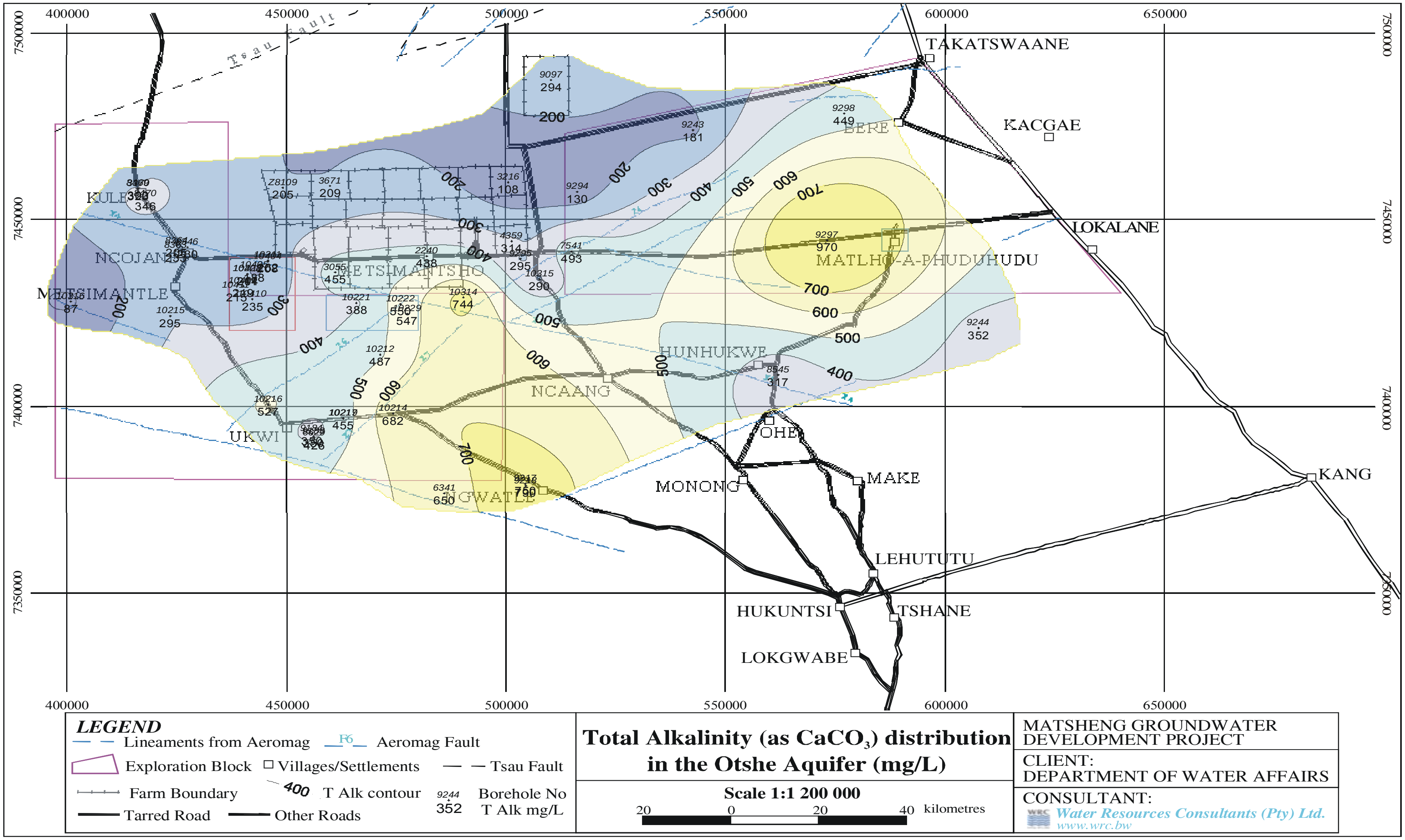

Figure 2.24 Total Alkalinity Distribution, Otshe aquifer

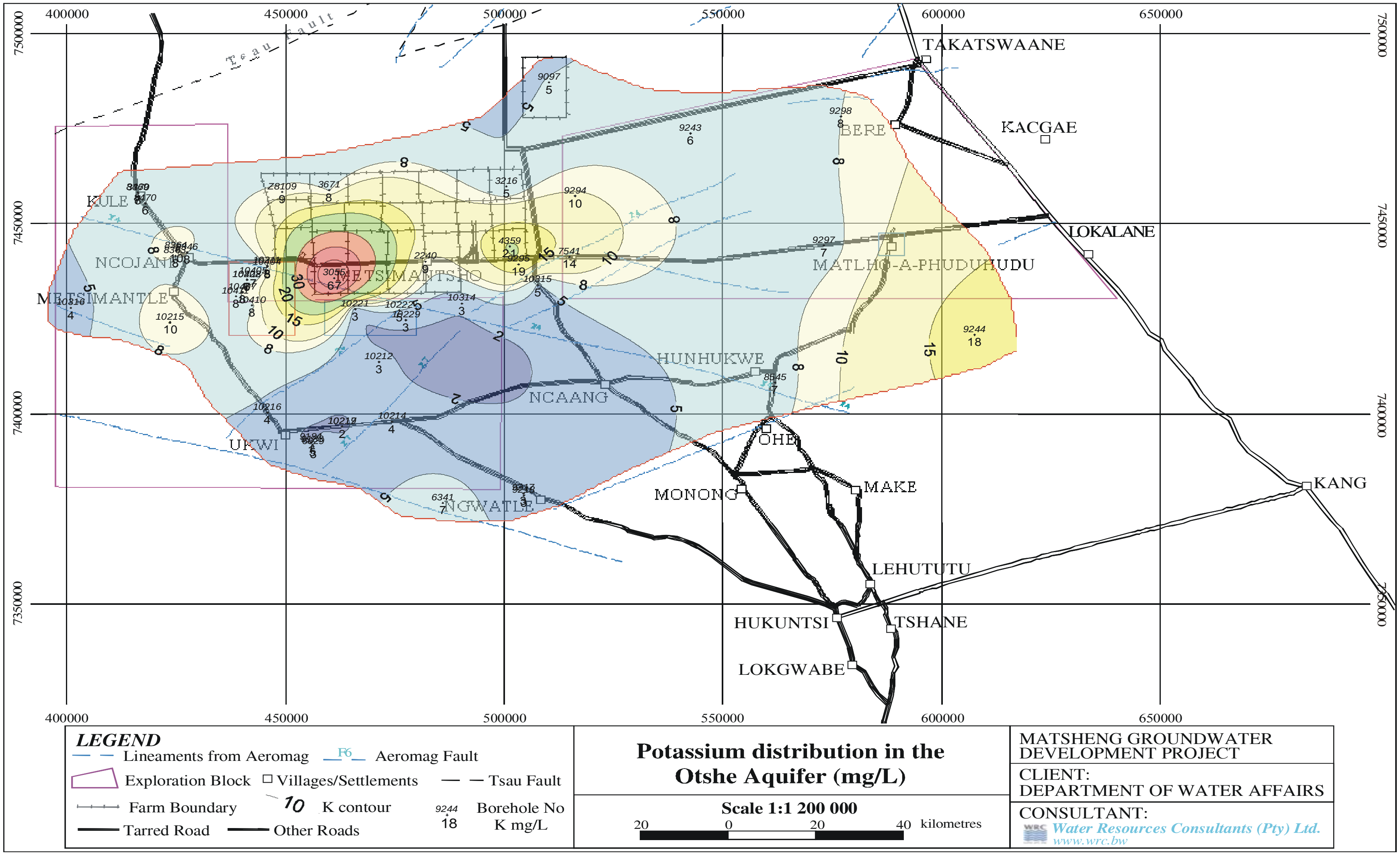

Figure 2.25 Potassium Distribution, Otshe aquifer

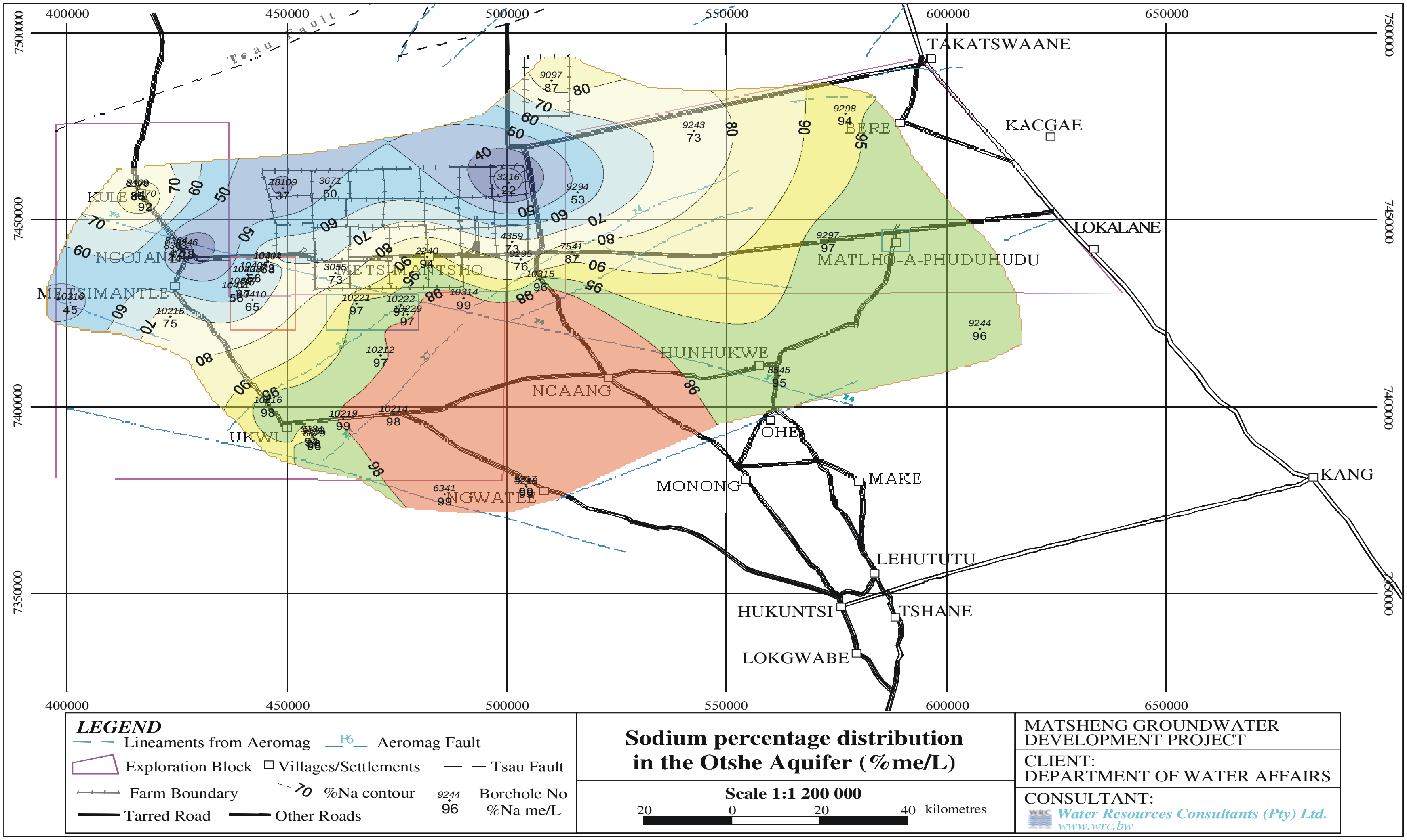

Figure 2.26 **Sodium Percentage Distribution Otshe Aquifer**

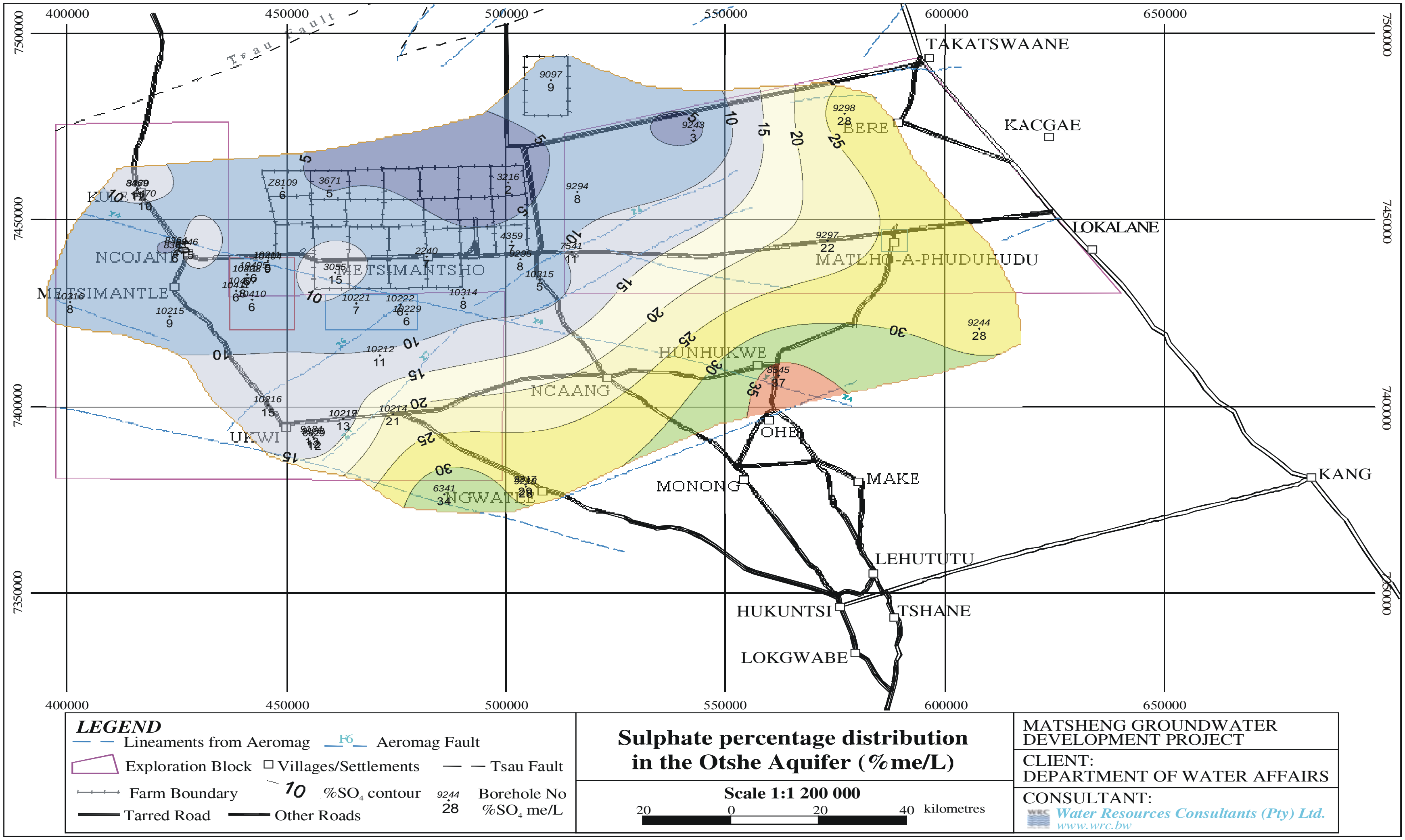

Figure 2.27 Sulphate Percentage Distribution, Otshe Aquifer

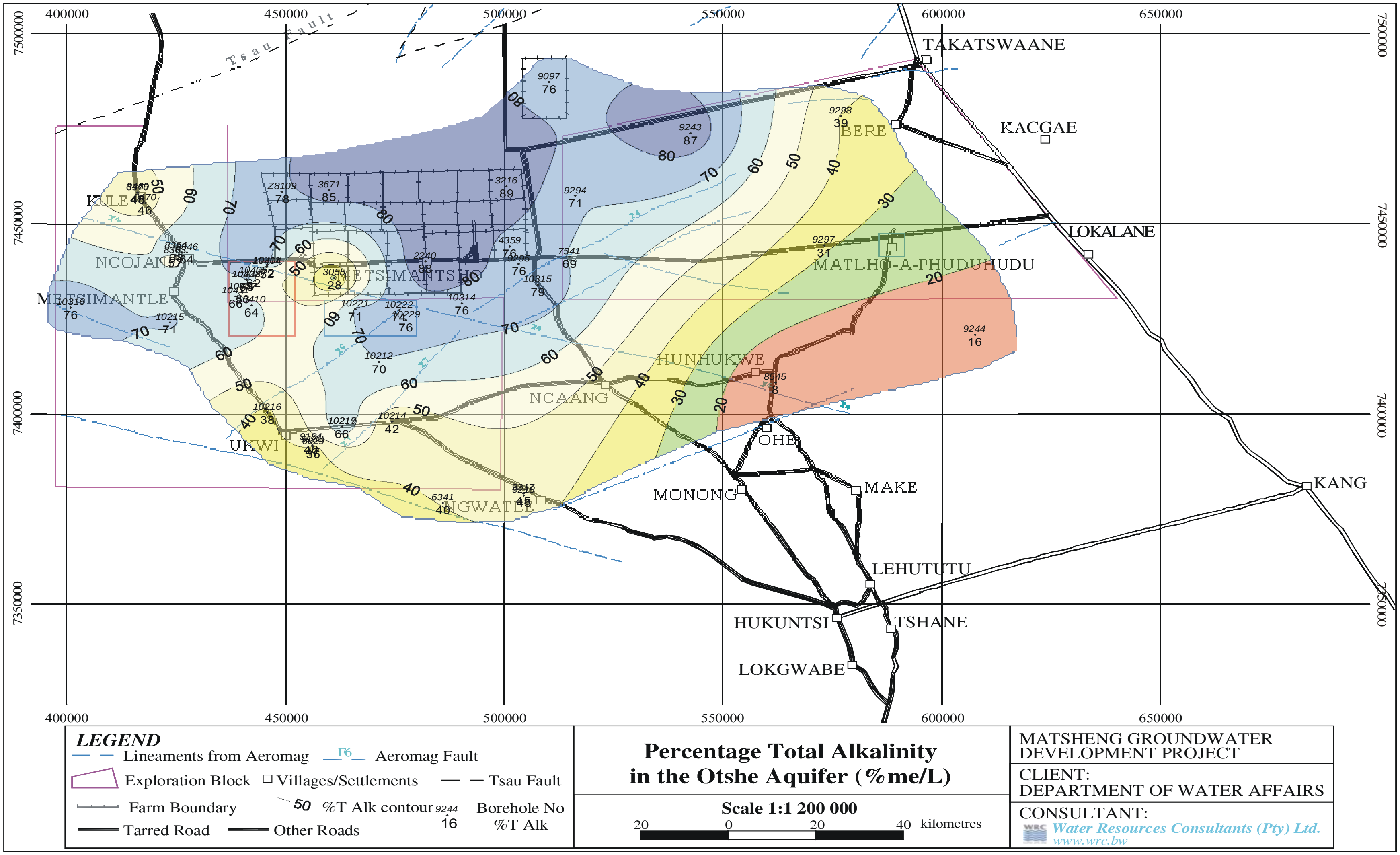

Figure 2.28 Total Alkalinity Percentage Distribution, Otshe Aquifer

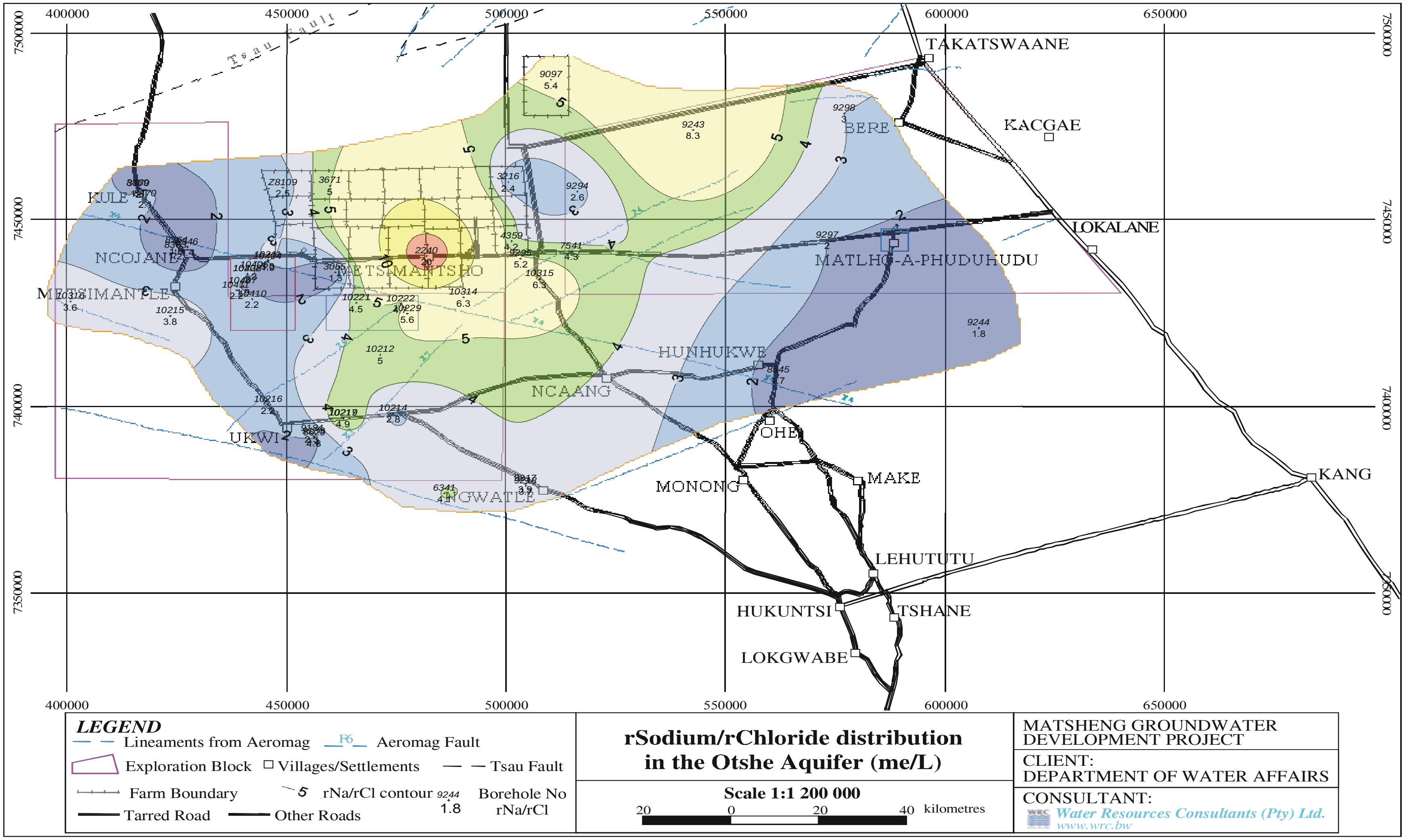

Figure 2.29 Sodium Vs Chloride Ionic Ratio Distribution, Otshe Aquifer

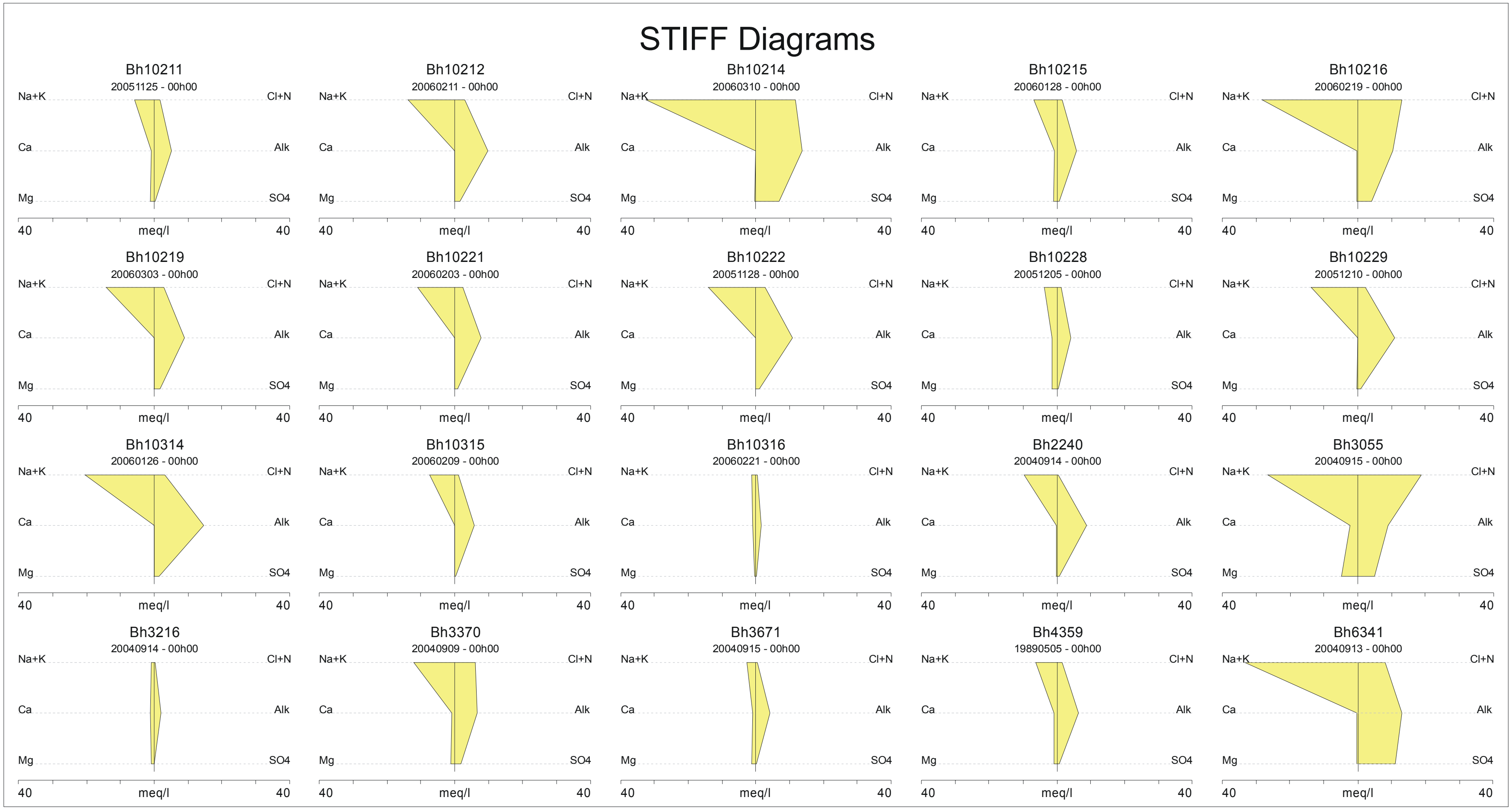

Figure 2.30 Stiff Chemical Composition Diagrams for Exploration Boreholes, Otshe Aquifer (Part 1)

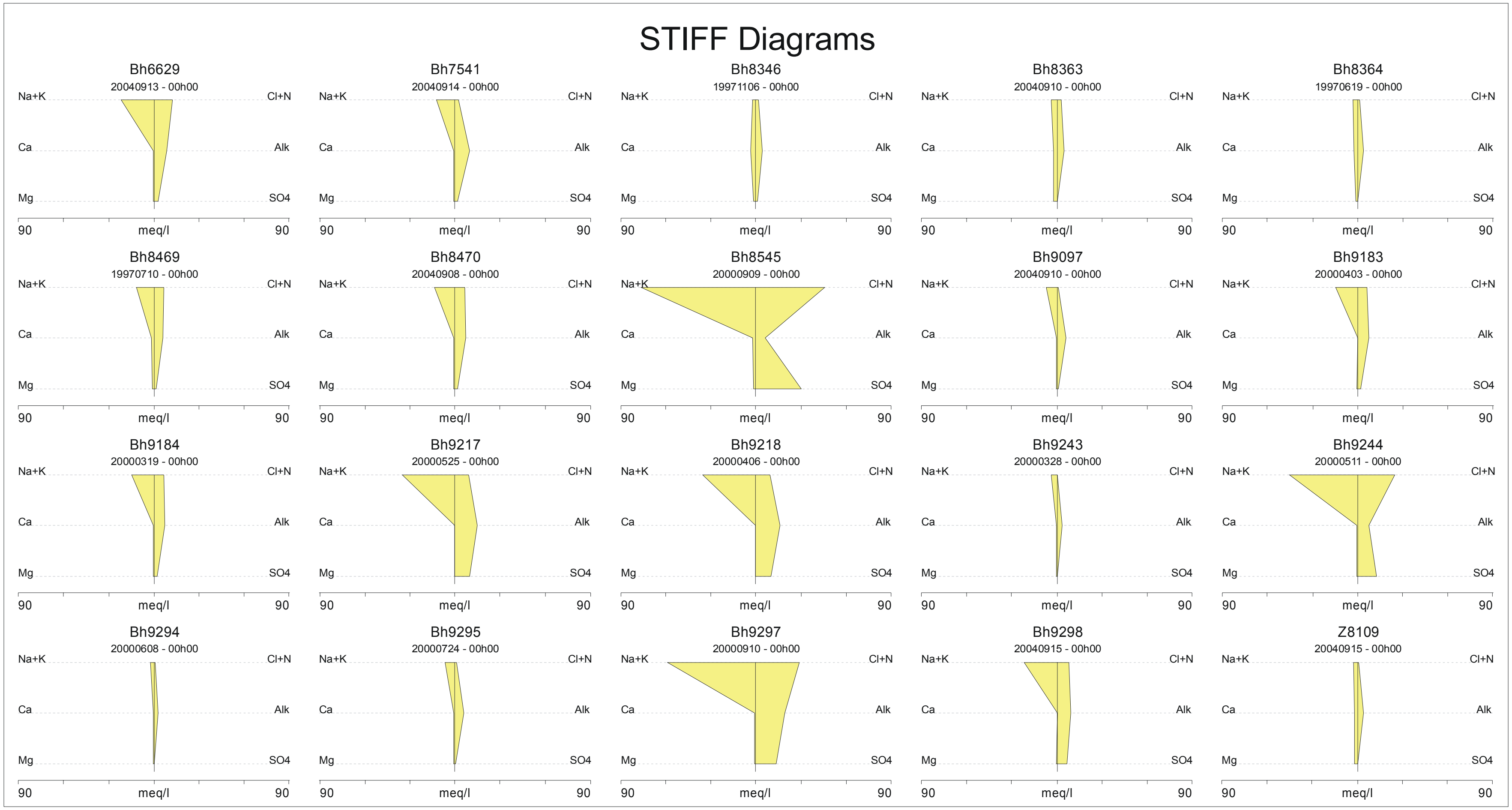

Figure 2.31 Stiff Chemical Composition Diagrams for Exploration Boreholes, Otshe Aquifer (Part 2)

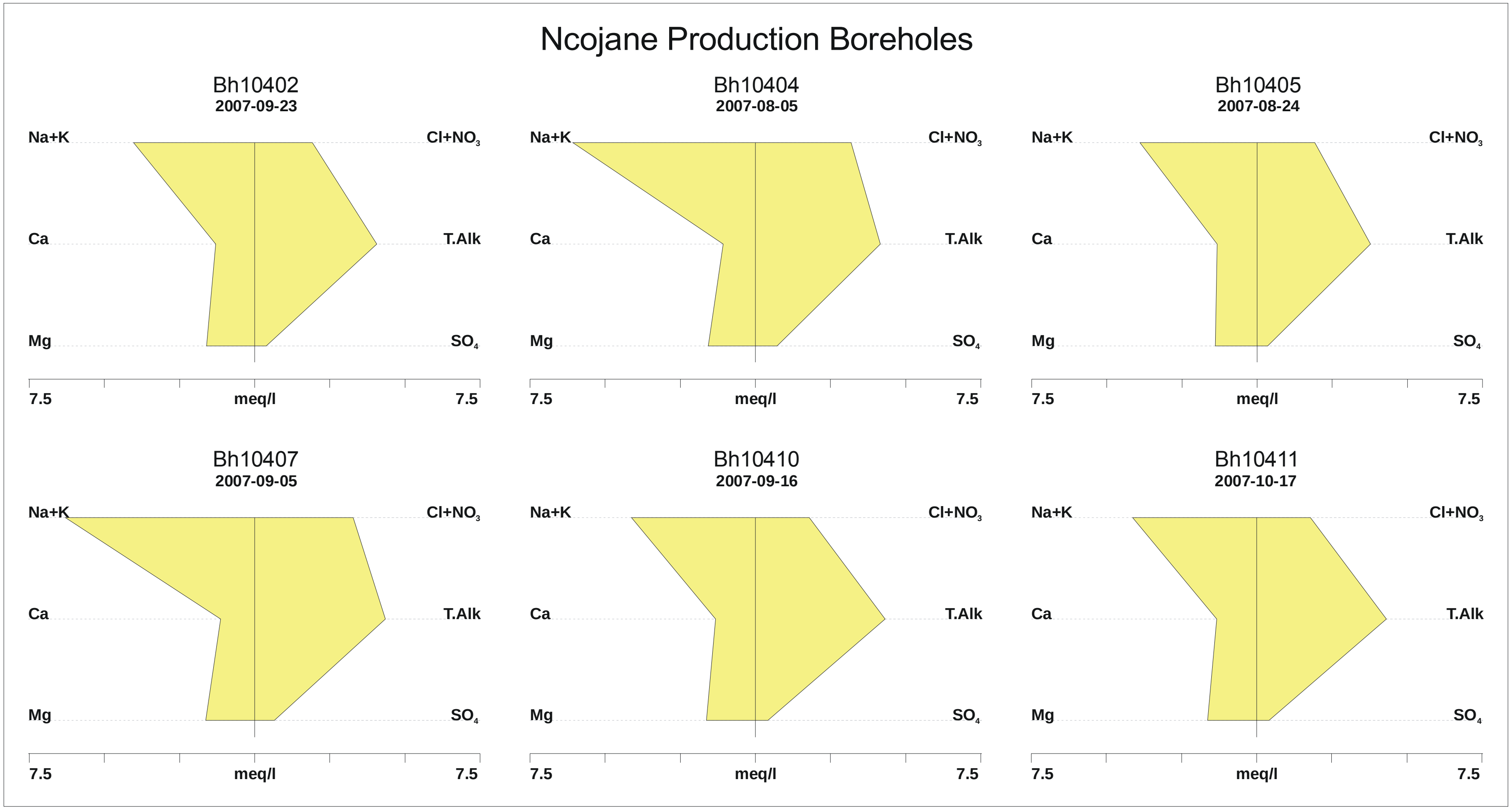

Figure 2.32 Stiff Chemical Composition Diagrams for Production Boreholes, Otshe Aquifer Ncojane Wellfield

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2.4 COMPARISON OF THE DIFFERENT AQUIFERS

2.4.1 CHLORIDE

The chloride distribution in the three aquifers are shown in different colours in one drawing (**Figure 2.33**). This confirms that the chloride concentration and the chemical composition of the water in the different aquifers differ greatly at any particular point, indicating that these aquifers are not connected.

2.4.2 SODIUM PERCENTAGE (MEQ/L)

As explained earlier, the sodium percentage depicts the hydrochemical evolution in that particular aquifer. An overlay for the three aquifer systems indicate that at any particular point in the project area the evolution in any one of the aquifers reaches a totally different stage compared to the other aquifers at that point (**Figure 2.34**).

2.4.3 TRILINEAR DIAGRAM (PIPER)

A trilinear diagram showing all sampling points in the various aquifers is given in **Figure 2.35**. The production boreholes are shown separately. The diagram illustrates that the groundwater in the Otshe undergoes a full hydrochemical evolution from recharge areas to discharge areas, whereas the groundwater in the Ntane sandstone has only undergone a partial evolution. The six production boreholes are also located in an area where the water in the Otshe has undergone only partial evolution.

2.4.4 DUROV DIAGRAM

