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School of Environmental Sciences

Investigation of Groundwater Potential in Naledi Local Municipality, North West Province, South Africa

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A Dissertation Submitted to the Department of Mining and Environmental Geology at the University of Venda in Partial Fulfilment of the Master of Earth Sciences in Mining and Environmental Geology

September 2016

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DECLARATION

I, **Ndwambi Khuthadzo, of the Student no 11561322, am hereby** declaring that this research for the Master's degree in Mining and Environmental Geology at the University of Venda, is my original work which has not previously been submitted by me at this or any other institution of higher learning for a degree and that all sources material I have consulted in this project have been fully acknowledged.

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ABSTRACT

The Naledi Local Municipality is located in the semi-arid regions of South Africa where there is low rainfall. The Groundwater provides the only means of water supply. The geological setting of the area is underlain by the basement rocks, with complex hydraulic properties. Although groundwater studies have been carried out previously, due to the limitation of the hydrogeological data, the groundwater potential and water quality in the area are still poorly understood. The aims of this study were to investigate the factors that control borehole yield in the area, to assess groundwater quality and to correlate the various physical and chemical parameters of groundwater and investigate their sources.

The groundwater potential of the area was assessed using principal component analysis (PCA). The reclassified thematic layers comprising of lithology, lineaments, soil, land use/land cover, drainage, and topography were used as input layers to the PCA. The weighting coefficient for each thematic layer was derived using the Eigenvectors of the PCA. The high lineament density, high stream density and the underlying lithological units were the significant parameters that were controlling the borehole yields. This was followed by the integration of the 6 thematic layers in accordance to their weighting coefficient. Consequently, the groundwater potential map of the area was established and comprises of low, moderate and high groundwater potential areas. The three groundwater potential classes coincide with the underlying lithological domains which are Ventersdorp crystalline aquifer, Kalahari sand aquifer and Malmani dolomite aquifer respectively.

Groundwater quality assessment was conducted based on the physiochemical parameters of the water quality. SANS241 water quality standard was used as the guideline for the interpretation of the water quality in the area. Auxiliary water quality data was supplemented with the field physicochemical data. The charge balance error (CBE) was performed to eradicate the contaminated data. The physiographical parameters were gridded into 200 m cell size grids and interpolated using the Inverse Distance Weight

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(IDW) to produce the spatial variation maps. The resulting interpolated maps indicated the pH was entirely within the regulatory standard. The EC, TDS, Cl and NO_3, and F for some of the boreholes exceed the maximum allowable limit for drinking water. The nitrate concentration is high in Stella due to anthropogenic sources such as sewage leaking, on-sight sanitation, and agricultural effluents. The TH in Malmani dolomite was significantly high. These values could be attributed to the dissolution of the dolomites and that consist of high Ca and Mg. Multivariate Factor Analysis was carried out to correlate the various physical and chemical parameters of groundwater and investigate their sources. The results indicated that the groundwater quality in the study area is controlled by both natural and anthropogenic sources.

Radiogenic isotopic analysis was conducted to assess the relative age of water resources within the study area. The Ventersdorp basement aquifer was generally characterized by low tritium values which correspond to the sub-modern groundwater age. The Malmani dolomite aquifer was defined by modern tritium values that hints that the groundwater recharge occurs at a significant level. Analysis of hydrochemical data shows that Na-HCO_3-Cl-SO_4, Mg-Na+K-Cl, Ca-Mg-HCO_3-Cl, and Ca-Mg-HCO_3 are the dominant hydrochemical facies in the area. The tritium content of groundwater in the study area is not indicative of recharge zones and relative age of groundwater.

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TABLE OF CONTENTS

DECLARATION i
ACKNOWLEDGEMENT ii
ABSTRACT iii
TABLE OF CONTENTS v
LIST OF FIGURES viii
LIST OF TABLES x
ACRONYMS AND ABBREVIATIONS xi
CHAPTER 1 1
INTRODUCTION 1
1.1 Background of the Study 1
1.3 Geology and Hydrogeology of the Area 7
1.3.1 The geological setting of the area 7
1.3.2 Hydrogeological setting of the study area 9
1.4 Statement of the Problem 13
1.5 Aims and Objectives of the Research 14
1.6 Research Questions 14
1.7 Justification of the Research 14
CHAPTER 2 16
LITERATURE REVIEW 16
2.1 The Demand for Water Resource in the Study Area 16
2.2 Groundwater Potential of the Area 17
2.3 Groundwater Quality in the Study Area 19
2.4 Summary of Previous Studies 21
CHAPTER 3 26
RESEARCH METHODOLOGY 26
3.1. The research was carried out based on the following sequential steps 26
3.1.1 Lithological data 28
3.1.2 Lineaments data 29