The Durov diagram also shows the relative chemical composition of the water but two fields are added to show the salinity and pH data. This is the only graph showing the high salinity of approximately 30 000 µS/cm for borehole 4939 located at Ukwi (**Figure 2.36**). The figure also shows the high salinity of the majority of the boreholes in Mosolotsane/ Kule (Kwetla) aquifer.

2.4.5 TDS AND IONIC RELATIONSHIPS

The interrelationships between the hydrochemical constituents were investigated using all available data. Only borehole 4939 at Ukwi was generally excluded because of its extremely high salinity. In certain instances, where the relationship between parameters in the potable range was important, only the points plotting in the lower range were included.

A graph of the TDS and EC values in the various aquifers show that there is a consistent relationship between these two parameters in all aquifers as expected (**Figure 2.37**). The ratio of TDS (in mg/L) to EC (in µS/cm) is approximately 0.63. Whereas the TDS for some samples may actually have been measured, the TDS for the samples analysed at the CSIR in Stellenbosch were calculated from the EC using a factor of 0.64. This to some extent explains the constant ratio for all aquifers. In actual fact the ratio will vary depending on the salinity of the water and the ionic composition as the contributions of the specific conductivities of the individual ions vary according to their electrochemical characteristics. However, the Stiff diagrams for the various aquifers showed the dominance of sodium in most of the groundwater. This leads to a close relationship between the sodium concentration and EC for most of the groundwater in all aquifers (**Figure 2.38**) which at least partly explains the close relationship between EC and TDS.

The relationship between the calcium concentration and electrical conductivity (EC) differs for the various aquifers (**Figure 2.39**). The majority of boreholes with water strikes in the Mosolotsane or Kule (Kwetla) Formations have low calcium values but very high salinities. The Otshe boreholes vary over a wide range but the production boreholes are exploiting the best range of possibilities. The Ntane aquifer has a relatively low salinity but higher calcium concentrations.

With regard to magnesium the Ntane sandstone shows a wide range of values (**Figure 2.40**). Magnesium also contributes to the hardness of the Otshe production boreholes near Ncojane.

At lower concentrations chloride, sulphate, and total alkalinity display a relatively close correlation with EC (**Figures 2.41, 2.42, and 2.43**). At higher concentrations there is little correlation with the EC. This illustrates the diversity in the hydrochemical evolution in different parts of the aquifers.

In the case of sodium no direct relationship exists (**Figure 2.44**). This was also partly illustrated in the contour diagrams showing the rNa/rCl ratio.

It is evident that there is practically no correlation between the sulphate and chloride concentrations in the various aquifers (**Figure 2.45**). The only relatively coherent group is the set of production boreholes drilled into the Otshe aquifer. Similarly there is no relationship between the total alkalinity and the chloride concentration in the various aquifers (**Figure 2.46**).

No correlation between the nitrate and chloride concentrations in the various aquifers exists except for one point in Ntane aquifer at borehole 9239 (**Figure 2.47**). Such a relationship is usually the case when groundwater pollution from anthropogenic or animal sources is present. Borehole 9239 is located at Mosiding Pan and it may be possible that this borehole is polluted. In most other cases the higher nitrate levels are associated with low chloride and this is probably an indication that the nitrate is of natural origin, i.e. nitrogen fixation. In the Ntane aquifer it was found that the nitrate concentration increased in south-easterly direction, which was not linked to an increase in salinity. With the exception of borehole 9239, which may be polluted, the nitrate concentration shows a tendency to decrease with increasing chloride (**Figure 2.47**). In the Mosolotsane and Kule (Kwetla) nitrate is generally present while a few boreholes with higher chloride (and salinity) have nitrate levels up to 20 mg/L (not visible in **Figure 2.47** due to scale limitations). In the Otshe aquifer there is one obvious outlier, borehole 8346 at Ncojane, which has a nitrate concentration of 43 mg/L at a chloride concentration of 52 mg/L. This has been identified as an anomaly in the Otshe aquifer nitrate contour diagram (**Figure 2.23**). The origin of the nitrate should be determined by ^{15}N isotope studies in order to establish whether this is a pollution phenomenon. In general, the nitrate levels in the Otshe aquifer are very low and decrease down gradient presumably due to denitrification. The production boreholes have very low nitrate level of less than 20 mg/L, i.e. well within the BOS 32:2000 Class I limit of 45 mg/L. One aspect that has not been explored is the accuracy of existing nitrate results. As nitrate is easily removed in the presence of bacteria and also when samples are exposed to sunlight it is quite probable that nitrate levels may be underestimated. In the case of the six production boreholes samples were taken with the necessary precautions and four of these boreholes had nitrate levels of between 17.1 and 17.7 mg/L.

However, a fifth one only had 14 mg/L nitrate but also 3 mg/L nitrite. From this it is concluded that despite the precautions nitrate reduction occurred in this sample. The sixth borehole (10410) showed neither nitrate nor nitrite and either the reduction had progressed beyond nitrite to nitrogen or there was not any nitrate in the sample at the outset. This will need to be checked during future monitoring.

The relationship between the nitrate and potassium concentrations was also investigated as given **Figure 2.48**). Practically all the Ntane aquifer boreholes had measurable nitrate concentrations. It would seem that there was an inverse relationship between nitrate and potassium, i.e. as potassium increased the nitrate decreased. This is similar to the findings in unpolluted areas of the Stampriet Artesian Basin (Kirchner & Tredoux, 1975). The Otshe aquifer did not show any significant relationship between nitrate and potassium while some of the Mosolotsane and Kule (Kwetla) boreholes had measurable nitrate also at slightly higher potassium concentrations. In a pollution situation where nitrate is derived from on-site sanitation or from pollution by livestock potassium also increases locally.

There is a strong relationship between the total alkalinity and the sodium concentration in the various aquifers (**Figure 2.49**). High sodium and alkalinity concentrations occur in the Otshe aquifer. As set out in the discussion of sodium occurrence in the Otshe aquifer (**Figure 2.17**) alkalinity increases as a result of ion exchange and dissolution of calcium carbonate from the aquifer matrix. However, at sodium concentrations above 500 mg/L increasing salinisation seems to dominate. This relates mainly to boreholes in the eastern part of the project area. In the Ntane aquifer total alkalinity reaches a maximum of 400 mg/L while sodium is largely below 200 mg/L with only four boreholes slightly exceeding this level while in only one case (borehole 9239) the sodium concentration approaches 400 mg/L.

Similar to sodium potassium occurs nearly ubiquitously in groundwater but generally at a level which corresponds to a tenth or a hundredth of the sodium concentration, and sometimes even less. As the sodium concentration increases during salinisation the potassium concentration will also increase unless it is removed by ion exchange or through binding to Illite. Some of these phenomena can be observed in the project area. In the case of the Ntane aquifer, the potassium concentration increases with rising sodium levels, i.e. increasing salinisation (**Figure 2.50**). This confirms the observation with regard to the nitrate-potassium relationship (**Figure 2.50**). In the Otshe, where ion exchange occurs and Illite may also be present, potassium levels decrease at higher sodium concentrations (**Figure 2.50**).

The fluoride concentration is generally inversely related to the calcium concentration regardless of the aquifer as indicated (**Figure 2.51**). Below 20 mg/L calcium the fluoride increases rapidly showing the importance of calcium to limit the fluoride levels as a result of the fluorite (CaF_2) solubility constraints. Higher fluoride in the presence of higher calcium will only occur in cases where the salinity is also higher and in such cases the high salinity is generally the limiting factor for potability.

The graph showing the relationship between the fluoride concentration and the sodium percentage concentrations in the various aquifers shows that above 90% sodium the fluoride can attain very high values (**Figure 2.52**). The relative increase in sodium is generally related to the decrease in calcium and the higher solubility of fluorite. The high fluorides are essentially restricted to the Otshe aquifer in the eastern half of the project area where the salinity is also high.

There is a close relationship between the fluoride concentration and the total alkalinity in the various aquifers as shown in **Figure 2.53**. The effect of the higher calcium in the Ntane aquifer manifests itself in the relatively lower fluoride at higher total alkalinities compared to the Otshe aquifer.

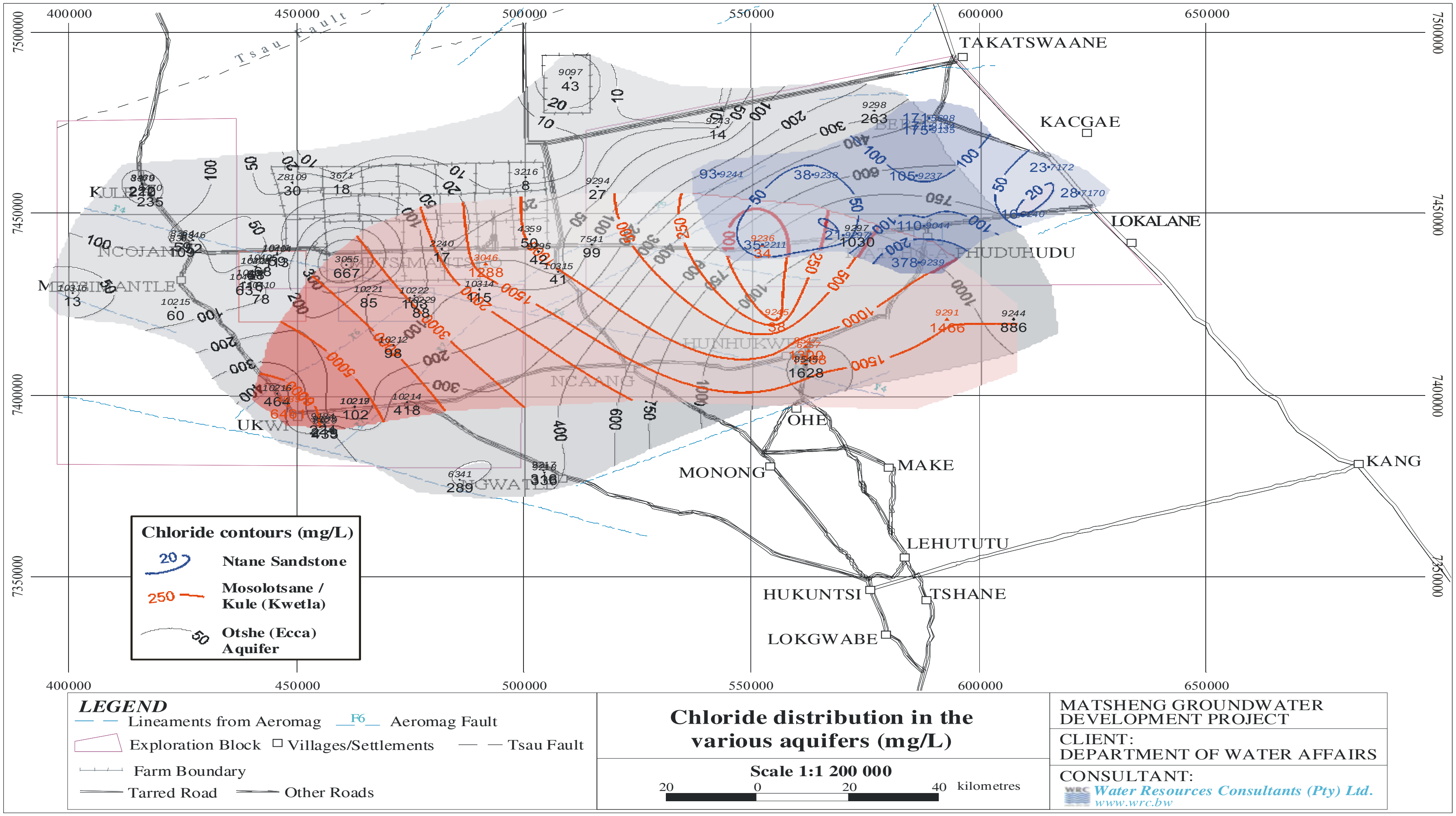

Figure 2.33 Chloride Distribution, Otshe, Ntane and Mosolotsane/Kule (Kwetla) Aquifer Systems

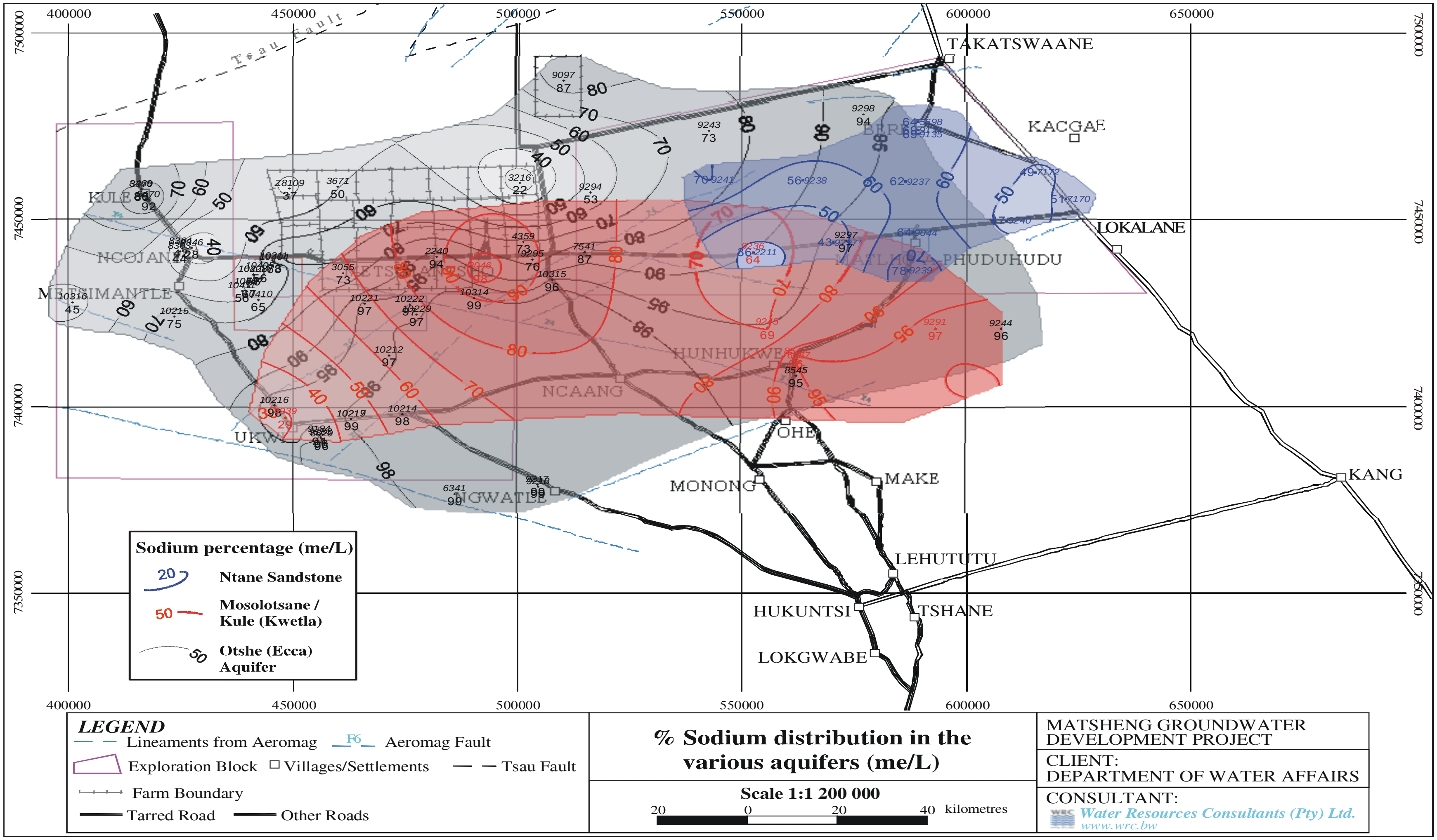

Figure 2.34 Sodium Distribution, Otshe, Ntane and Mosolotsane/Kule (Kwetla) Aquifer Systems

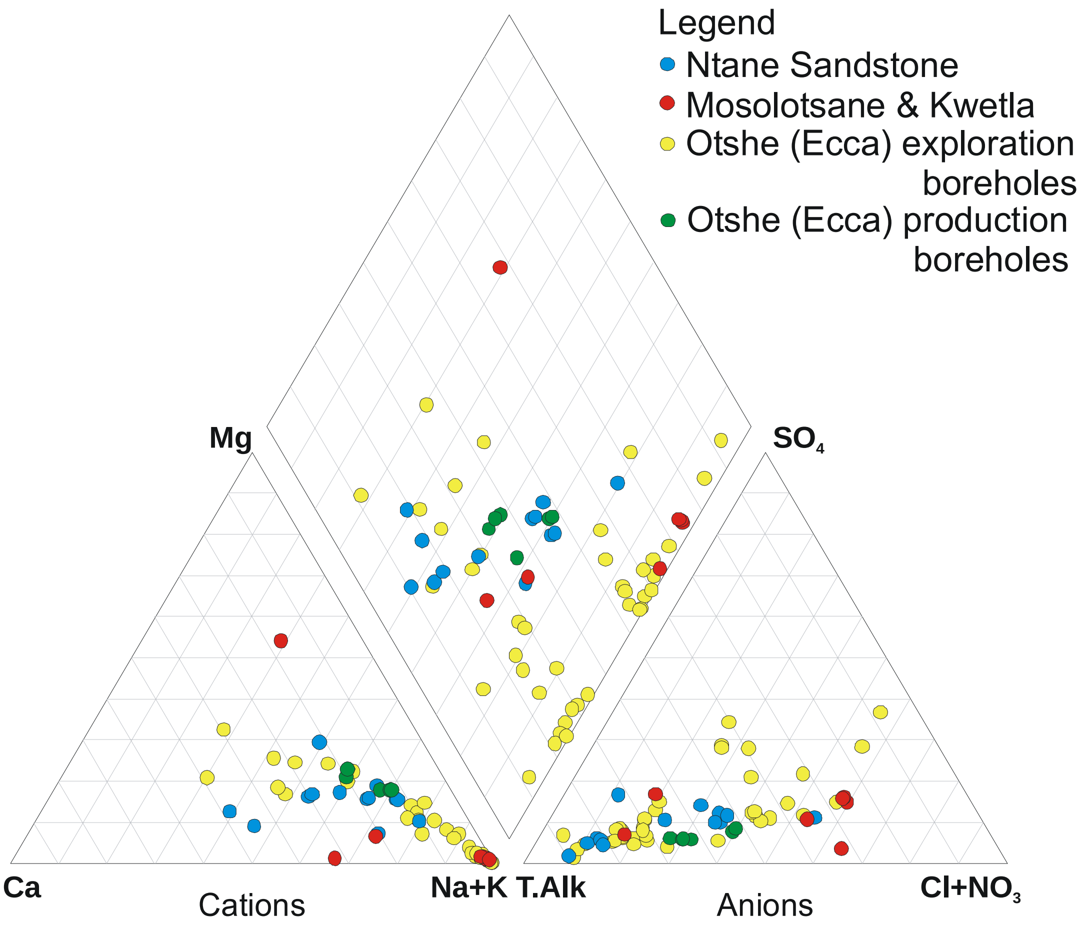

Figure 2.35 Trilinear Diagram Showing Relative Chemical Composition of Otshe, Ntane and Mosolotsane/Kule (Kwetla) Aquifer Systems

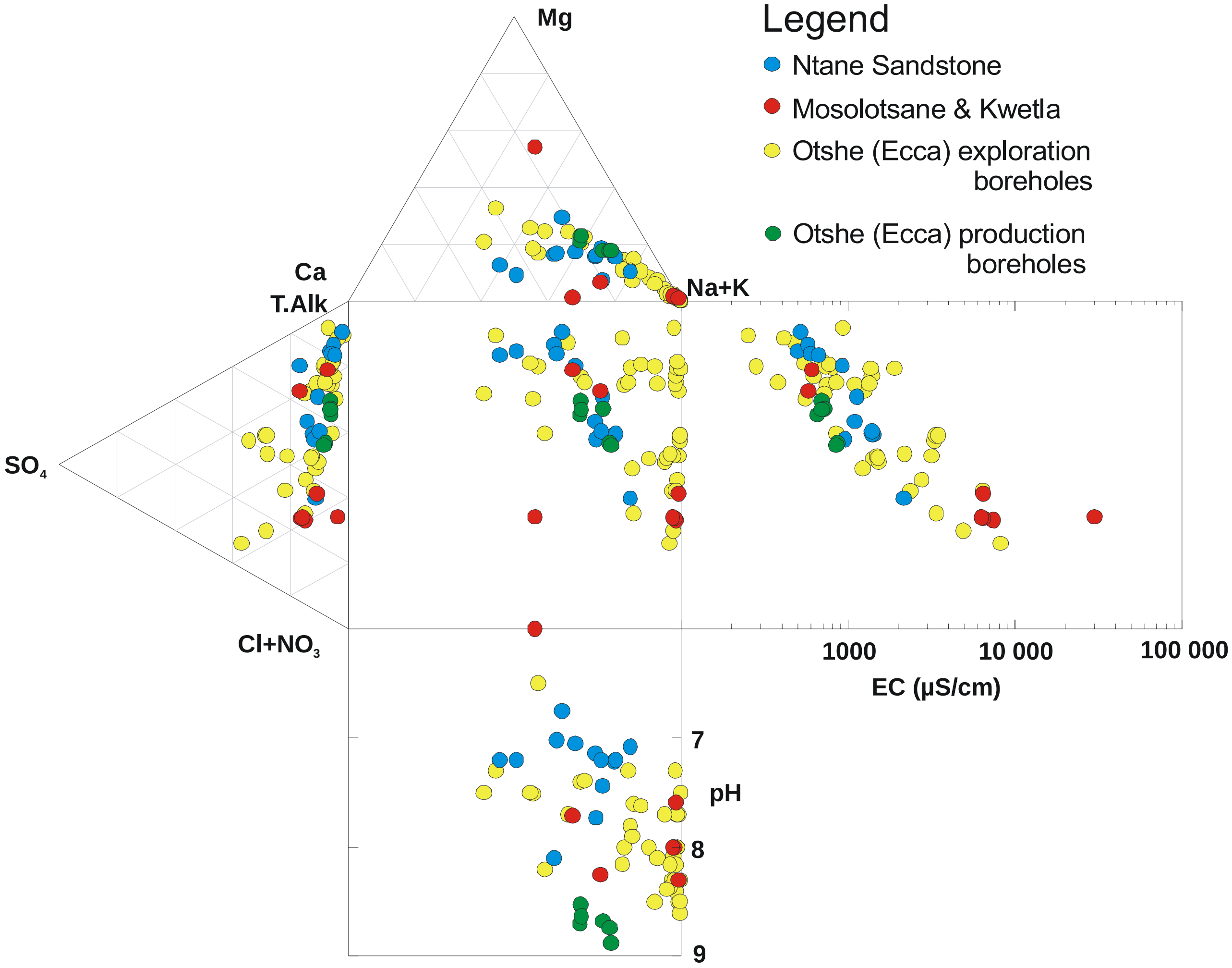

Figure 2.36 **Durov Diagram Showing Relative Composition of Groundwater in Otshe, Ntane ,Mosolotsane/Kule (Kwetla) Aquifer Systems**