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3.1.3 Drainage map 30
3.1.4 Soil map 31
3.1.5 Topographic map 32
3.1.6 Land use and land cover 33
3.2 Integration of the Rasterized Thematic Layers 34
3.2.1 The significance of the parameters 34
3.2.2 Establishing the groundwater potential map 35
3.3 Groundwater Quality Assessment 35
3.4 Laboratory Analysis of Water Samples 37
3.4.1 Stable isotopes of hydrogen and oxygen 38
3.4.2 Analysis of tritium radiogenic 38
3.5. Data Accuracy Checking 39
3.6 Data Presentation 40
3.6.1 Descriptive statistical analysis 40
3.6.2 Graphical presentation 40
3.6.3 Interpolated physical parameters 41
3.7 Multivariate Statistical Analysis 42
CHAPTER 4 44
RESULTS AND DISCUSSION 44
4.1 Interpretation of the Reclassified Thematic Layers 44
4.1.1 Interpretation of lithological map 44
4.1.2 Analysis of the lineaments density map 46
4.1.3 Reclassified soil types map 47
4.1.4 Land use and land cover map 49
4.1.5 Drainage density map 51
4.1.6 Topographic relief map 52
4.2 Principal Component Analysis 55
4.3 Integration of the Thematic Layers 57
4.3.1 The groundwater potential map of the study area 58
4.3.2 Superimposing of borehole yield on groundwater potential-prediction map 62
4.4 Water Quality Parameters 64

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4.4.1 Distribution of the pH in Groundwater 65
4.4.2 Electrical conductivity 67
4.4.3 TDS distribution in groundwater 69
4.4.4 Nitrate distribution in groundwater 71
4.4.5 Distribution of chloride 73
4.4.6 Fluoride distribution in groundwater 74
4.4.7 Spatial distribution of the total hardness 76
4.4.8 Suitability of water for irrigation 78
4.5 Multivariate Statistical Analysis 79
4.5.1 Factor analysis 79
4.5.2 Correlation of the physicochemical parameters 81
4.5.3 Factors loading 82
4.6 Hydrochemical Facies 85
4.6.1 Water types in Kalahari aquifer 85
4.6.2 Water types in Transvaal aquifer 89
4.6.3 Water types in the basement aquifer 89
4.7 Groundwater Isotopes 90
4.7.1 Tritium concentration in groundwater 91
4.7.2 Stable isotopes of groundwater 93
4.8 Summary of Results and Discussion 95
4.8.1 Contribution of the Study 97
4.8.2 Limitations of the Study 98
CHAPTER 5 99
CONCLUSION AND RECOMMENDATIONS 99
5.1 Conclusion 99
5.2 Recommendations 100
REFERENCES 102

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LIST OF FIGURES

Figure 1. 1: Locality map of the study area showing settlements and water management areas with superimposed drainage lines. 5
Figure 1. 2: A locality map of the study area showing topographic relief of the area. 6
Figure 1. 3: The simplified geological map showing the lithological distribution in the area 8
Figure 1. 4: Map showing simplified aquifer types in the study area. 11

Figure 3. 1: Flowchart of generalized procedure used for assessment of groundwater potential in the area. 27

Figure 4. 1: Interpretation of the Lithological map. 45
Figure 4. 2: Reclassified lineaments density map. 47
Figure 4. 3: Reclassified soil type map. 49
Figure 4. 4: Land use and land cover map. 50
Figure 4. 5: A map showing drainage density. 52
Figure 4. 6: Map showing the topographical relief. 53
Figure 4. 7: Groundwater potential map of the area. 60
Figure 4. 8: Borehole yields in groundwater potential classes 62
Figure 4. 9: Borehole yields superimposed on groundwater potential map. 63
Figure 4. 10: The frequency distribution histogram of water quality parameters 66
Figure 4. 11: A map showing the pH of groundwater in the study area 67
Figure 4.12: The spatial distribution trend map of the EC. 68
Figure 4. 13: Map showing the TDS distribution in the study area. 70
Figure 4. 14: Map showing nitrate content in groundwater. 72
Figure 4. 15: The map illustrating the Cl content in groundwater. 73

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Figure 4. 16: Shows the frequency distribution histogram. 75
Figure 4.17: Concentration of fluoride in groundwater. 76
Figure 4.18: Map showing the TH trend in the aquifers. 77
Figure 4. 19: Map of SAR in the study area. 78
Figure 4. 20: The piper and the Durov diagrams for the Kalahari Formation. 86
Figure 4.21: The piper trilinear and the Durov diagrams for the different lithologies in the Malmani dolomite aquifer. 87
Figure 4. 22: The piper and the Durov diagrams for the Ventersdorp volcanic rocks. ... 88
Figure 4. 23: The tritium concentration in the groundwater (Basement and Transvaal aquifers). 92
Figure 4. 24: Stable isotopes plot depicting the relationship between groundwater. 94

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LIST OF TABLES

Table 4. 1:The simplified table of the reclassified thematic layers and their rankings.....54
Table 4.2: Eigenvectors derived from the covariance matrix of the principal components. 55
Table 4. 3: The correlation matrix of the groundwater potential parameters.....56
Table 4. 4: The weight assigned to each reclassified thematic layer.....57
Table 4.5: Groundwater potential classes and relative coverage in percentage. 59
Table 4. 6: WHO and SANS241 water quality guidelines. 64
Table 4. 7: The descriptive statistical analysis of critical water quality parameters. 65
Table 4.8: The communalities assessment of the water quality. 80
Table 4.9: KMO and Bartlett significance test. 81
Table 4.10: The correlation amongst the physio-chemical parameters. 82
Table 4.11: Factor loading of groundwater quality. 83
Table 4.12: Shows the Eigenvalues and the Variance explained by the factors. 84
Table 4.13: The results of the environmental isotopes of the water molecule. 90

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ACRONYMS AND ABBREVIATIONS

$\partial^{18}O$:	Oxygen 18 isotope
$\partial^{2}H$:	Deuterium
AAS:	Atomic Absorption Spectrometry
AMSL:	Above mean sea Level
GIS:	Geographical Information System
b.m.g.l:	below mean ground level
Ca:	Calcium
CBE:	charge balance error (%)
CGS:	Council for Geosciences
Cl^-:	Chloride
CO_3^-	Carbonates
DEM:	Digital Elevation Model
DWA:	Department of Water Affairs
Ec:	Electrical Conductivity
F^-:	Fluorine
FA:	Factor analysis
GIS:	Geographical Information System
GMWL:	Global Meteoric Water Line
GPS:	Global Positioning system
HCO_3 :	Bicarbonate
HGWP:	High groundwater potential
ICP-AES:	Inductively coupled plasma atomic emission spectroscopy
ICP-OES:	Inductively coupled plasma optical emission spectrometry
IDW:	Inverse Distance Weighting
IMS:	Ion Mobility Spectrometry
IRMS:	Isotope ratio Mass Spectrometer
ISE:	Ion Selective Electrode

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K:	Potassium
Km/km^2	kilometres per square kilometre
KMO:	Kaiser-Meyer-Olkin
l/s:	Litres per second
LGWP:	Low groundwater potential
LMWL:	Local Meteoric Water Line
LU/LC:	Land uses and land cover
M.a.m.s.l:	Metres above mean sea level
m^3/h:	Cubic metres per hour
Ma:	Million years ago
Mamsl:	metres above mean sea level
Mbgl:	Metres below the ground
meq/L:	mill equivalents per litre
Mg:	Magnesium
Mg/l:	Milligram per liter
MGWP:	Moderate groundwater potential
Mm/a:	millimetres per annum
MS/m:	micro Siemens per metre
Na:	Sodium
NGWA:	National Groundwater Archive
NO_3^-:	nitrate ion
NWPSoER:	North West Province State of environmental report
PCA:	Principal Component Analysis
pH:	Measure of the Acidity or Alkalinity of a Solution
R:	coefficient of correlation
SACS:	South African Committee of Stratigraphy
SAR:	Sodium Adsorption Ratio
SAWS:	South African Weather Services
SO_4:	Sulphates
TAL:	Total Alkalinity
TDS:	Total Dissolved Solids