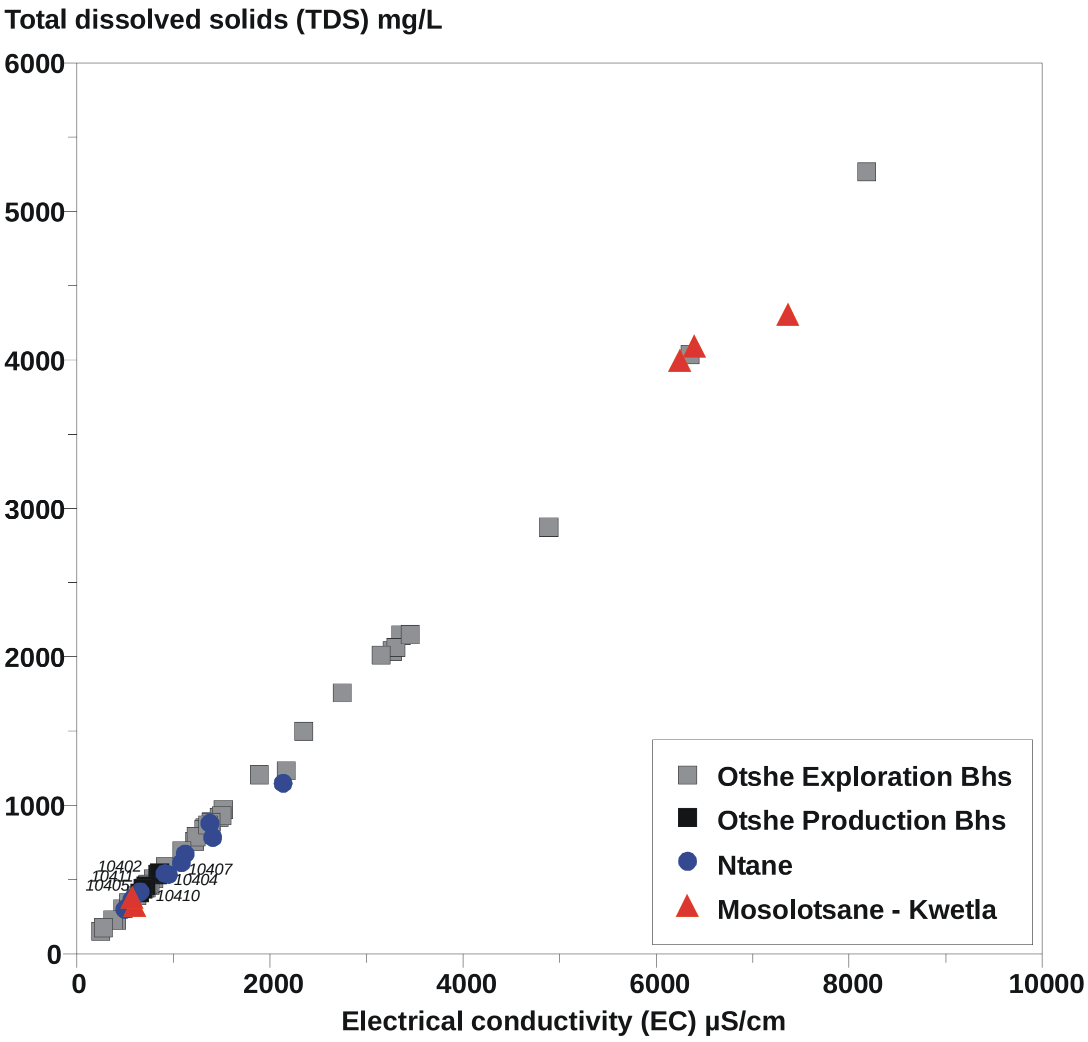

Figure 2.37 Relationship between Total Dissolved Solids (TDS) and Electrical Conductivity (EC) in the Various Aquifers

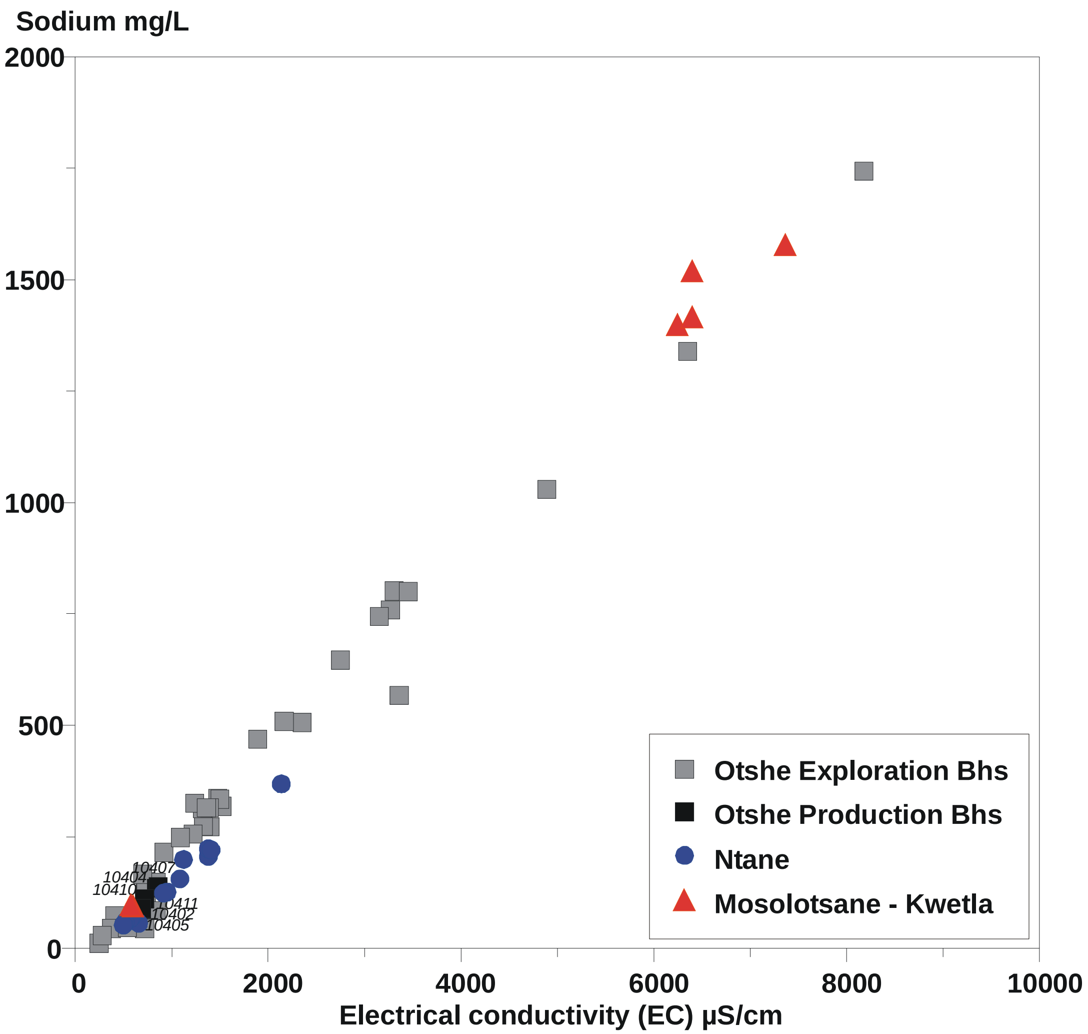

Figure 2.38 Relationship between the Sodium Concentration and Electrical Conductivity (EC) in the Various Aquifers

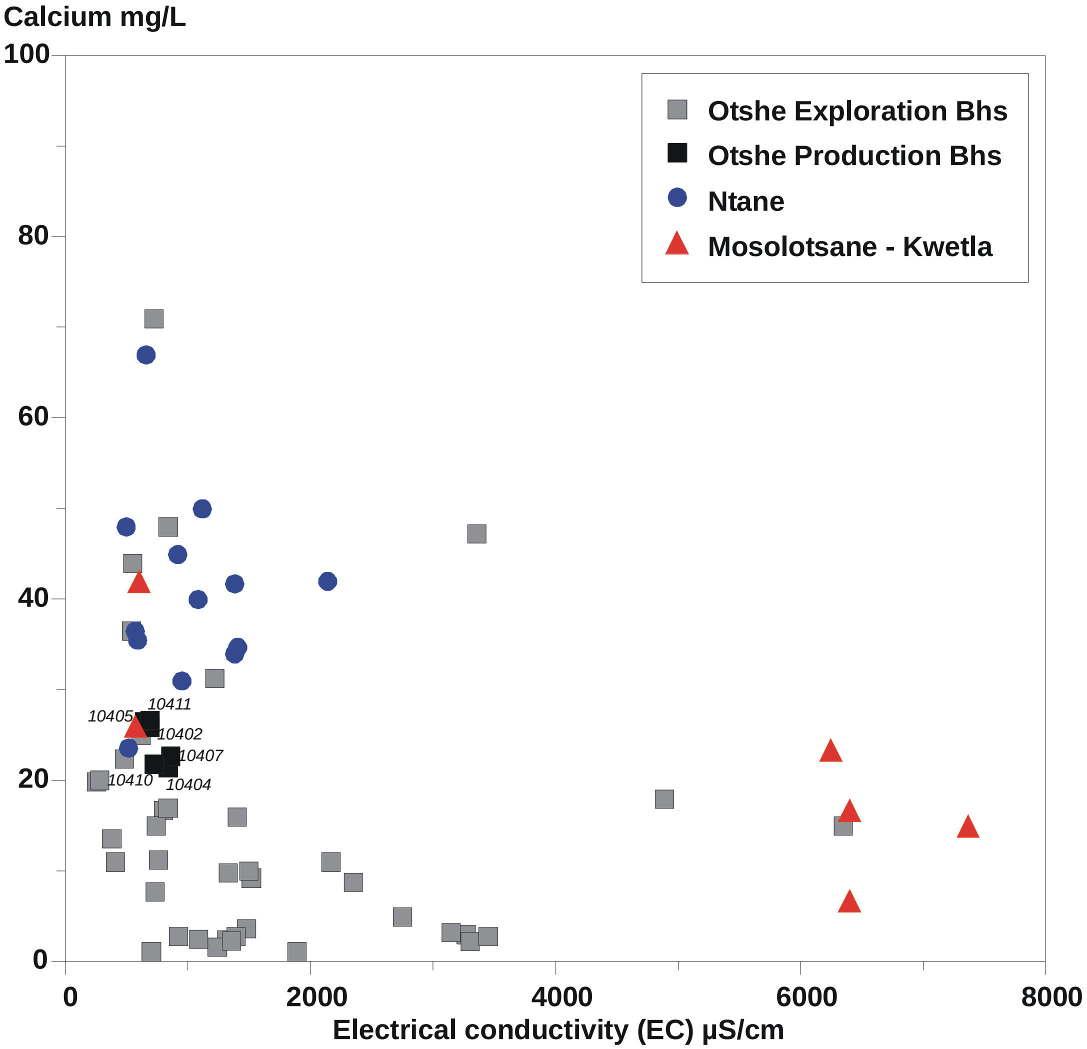

Figure 2.39 Relationship between the Calcium Concentration and Electrical Conductivity (EC) in the Various Aquifers

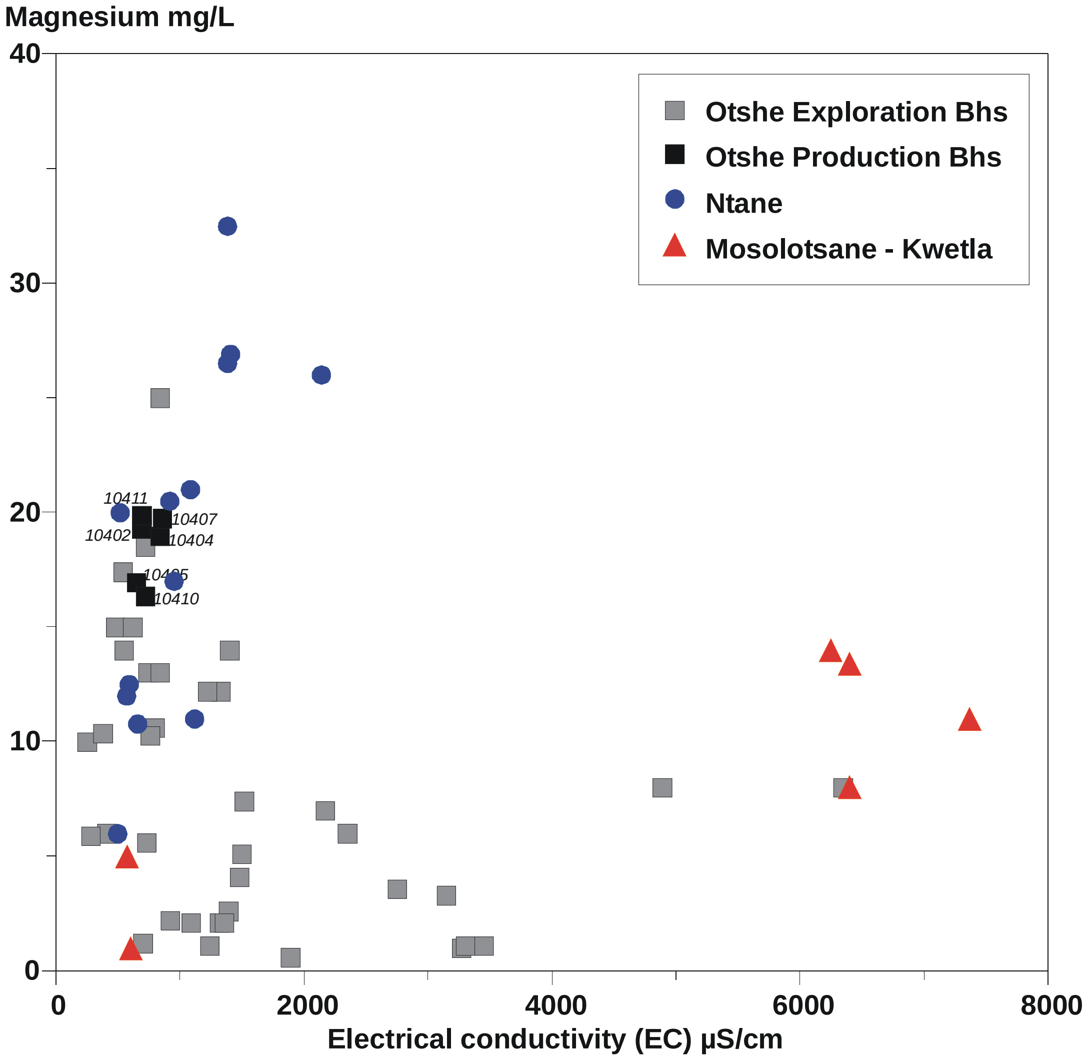

Figure 2.40 Relationship between the Magnesium Concentration and Electrical Conductivity (EC) in the Various Aquifers

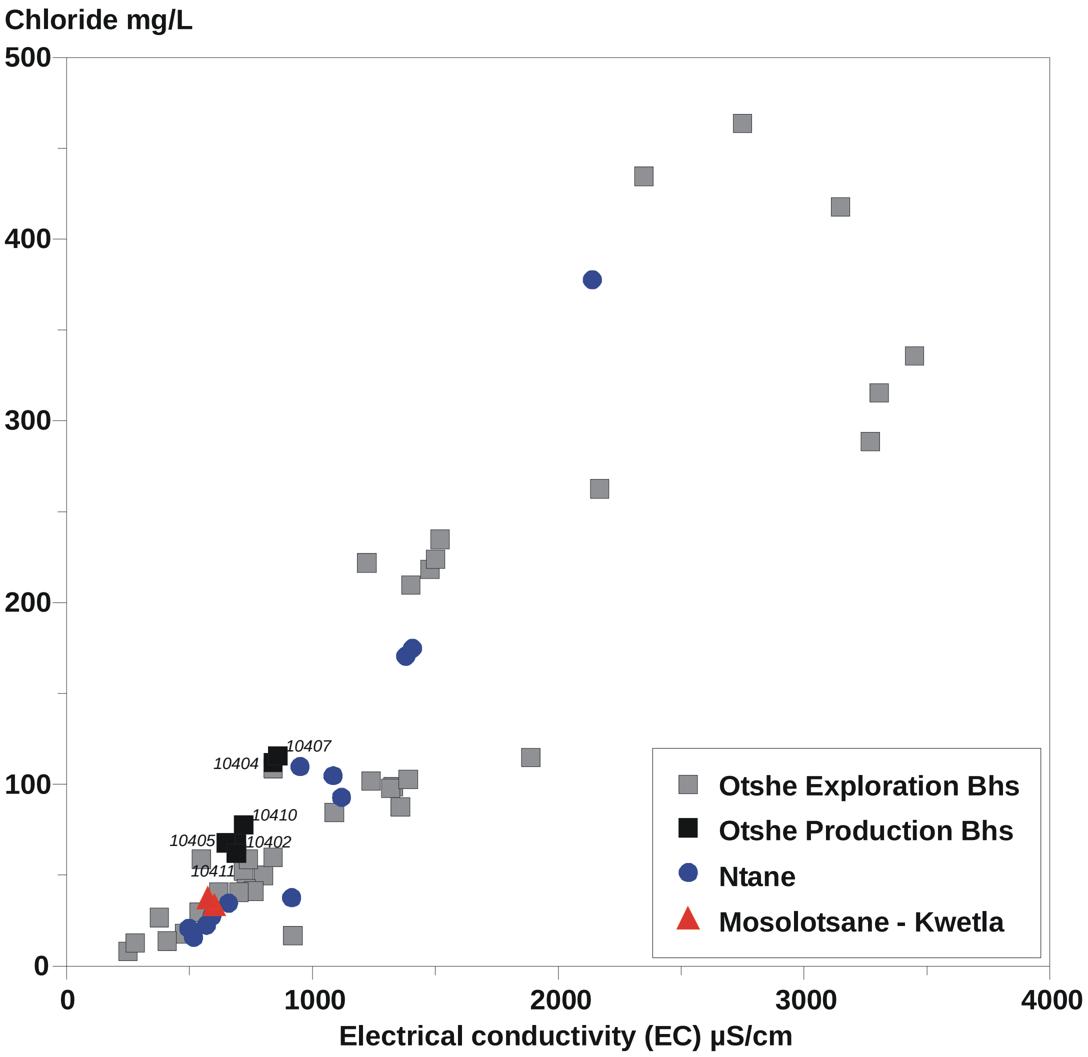

Figure 2.41 **Relationship between the Chloride Concentration and Electrical Conductivity (EC) in the Various Aquifers**

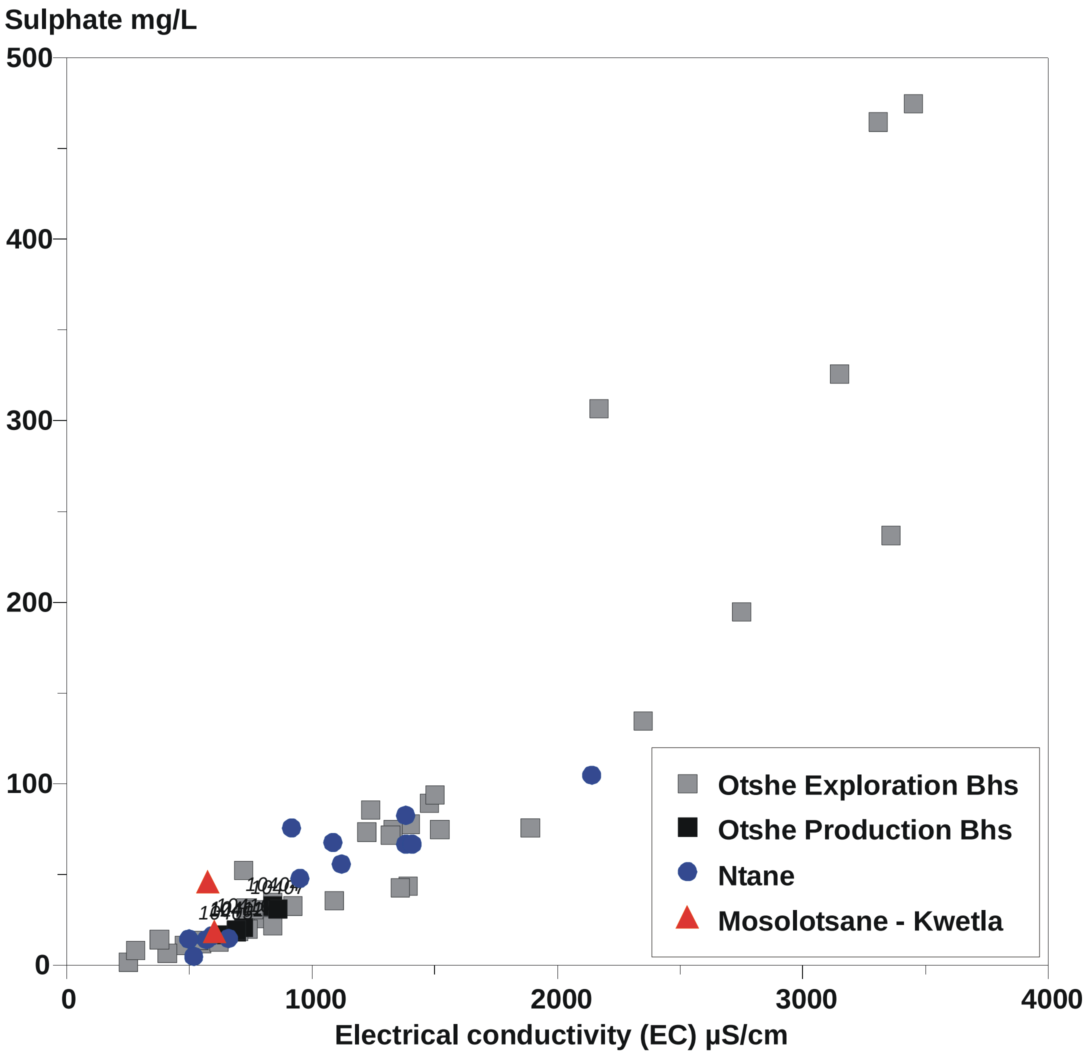

Figure 2.42 Relationship between Sulphate Concentration and Electrical Conductivity (EC) in the Various Aquifers

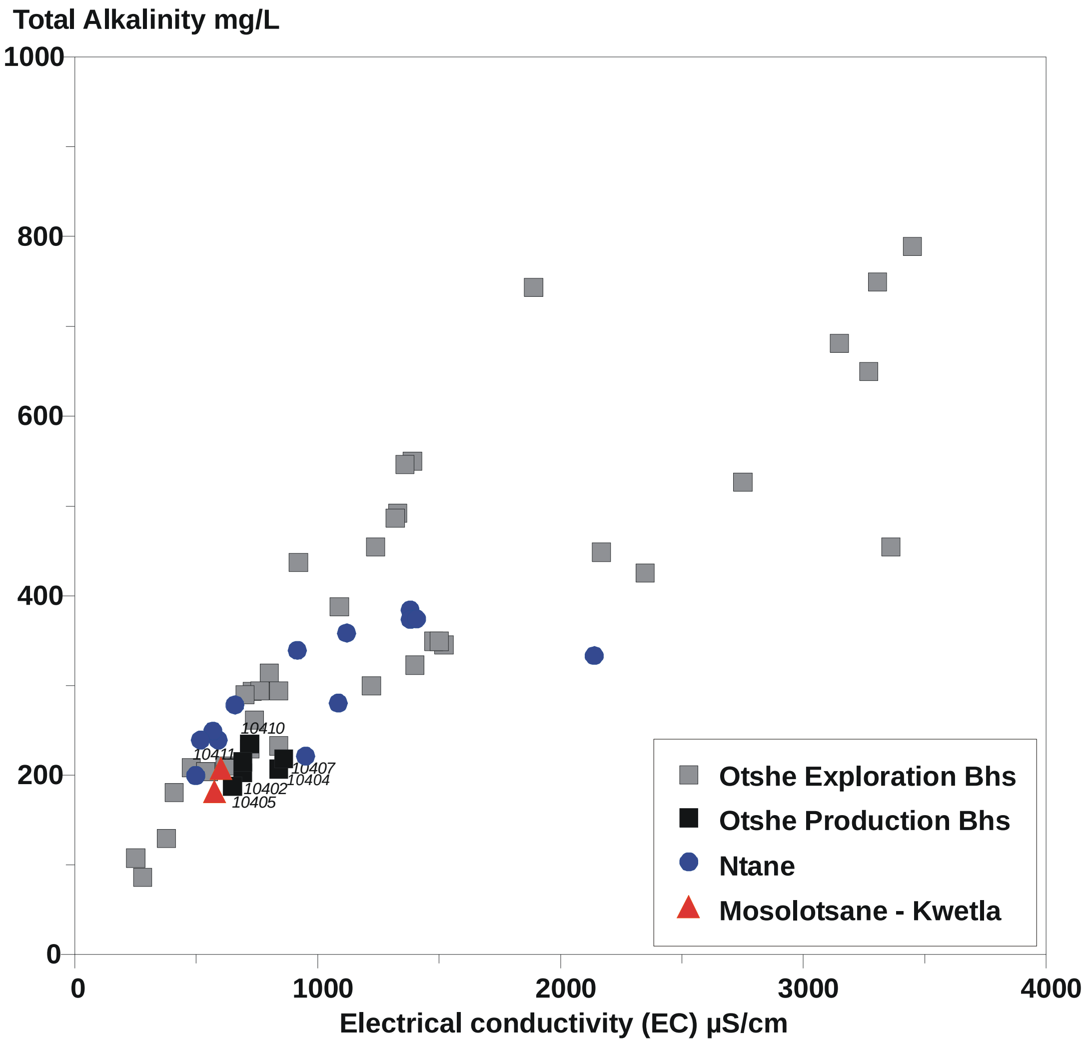

Figure 2.43 **Relationship between the Total Alkalinity and Electrical Conductivity (EC) in the Various Aquifers**

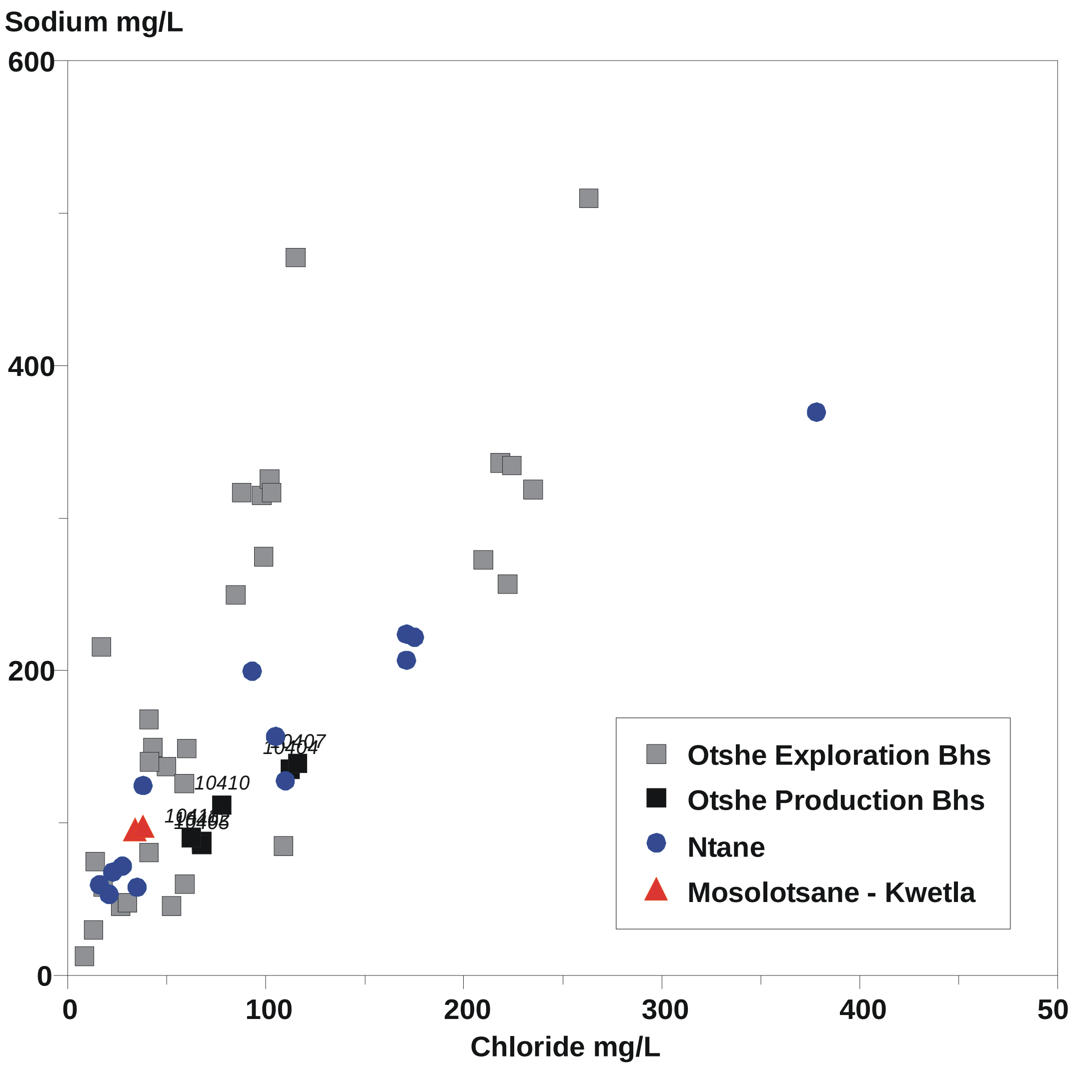

Figure 2.44 **Relationship between the Sodium and Chloride Concentrations in the Various Aquifers**

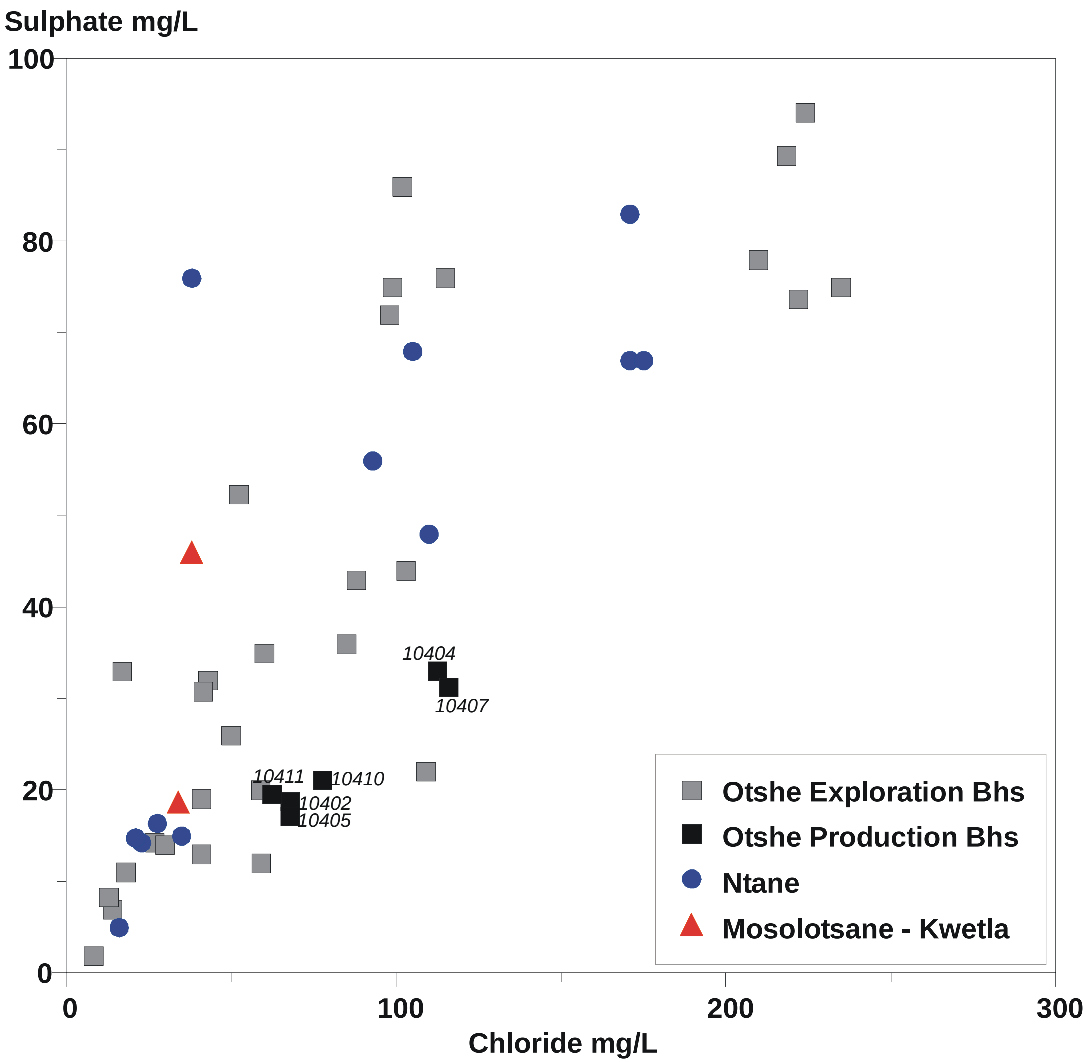

Figure 2.45 Relationship between the Sulphate and Chloride Concentrations in the Various Aquifers

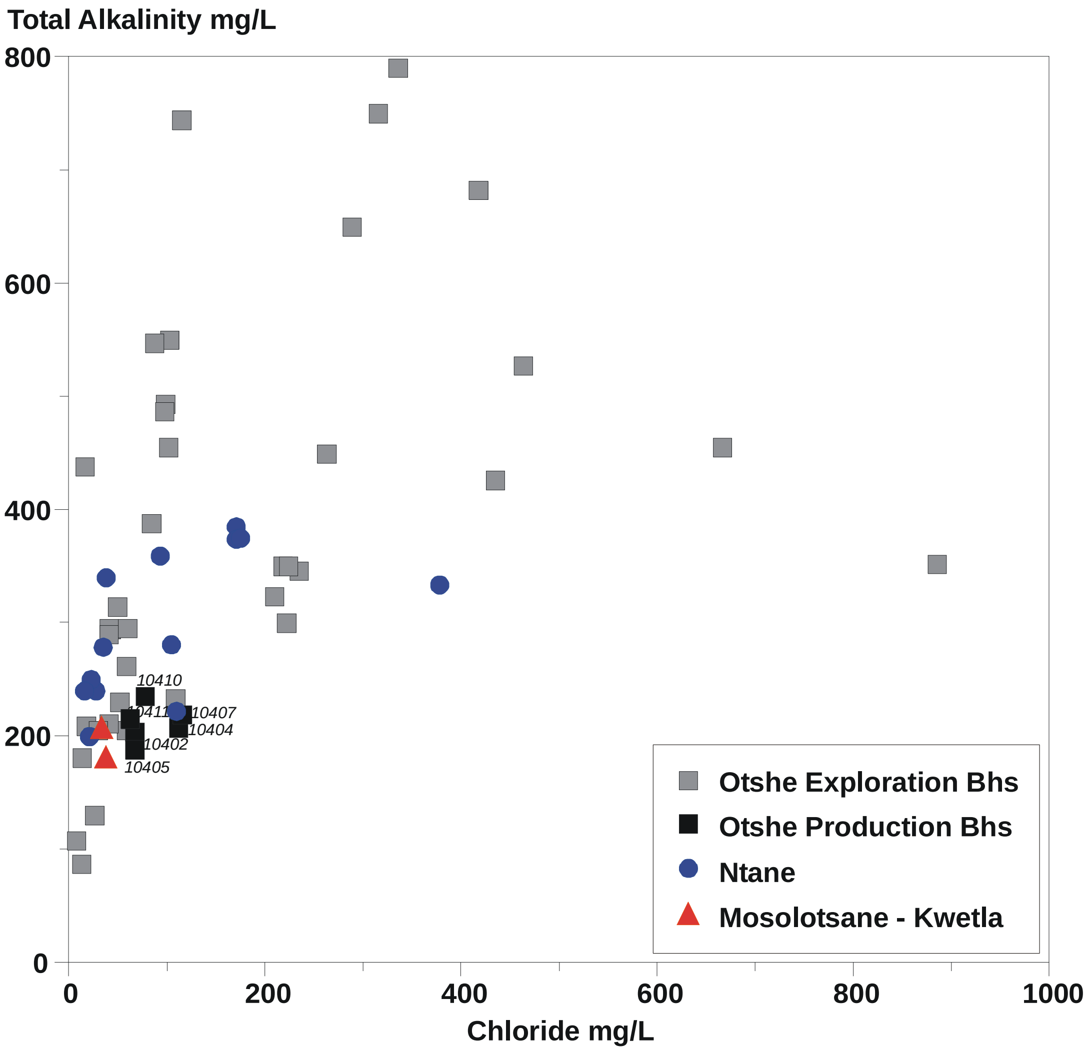

Figure 2.46 **Relationship between the Total Alkalinity and the Chloride Concentration in the Various Aquifers**