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TH:	Total Hardness
Tu:	Tritium unit
UNESCO:	United Nations Educational, Scientific, and Cultural Organization
UTM (35):	Universal traverse Mercator coordinate system
VSMOW:	Vienna Static Mean Oceanic Water
WGS84:	World geodetic system
WHO:	World Health Organization
WMA:	Water Management Areas
WRC:	Water Research Commission

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Crystalline basement aquifers are common throughout the world, but significant extent in tropical regions occur in South Asia, South America, Australia and Sub-Saharan Africa (Wright, 1992). They are of great importance because of lateral extent, availability and often serve as the only source of water supply in semiarid regions where the rainfall is low and the rate of evapotranspiration is high (Wright, 1992).

Wright (1992) defined the crystalline rocks as a dual aquifer system, which comprises the weathered overburden (regolith) and fractured bedrock (saprolite). The crystalline rock aquifers are characterized by the absence of primary porosity and aquifer yield rely on post-formational structures resulting from tectonic deformation and regoliths that are products of weathering. The structures include lineaments, fractures, joints and faults (Chilton and Foster, 1995).

Shafick (2009) defined the basement rocks as minor aquifers because of low borehole productivity and poor water quality. For these reasons, they are globally disregarded for water supply. In 1984, UNESCO published a book titled Ground Water in Hard Rocks that provides guidance on how to evaluate groundwater potential within the crystalline rock terrains. In spite of the rapid improvements in understanding the hydrological characteristics of crystalline rocks, there are still challenges in understanding aquifer parameters such as specific yield, transmissivity, and hydraulic conductivity (Chilton and Foster, 1995).

The hydrogeological setting of crystalline basement aquifers is complex. The borehole yields in these aquifers are highly variable over a short distance (Holland and Withüser, 2011). Successful boreholes are often accompanied by sudden failure, the decline in the

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borehole yields and water level. The factors that contributed to a decline in borehole yield include poor fracture connectivity, the thickness of the overlying impervious layer, the weathered and permeable regolith, the depth of the permeable unit, among others.

One of the significant challenges in understanding the complexity of crystalline rock aquifers is the variability and erratic behavior of the hydraulic conductivity, which makes identification of drilling difficult (Holland and Witthüser, 2011). According to Clark (1985), defining the hydraulic properties (conductivity and transmissivity) of the basement aquifers is a complex task. According to Magowe and Carr (1999), lineaments have a fundamental impact on groundwater occurrence; a significant relationship exists between structures and borehole yields. Nevertheless, not all structures are important indicators of high borehole yield (Karim, 2009). According to Kellet (2004), crosscutting lineaments often serve as an indicator of groundwater occurrence and often associated with productive boreholes. Holland and Witthüser (2011) suggest that groundwater in basement aquifers is spatially and temporary variable and is a function of the prevailing climate, lineaments (structures) geology, topography, and drainage density and patterns.

Successful borehole siting in basement aquifers can be achieved through multi-data integration approach that involves the use of geology, geomorphology, elevation, soil cover and drainage (Krishnamurthy *et al,* 1996; Mukherjee, 1996, Jaiswal *et al,* 2003). Geophysical methods may also be employed in basement aquifers; they define the extent of lineaments and the thickness of the regolith (Karim, 2009).

The hydrogeological setting of Sub-Saharan Africa comprises of four hydrogeological provinces, namely; crystalline basement, volcanic rocks, unconsolidated sedimentary rocks and consolidated sedimentary (Braune and Mutheiwana, 2009). The hard-rocks constitute an integral part of water resource supply in this particular area as they constitute 55% of the four hydrogeological provinces. About 220 million people live in areas that are underlain by these aquifers and approximately 60 to 90% of the inhabitants rely on them (Braune and Mutheiwana, 2009).

Crystalline basement aquifers are very important source of water supply in South Africa. They are quite extensive, covering over 80% of the country (Woodford and Rosewarne,

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2006). The majority of people in rural areas largely depend on this aquifer for domestic and agricultural use. According to Woodford and Rosewarne (2006), in spite of the rural communities in many parts of the country entirely relying on basement aquifers, these aquifers are underutilized. Sami *et al,* (2009), suggest that basement aquifers have higher groundwater potential when explored using suitable exploration techniques.

The crystalline basement terrains underlay a significant portion of North West Province. According to Vegter (1990), the basement rocks dominate the five hydrogeological regions in the province. These regions consist of the fractured aquifer, intergranular aquifer, karst aquifer and intergranular and fractured aquifer (DWA, 2008).

The crystalline basement aquifer underlays a significant portion of the current study area. These aquifers have been a subject of groundwater exploration projects by private and government organizations with limited success (Nel and van Wyk, 1999; Du Toit and van Dyk, 1993). The key issues that are often responsible for the limited success of groundwater exploration (poor borehole yields or decline yields with time) in basement aquifers include, but not limited to; spatial variability of groundwater resource (Chilton and Foster, 1995), improper exploration approach (Adams, 2009) and limited understanding of groundwater control (Holland and Witthüser, 2011). In spite of low success rates encountered in the previous studies, according to Jha *et al,* (2007), Machiwal *et al,* (2011), Mukherjee *et al,* (2012) and Singh *et al,* (2013), the basement rocks are a potentially good source of water supply depending on the availability of structural development and thick regolith derived from weathering processes.

The integration of the geology, geomorphology, soil-cover, vegetation, and structures is important to assess the factors that control groundwater development. This research work is, therefore, an effort to have a better understanding of the groundwater potential in the Naledi Local Municipality. The local authority will be guided by the outcome of this study to make an informed decision to facilitate systematic planning, development, and management of groundwater resources can use the outcome of this project. Furthermore, this will aid towards ensuring sustainable use of water resource through proper planning and management.

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1.2. Description of the Study Area

The study area covers the Naledi Local Municipality, which is situated in the central part of the North West Province. The area is hydrologically divided into the Crocodile and Lowervaal Water Management Areas (WMA). As shown in Figure 1.1, the Crocodile WMA covers a minor part of the present study area (DWA, 2009). The Lowervaal WMA constitutes a significant portion of the study area, extending from the north to the south. It is divided into five Quaternary catchments; C32A, C32B, C32C, C32E and C32F which are the tributaries of the Dry Harts River (DWA, 2004).

The study area falls within an arid region of South Africa, where the climatic conditions are characterized by dry cold winter and hot wet summer. There is spatial variability of rainfall intensity; the eastern part is generally characterized by higher annual precipitation rates of about 450 mm per annum as compared to 300 mm in the western zone (SAWS, 2010). The rainfall patterns in the area are erratic; about 95% of the precipitation occurs during summer (SAWS, 2010). In spite of the low precipitation, the temperature is high in summer and often reaches up to 40°C. As a result, the annual rate of evapotranspiration is excessively high (1500 mm/yr) (NWPSoER, 2002). During the winter season, the area exhibits low temperature, which often goes below 0°C and is entirely dry with precipitations that barely exceed 20 mm.

The topographic relief of the study area is characterized by flat terrain (Figure 1.2). The highest elevation is 1500 m above the mean sea level, and it is situated in the eastern part of the area. The western side is also slightly elevated with altitude varying from 1250 to 1300 m above mean sea level. The topography relief gradually declines from the north to the south with altitude varying from 1300 m in the north to 1100 m in the south.

There are about 70 000 inhabitants residing within the present study area and most of the settlements are clustered in Vryburg, Stella and Dethakwaneng towns. The settlements in these areas are mainly confined to surface water sources, and they are not able to meet their needs.

In spite of the scarcity of water resources in the area, there is considerable agricultural activities mainly crop farming and animal breeding. Some of the agricultural products in

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the eastern part include tobacco, citrus, paprika, wheat, pepper, cotton and sunflowers (de Villers and Mangold, 2002).