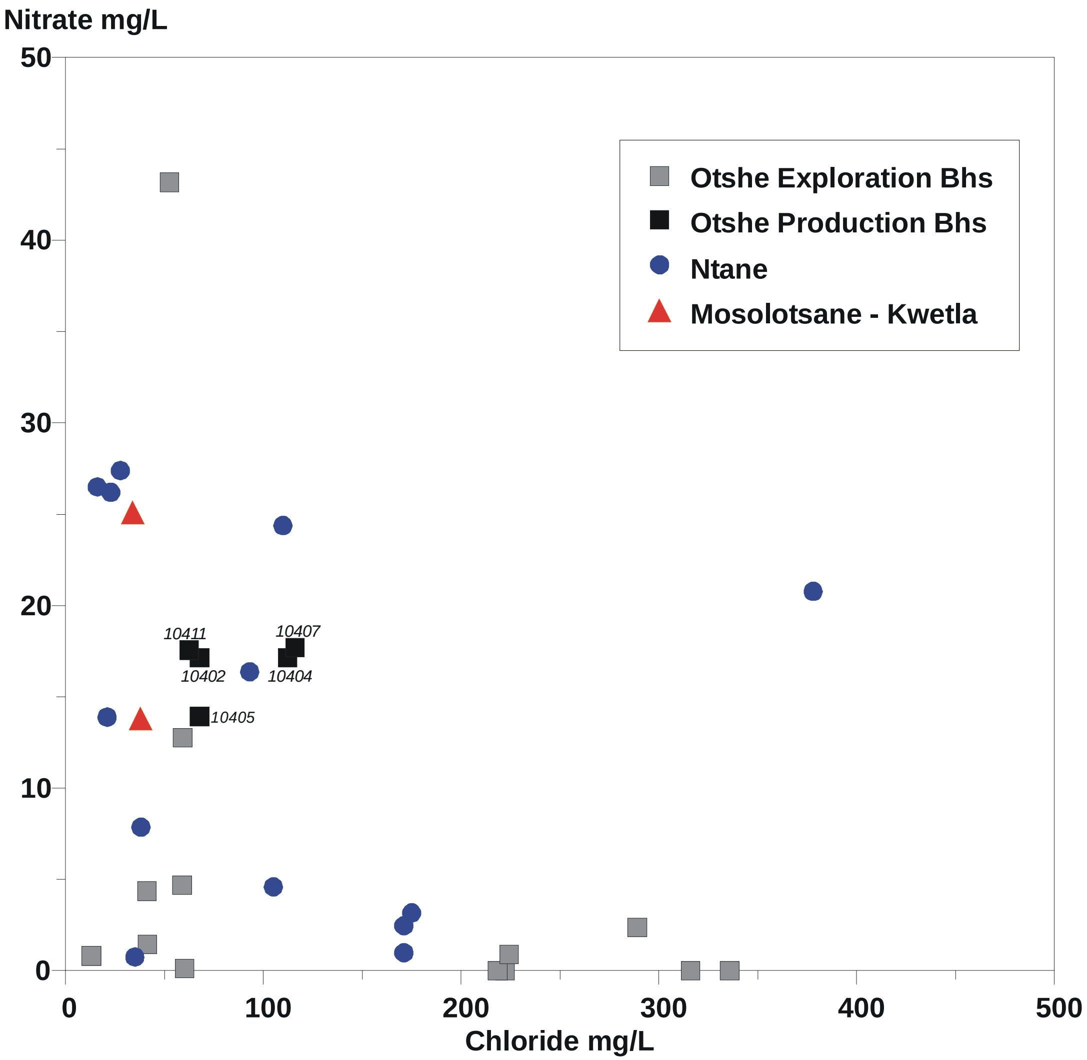

Figure 2.47 **Relationship between the Nitrate and Chloride Concentrations in the Various Aquifers**

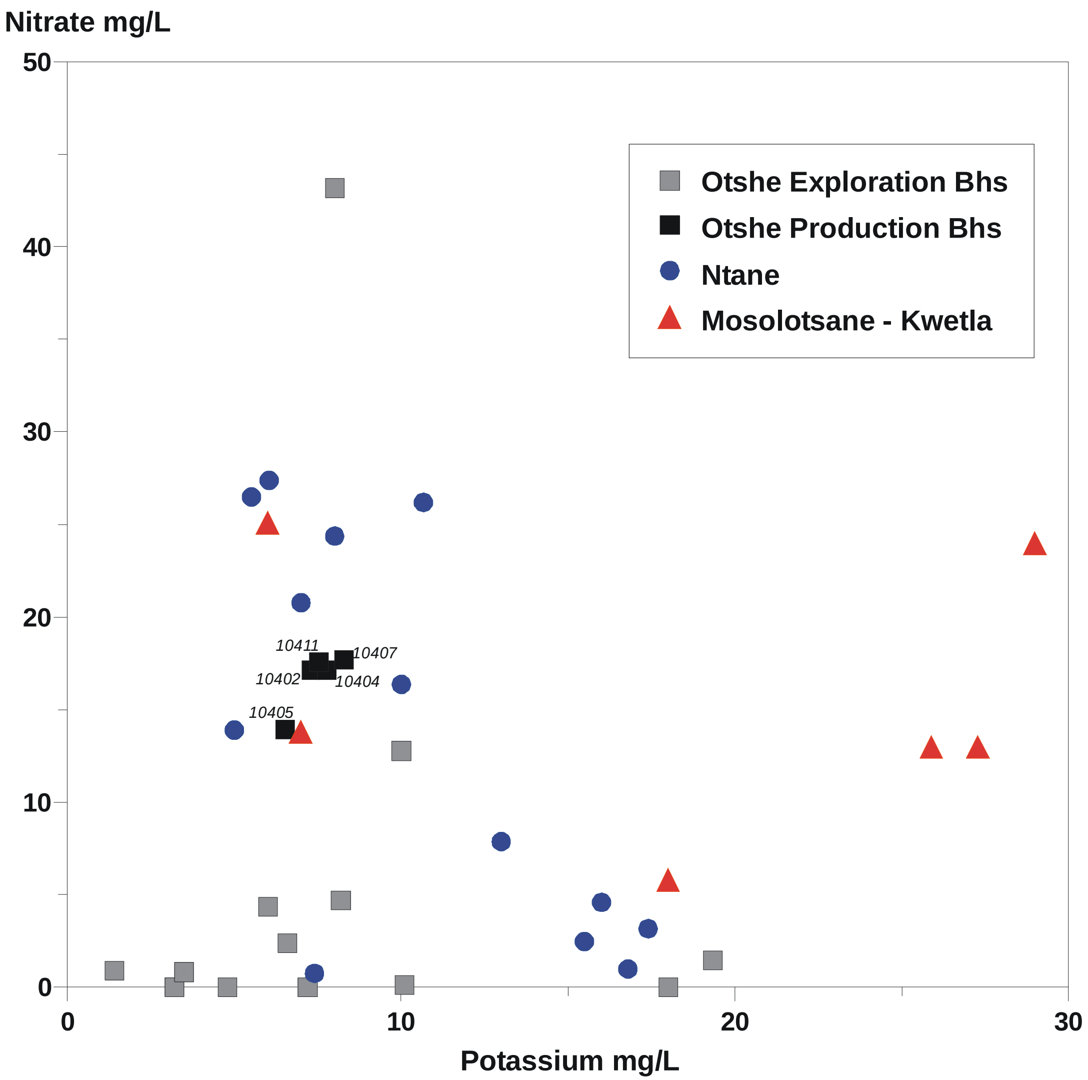

Figure 2.48 Relationship between the Nitrate and Potassium Concentrations in the Various Aquifers

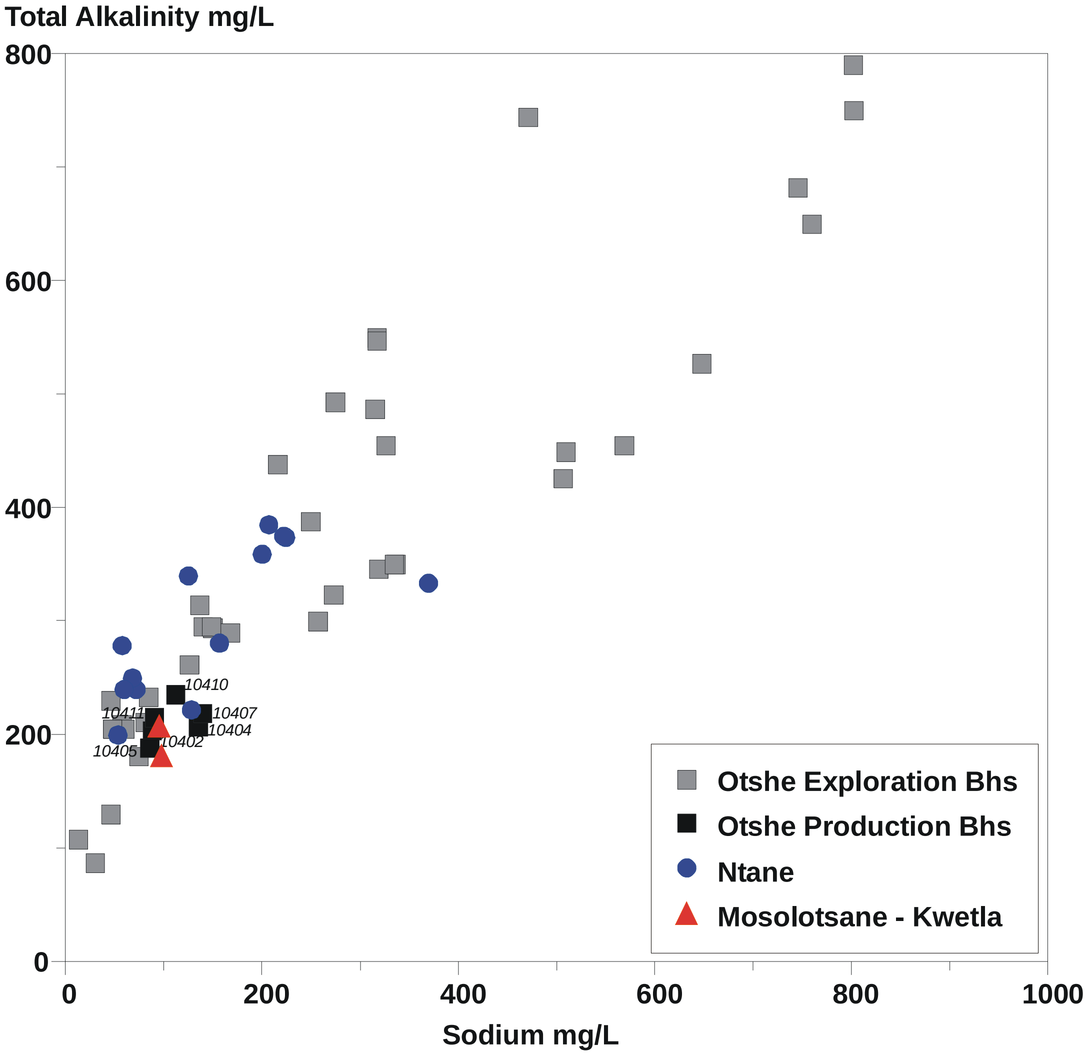

Figure 2.49 **Relationship between the Total Alkalinity and the Sodium Concentration in the Various Aquifers**

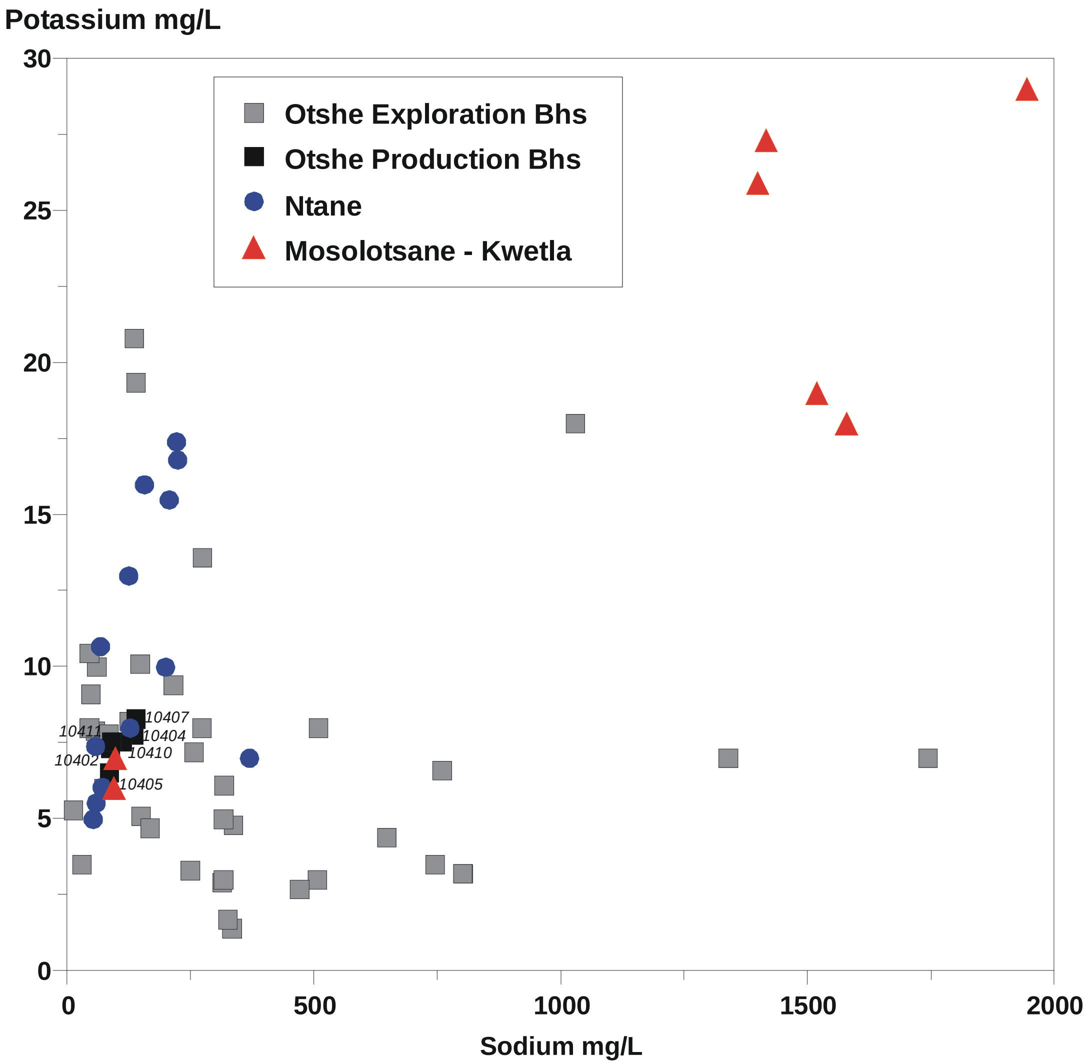

Figure 2.50 Relationship between the Potassium and Sodium Concentrations in the Various Aquifers

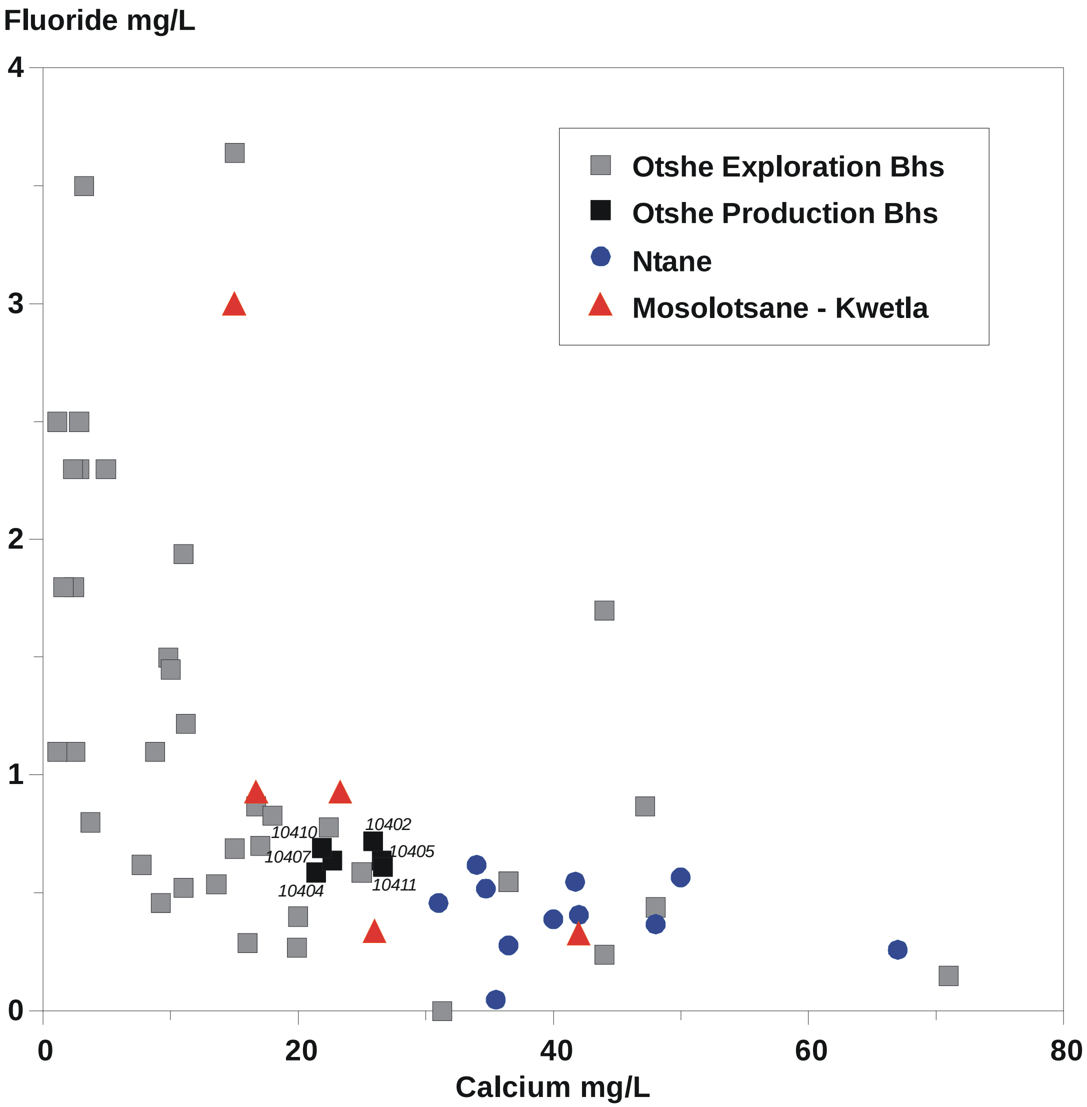

Figure 2.51 **Relationship between the Fluoride and Calcium Concentrations in the Various Aquifers**

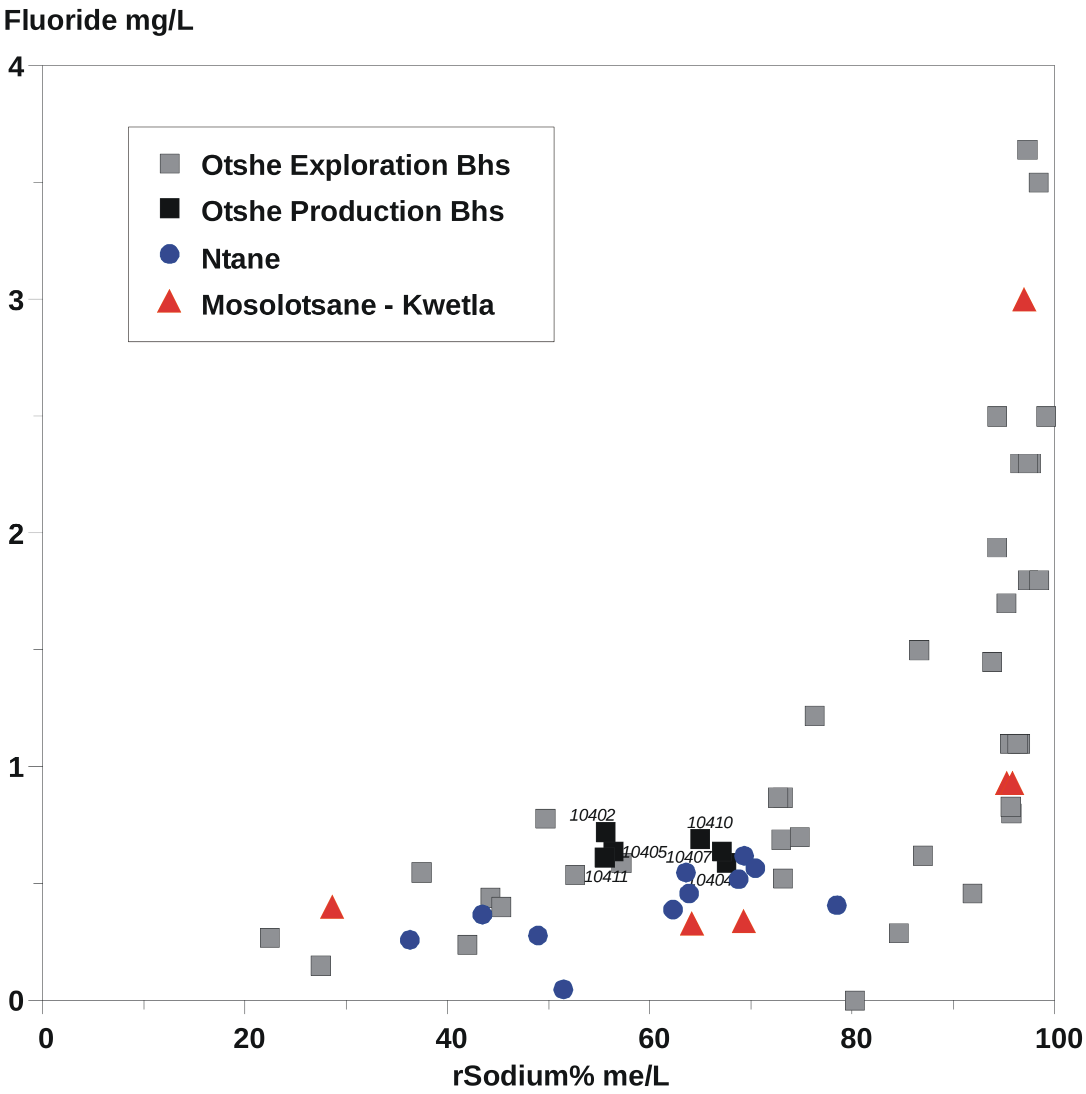

Figure 2.52 Relationship between the Fluoride and Sodium Percentage Concentrations in the Various Aquifers

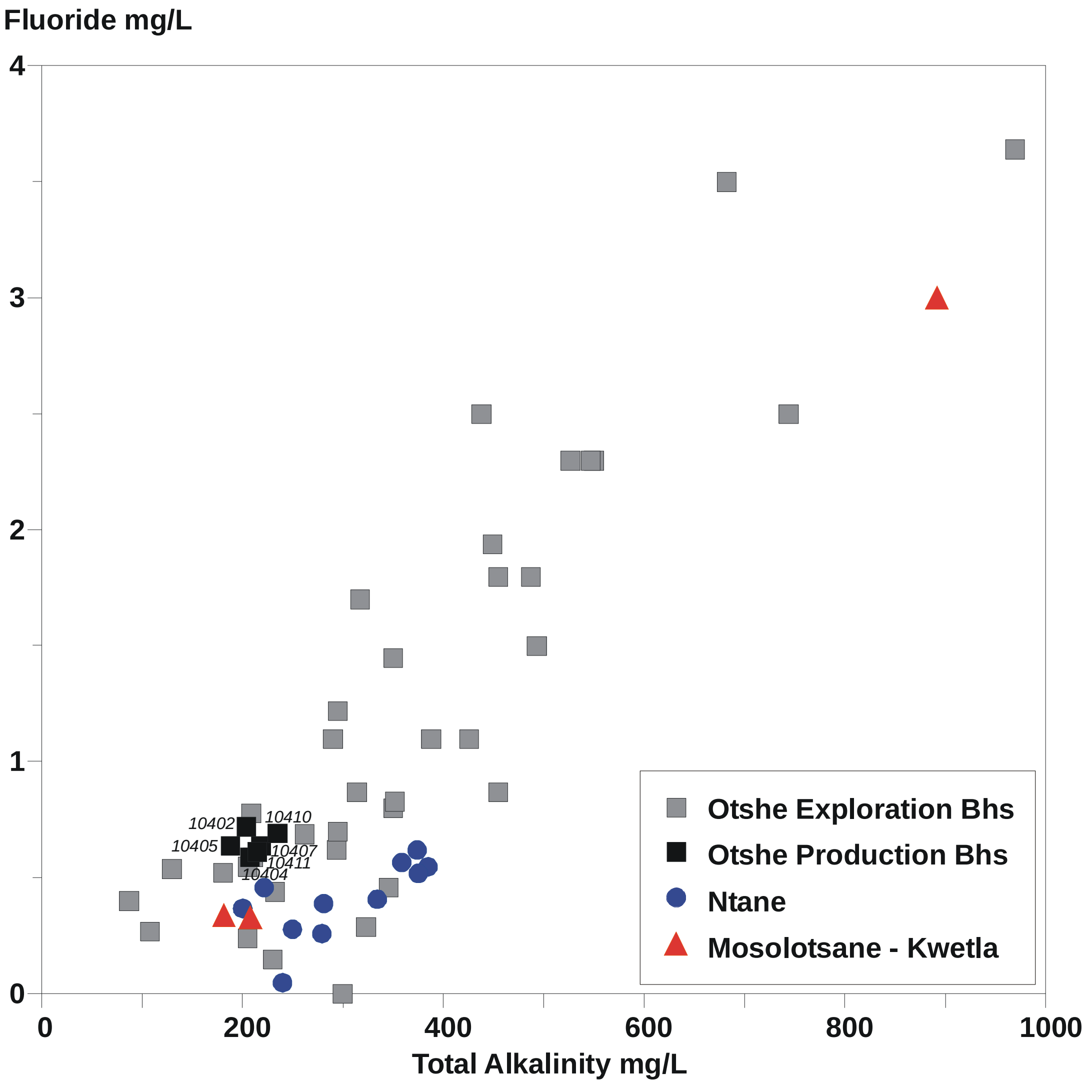

Figure 2.53 Relationship between the Fluoride Concentration and the Total Alkalinity in the Various Aquifers

2.5 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 2.1**).

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

Physical and Organoleptic (aesthetic) requirements

		Upper limit and ranges		
		Class I	Class II	Class III
Determinants	Units	**(Ideal)**	**(Acceptable)**	**(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

	Upper limit and ranges		
Determinants	**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

	Upper limit and ranges		
Determinants	**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 2.2 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.

2.5.1 NTANE SANDSTONE AQUIFER

Chemical analysis results from boreholes tapping the Ntane Sandstone aquifer are given **Table 2.3**. 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 2.3**).

Table 2.3 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)

2.5.2 ECCA (OTSHE) AQUIFER

Chemical analysis results from project boreholes tapping the Otshe aquifer are given **Tables 2.4** and **2.5** 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 not in an area 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 limit should be considered if no alternative source available. This is because sodium is the major constituent of groundwater in Botswana as a whole and sticking to the Class II will exclude a lot potential 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 2.5**). 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.

Table 2.4 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	20.8	0.69	740	474	90
10222	28-Nov-06	5	317	2.8	2.6	<0.1	44	103	550	<0.4	2.3	1390	890	18
10228	5-Dec-06	6	81	25	15	<0.1	13	41	211	19.5	0.59	620	397	126
10229	10-Dec-06	3	317	2.3	2.1	<0.1	43	88	547	<0.4	2.3	1360	870	14
10221	3-Feb-06	3.3	250	2.5	2.1	0.1	36	85	388	<0.4	1.1	1090	698	15
10215	28-Jan-06	10.1	149	17	13	<0.1	35	60	295	0.70	0.7	840	538	96
10314	26-Jan-06	2.7	471	1.1	0.6	<0.1	76	115	744	<0.4	2.5	1890	1210	5
10214	10-Mar-06	3.5	746	3.2	3.3	0.1	326	418	682	<0.4	3.5	3150	2016	21
10316	21-Feb-06	3.5	30	20	5.9	<0.1	8.3	13	87	3.8	0.4	280	179	74
10219	3-Mar-06	1.7	326	1.6	1.1	<0.1	86	102	455	<0.4	1.8	1240	794	8.6
10212	11-Feb-06	2.9	315	2.4	2.1	<0.1	72	98	487	<0.4	1.8	1320	845	15
10216	19-Feb-06	4.4	648	4.9	3.6	<0.1	195	464	527	<0.4	2.3	2750	1760	27
10315	9-Feb-06	4.7	168	1.1	1.2	<0.1	19	41	290	<0.4	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 2.5 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

3 RECHARGE ESTIMATES FROM CHEMISTRY AND ISTOPES

3.1 OVERVIEW

During the project, an assessment of aquifer recharge using multiple techniques guided by the conceptual understanding of the hydrogeologic system was carried out. The focus of the recharge assessment was to develop an understanding of recharge dynamics of the project area with an aim of delineating actively recharging areas or areas which are close to active recharge zones and try to estimate recharge quantities. The recharge study was based on the chloride mass balance method as well as stable and radioactive isotopes. Each method is discussed in the following sections. Sampling was focused in the Ecca (Otshe) aquifer which was the main target aquifer during the current project.

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 .

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)

3.1.1 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, through outcrops and direct river recharge, will not be subject to evaporation losses and not show up in 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.

3.1.2 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.

3.1.3 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 mm/yr for the Ecca and 0.6 to 2.5 mm/yr 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 large study areas.

3.2 RECHARGE EVALUATION FROM PROJECT DATA

3.2.1 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/yr.

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.

3.2.2 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 3.1**). 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 3.1 **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 3.1**). The resulting chloride levels of rainfall range between 0.21 and 1.12 mg/L with lower values during the rainy season (**Table 3.1**). The chloride contents from the five stations showed acceptable patterns for each season when compared with the rainfall (**Figure 3.2**). 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 of less 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 3.2 **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 3.2**) is comparable with annual data obtained from other studies. A value of 300mg/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 3.1**). Those from the wetter second period, in contrast, show significantly lower ^{18}O and deuterium content (**Figure 3.3**). 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:

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

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 3.3**).

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.

3.2.3 CHLORIDE MASS BALANCE

As is shown by the ^{14}C data (**Table 3.4**), the Ntane sandstone which is saturated only in the eastern part of the project area, 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 3.4**) 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..

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 are intercepted. The new groundwater data obtained in the present project for the Ecca (Otshe) aquifer represent deep water of old age (>11 000years, see **Table 3.4**). 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 2.20**) 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 2.20**) 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 3.4**) 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

3.2.4 STABLE ISOTOPES (^{2}H AND ^{18}O)

Results of stable isotope analysis for the groundwater samples obtained during the present project are shown in **Table 3.3**. Overall the stable isotope (δ^{13}C, δ^{18}O and δD) data are quite similar throughout the Otshe aquifer, suggesting that no separate water bodies are involved within the subdivisions of the Ecca. Vertically the water properties are quite uniform: δ^{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 3.5**). The combination of ^{18}O and deuterium (**Figure 3.6**) 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 3.6**).

The four available δD, δ^{18}O pairs from the Ntane data of the 2000 project (**see Figure 3.6**) 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 3.3 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	Otshe	CRT 48hrs	-7.3	-50				59
BH 10212	11-02-06	275 .48-281.61 & 284.74-297	Otshe	CRT 48hrs	-7.5	-52		2.8 ± 0.4	-13.9	98
BH 10214	10-03-06	174 & 300	Open in Otshe & Kobe	CRT 72hrs	-7.1	-50		3.7 ± 0.1	-16.3	418
BH 10215	28-01-06	211.68-247.76	Otshe	CRT 72hrs	-7.7	-52		<1.2	-12.8	60
BH 10216	08-11-05	134	Mudstone 1 (Otshe)	Strike 1	-6.7	-49	0.0 ± 0.1			
BH 10216	08-11-05	168	Mudstone 1 (Otshe)	Strike 2	-7	-48				
BH 10216	14-11-05	173	Mudstone 1 (Otshe)	Strike 3	-6.7	-48				
BH 10216	16-11-05	191	Mudstone 2 (Otshe)	Strike 4	-6.6	-45				
BH 10216	19-02-06	173.15 – 185.40	Otshe Sandstone 1 & Mudstone 2 (Otshe)	CRT 75hrs	-7.6	-52		1.0 ± 0.1	-12.7	464
BH 10217	25-11-05	169	Mudstone 1 (Otshe)	Strike 1	-7.2	-49	0.0 ± 0.1			
BH 10217	25-11-05	182	Otshe Sandstone 1	Strike 2	-7	-48				
BH 10217	25-11-05	188	Otshe Sandstone 1	Strike 3	-7.4	-50				
BH 10217	26-11-05	229	Otshe Sandstone 1	Strike 4	-7.2	-49				
BH 10217	28-11-05	275	Otshe Sandstone 2	Strike 5	-7.3	-49				
BH 10217	05-12-05	335	Kobe	Strike 6	-5.6	-45				
BH 10219	03-03-06	172.94-246.43	Otshe Sandstone 1	CRT 51hrs	-7.3	-52		1.7 ± 0.2	-14.3	102
BH 10221	03-02-06	276-299.20	Otshe Sandstone 1	CRT 72hrs	-7.5	-52		1.1 ± 0.1	-13.5	85
BH 10222	28-11-05	274.60-286.00	Otshe Sandstone 1 & 2	CRT 72hrs	-7.1	-51				103
BH 10228	05-12-05	191.00-250.90	Otshe Sandstone 1	CRT 115hrs	-6.5	-47	0.0 ± 0.1	1.6 ± 1.5	-8.3	41
BH 10229	15-11-05	183	Otshe Sandstone 1	Strike 1	-7	-48	0.0 ± 0.1	0.0 ± 1.5	-12.1	
BH 10229	16-11-05	198	Otshe Sandstone 1	Strike 2	-6.8	-48	0.0 ± 0.1			
BH 10229	21-11-05	253	Mudstone 2 (Otshe)	Strike 3	-6.8	-48				
BH 10229	21-11-05	266	Mudstone 2 (Otshe)	Strike 4	-6.9	-49				
BH 10229	21-11-05	282	Otshe Sandstone 2	Strike 5	-7.1	-50				
BH 10229	21-11-05	289	Otshe Sandstone 2	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	Mosolotsane/ Kule Mudstone 2 (Otshe)	CRT 72hrs	-7.2	-50		<0.5	-14.0	115
BH 10315	09-02-06	248.31-279	Mosolotsane/ Kule Sandstone 1 (Otshe)	CRT 72hrs	-6.7	-45		<1.8	-12.2	41
BH 10316	21-02-06	173.09-215.99	Sandstone 1 (Otshe)	CRT 72hrs	-6.6	-45		6.5 ± 0.1	-12.9	13

3.2.5 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 3.3**). 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 3.3**). 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 3.4**). 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 3.7**). These boreholes are located much closer to the Ntane where ^{14}C contents between 21 and 58 were found (**Table 3.4**). This suggests that either there is recharge to the Ecca in the north eastern part of the present study area. This was also indicated by the hydrochemical data

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 3.4**. 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 3.4 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/Kule (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?	Otshe	14.2 ± 0.3	-13.4	11 400
BH 7752	2000	Unknown?	Otshe	9.0 ± 0.3	-14.0	15 900
BH 10316	2006	173.1-216.0	Otshe	6.5 ± 0.1	-12.9	18 800
BH 9297	2000	? Unknown?	Otshe	4.1 ± 0.2	-10.4	21 700
BH 7760	2000	Unknown??	Otshe	3.7 ± 0.4	-10.5	22 600
BH 10214	2006	170	Otshe	3.7 ± 0.1	-16.3	22 600
BH 10212	2006	275 .5-281.6 & 284.7-297.0	Otshe	2.8 ± 0.4	-13.9	24 900
BH 10219	2006	172.9-246.4	Otshe	1.7 ± 0.2	-14.3	29 000
BH 10228	2005	191.0-250.9	Otshe	1.6 ± 1.5	-8.3	29 500
BH 10221	2006	276.0-299.2	Otshe	1.1 ± 0.1	-13.5	32 600
BH 10216	2006	?	Otshe	1.0 ± 0.1	-12.7	33 400
BH 10315	2006	248.3-279.0	Kule/Otshe	<1.8	-12.2	>28 000
BH 10229	2005	183	Otshe	<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/Kule (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 3.5** all use a porosity of 20% based on data from neutron porosity logging data from the current project as well as previous studies by 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 3.5** 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 3.5 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

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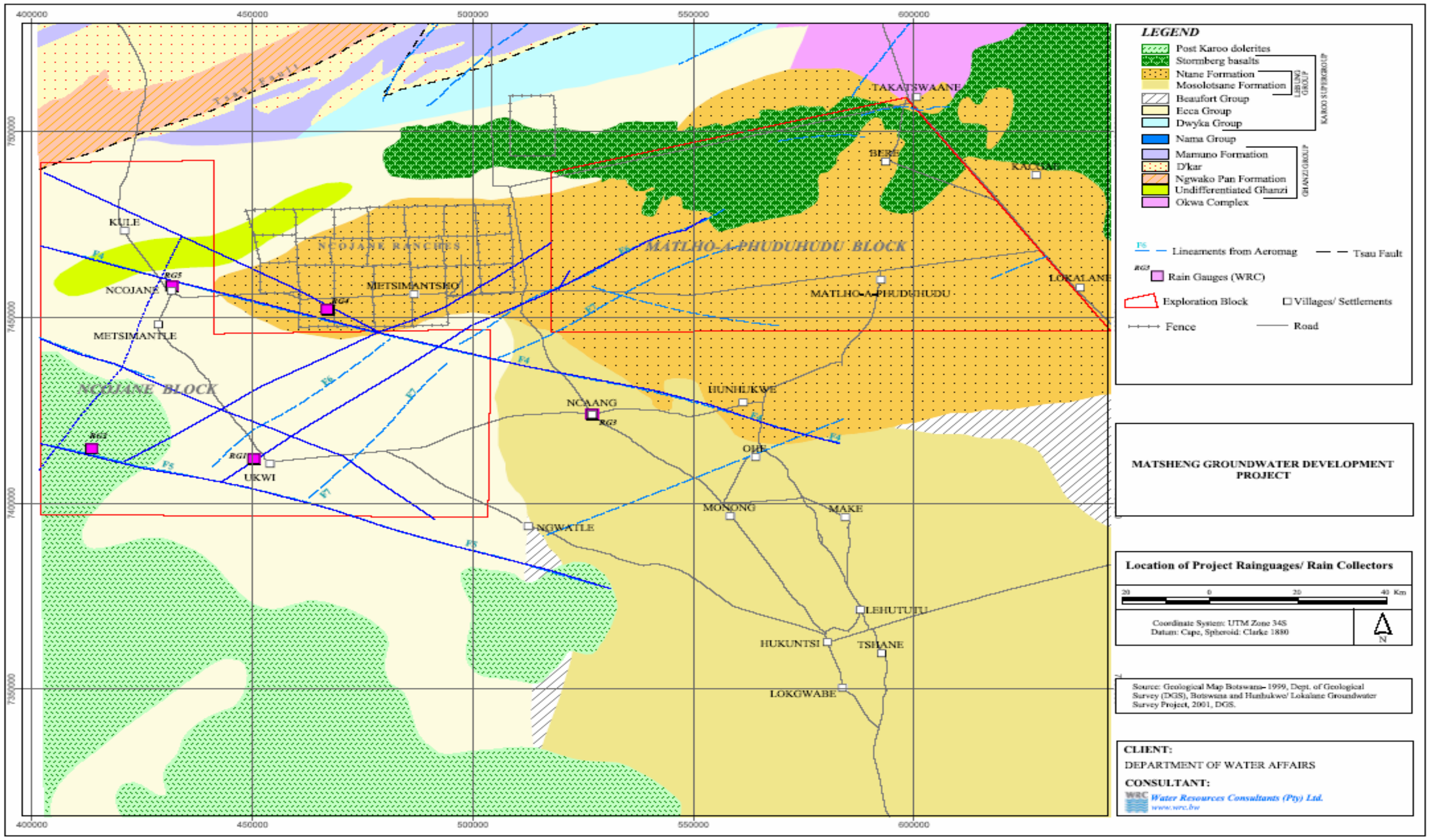

Figure 3.1 **Location Rain Gauges/Collectors**

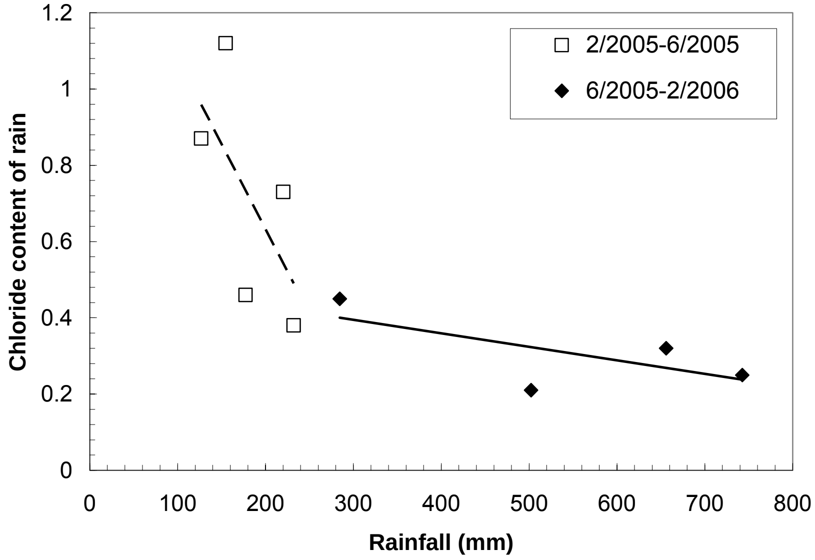

Figure 3.2 Chloride concentrations of rainfall samples collected in the cumulative rainfall samplers

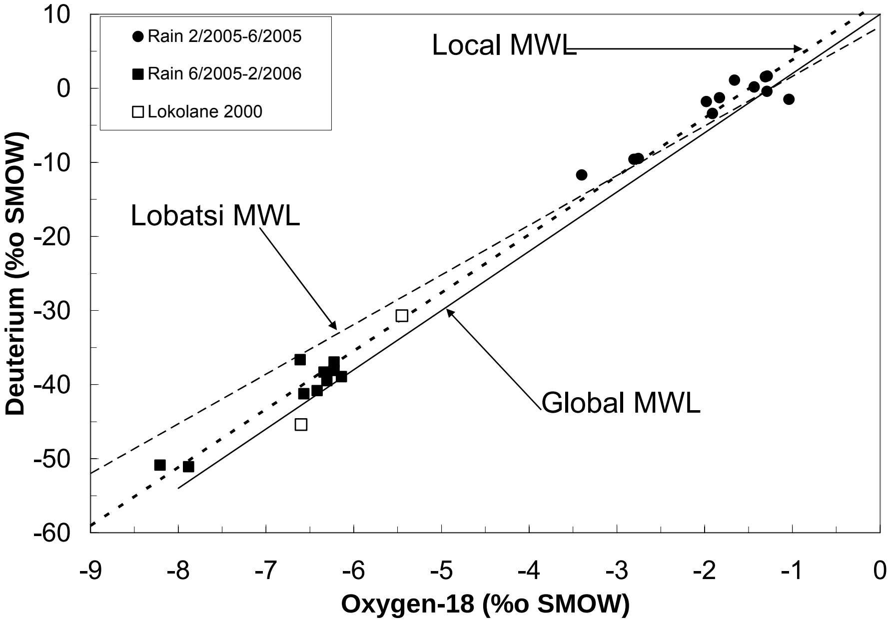

Figure 3.3 Plot of deuterium against ^{18}O of Rainwater Samples Collected During the present project[1]

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[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)

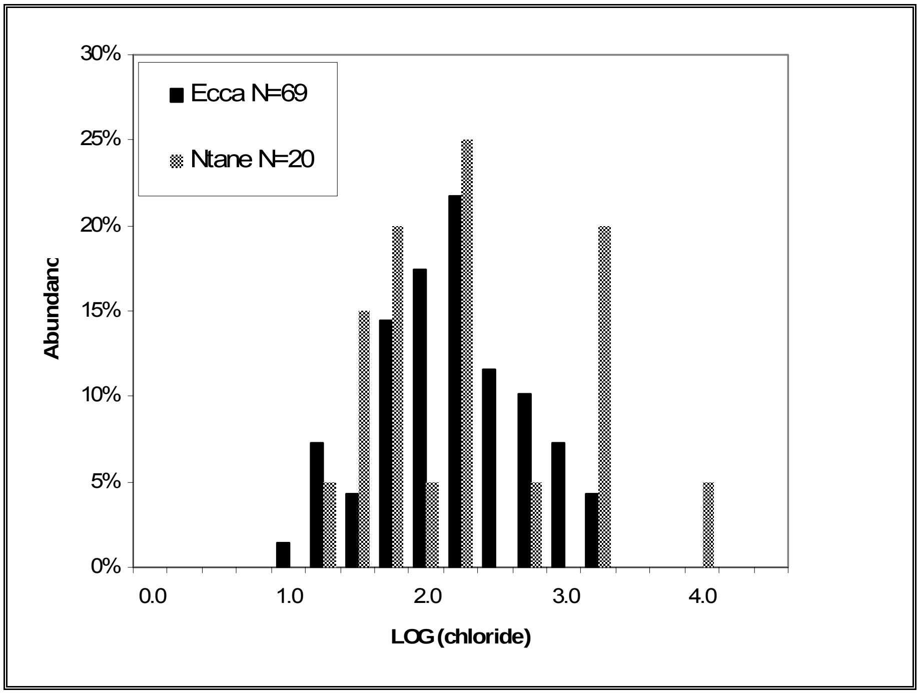

Figure 3.4 Distribution Of Chloride Values in the Two Main Aquifers Of The Project Area[2]

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

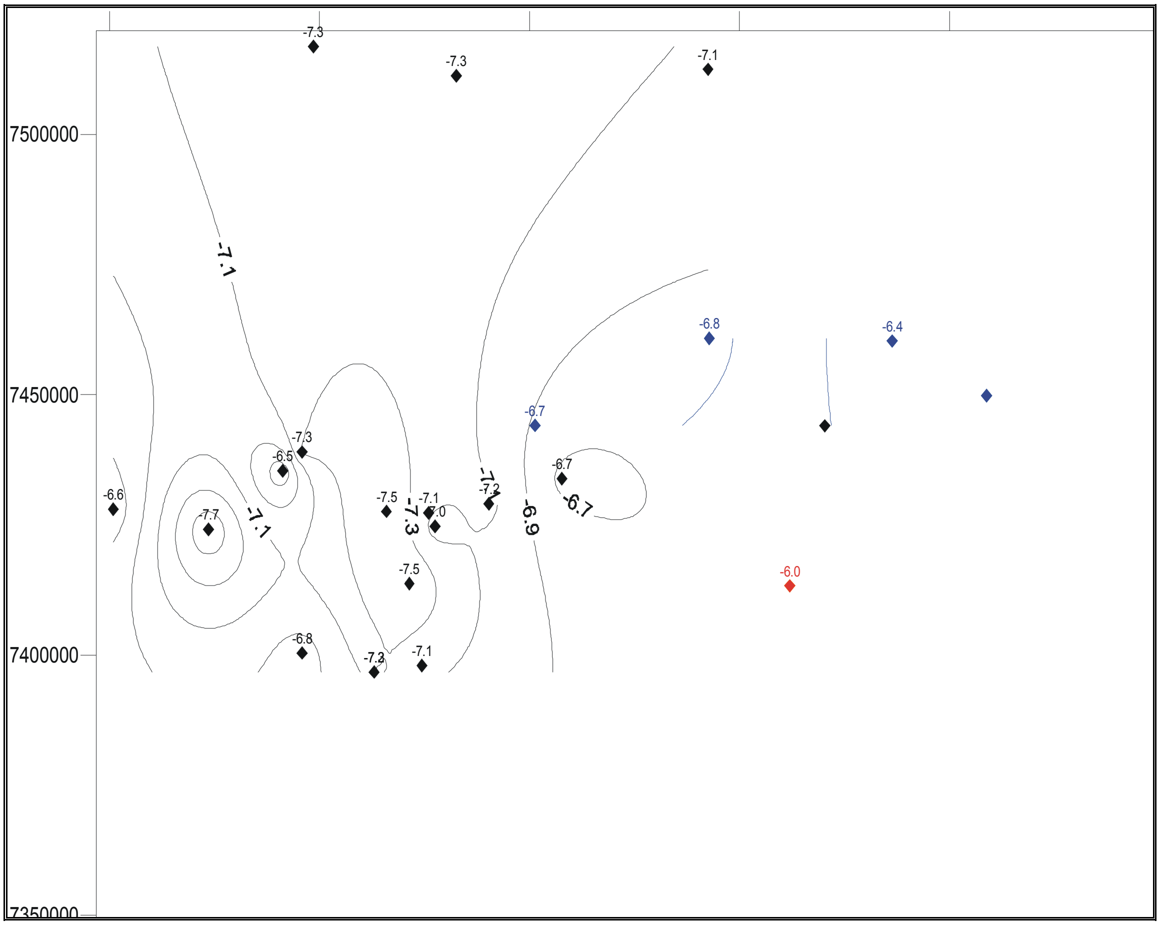

Figure 3.5 Distribution of ^{18}O in the Study Area[3]

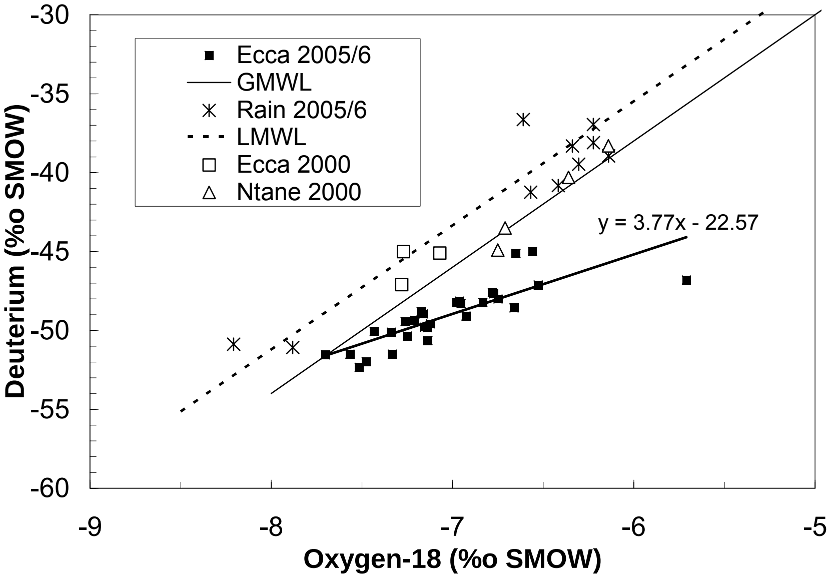

Figure 3.6 Plot of ^{18}O and deuterium in the present study area[4]

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

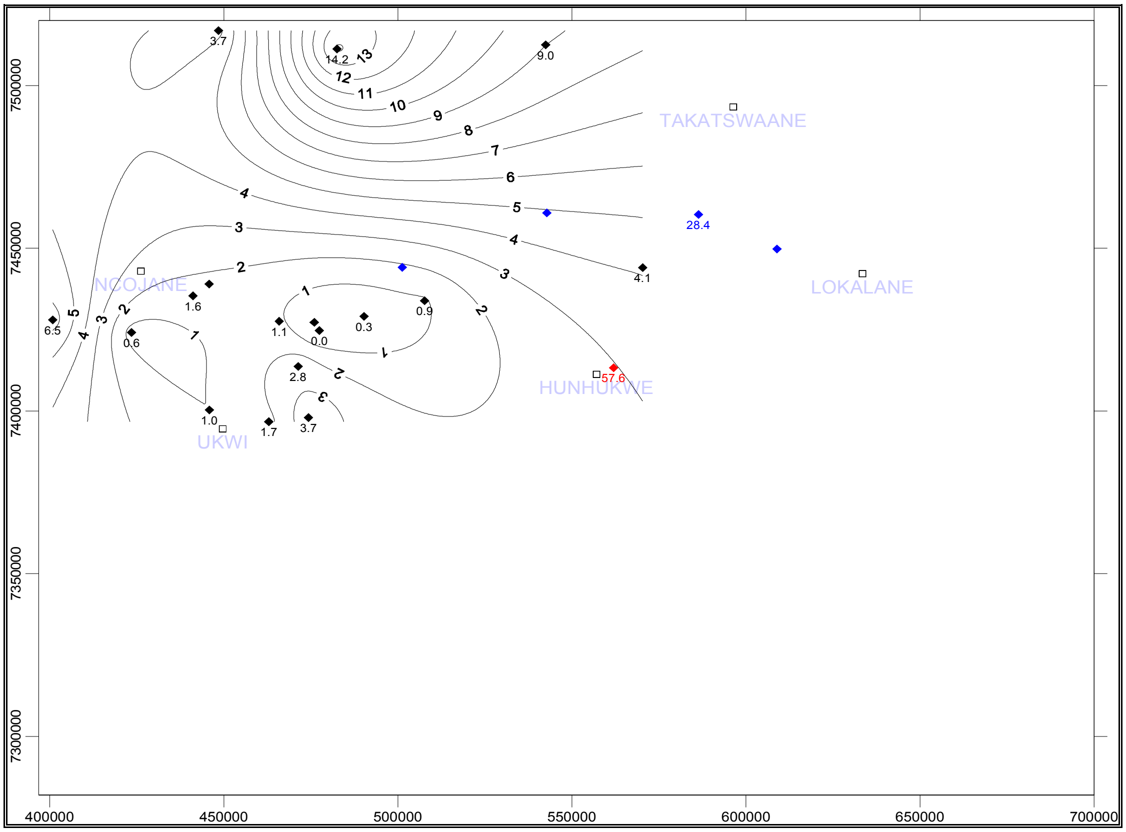

Figure 3.7 Distribution of ^{14}C content through the study area: based on the Present Project Data & WCS 2000[5]

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

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

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4 CONCLUSIONS

4.1 HYDROCHEMISTRY

4.1.1 GENERAL

From a hydrochemical perspective both the Ntane and the Otshe aquifers may yield water suitable for potable purposes. However, exploitable areas are geographically restricted. For the Ntane aquifer, the exploitable area is restricted to the eastern part of the Matsheng investigation area while for the Otshe aquifer only the western part has exploitable reserves.

For the Otshe sandstone aquifer hydrochemical data were 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 (15) 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 Kule (Kwetla) aquifers have been discussed in detail as the number of boreholes is very small and the exploitation potential 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.

4.1.2 NTANE AQUIFER

The recharge area(s) of the Ntane sandstone aquifer are not clearly defined from the water quality 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 this aquifer.

Available data seem to confirm that recharge has to take place in several areas which may be expected due to the semi-confined to unconfined nature of this 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 strategy needs might have to developed.

4.1.3 OTSHE AQUIFER

According to the hydraulic gradient, groundwater flow in the Otshe Aquifer is mainly from west to east with a northwest to southeast component in the southern part of the Ncojane block. Hydrochemical evolution in the Otshe sandstone aquifer mainly takes place in an (south)easterly direction and recharge seems to take place in the west in an area where the Otshe sandstones are expected to subcrop 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/Kule (Kwetla) Formations. To the east of these faults the Otshe aquifer is found at greater depth 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.

4.1.4 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 through corrosion, and seepage from surface pollution points.

Adequate protection zones should be maintained around well fields 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 are 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.

4.2 ISOTOPES AND CHEMISTRY

- 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 the two sandstones of the Otshe Aquifer

- 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) yielded 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 old 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 values 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 old age of this water body and its low replenishment rate necessitates great caution in its exploitation.

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