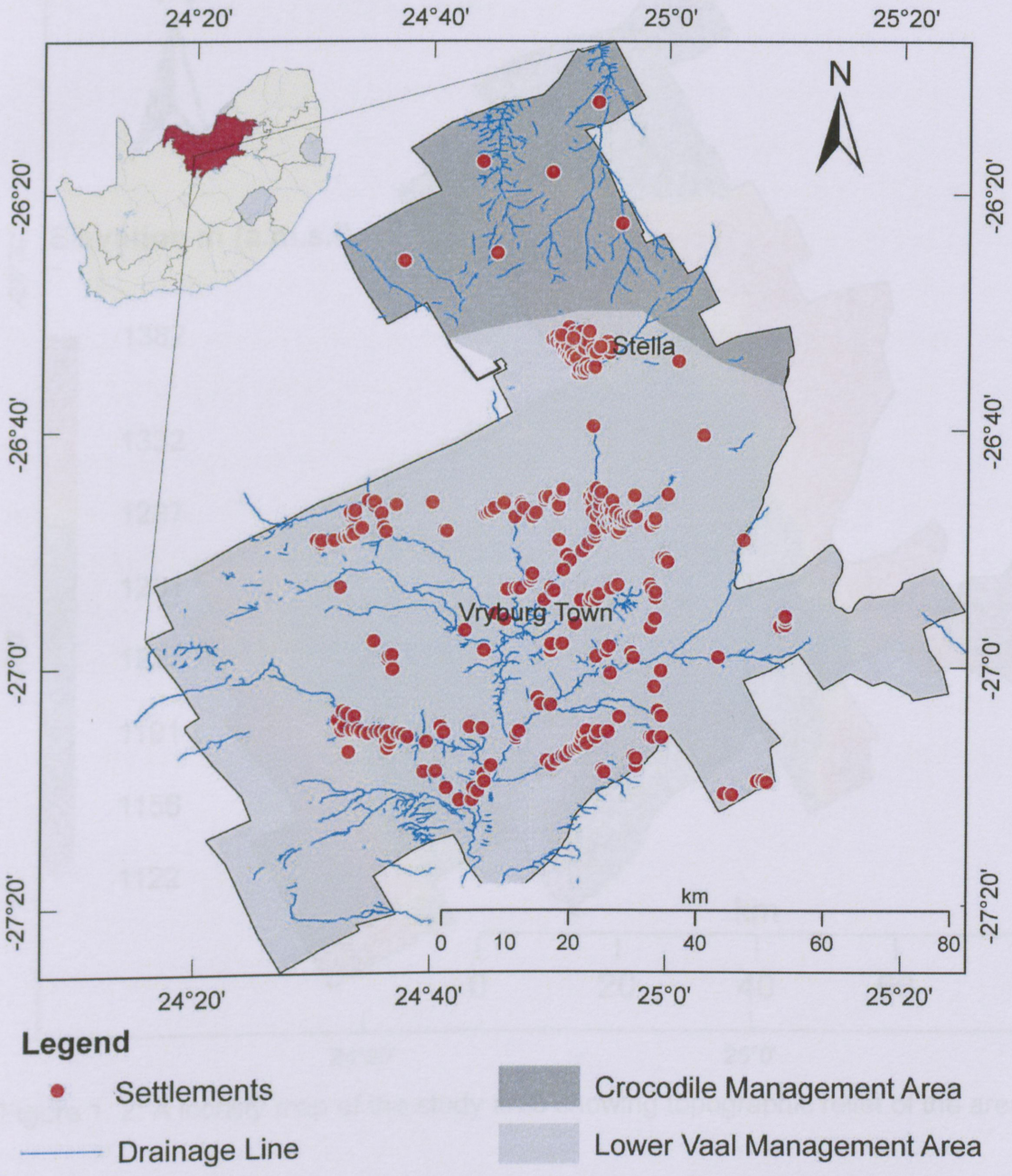

Figure 1. 1: Locality map of the study area showing settlements and water management areas with superimposed drainage lines.

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1.3 Geology and Hydrogeology of the Area

1.3.1 The geological setting of the area

The geological setting of the area comprises of four major lithological domains. From the oldest to the youngest, the Archean Kraaipan greenstone belt, the Ventersdorp Supergroup, Transvaal Supergroup and the Kalahari Formation (Figure 1.3). The Archean Kraaipan greenstone belt covers a small area and occurs in the northern part while the Ventersdorp Supergroup underlies the central part of the study area. The Transvaal Supergroup occurs in the southern part and the Kalahari Formation is situated in the northern part of the study area.

The Archean Kraaipan greenstone belt comprises the oldest rock units in the study area, with an age of about 3640 Ma (SACS, 1980). It consists of slightly metamorphosed volcano-sedimentary assemblages that occur along the narrow north-south striking linear belt. These rocks are poorly exposed due to the overlying younger Kalahari Formation. The weathering horizon corresponding to these rocks is moderate, but the rocks were subjected to multiple tectonic events that resulted in the formation of crosscutting structures, which possibly develop fractured bedrock aquifer (Keyser and Du Plessis, 1993).

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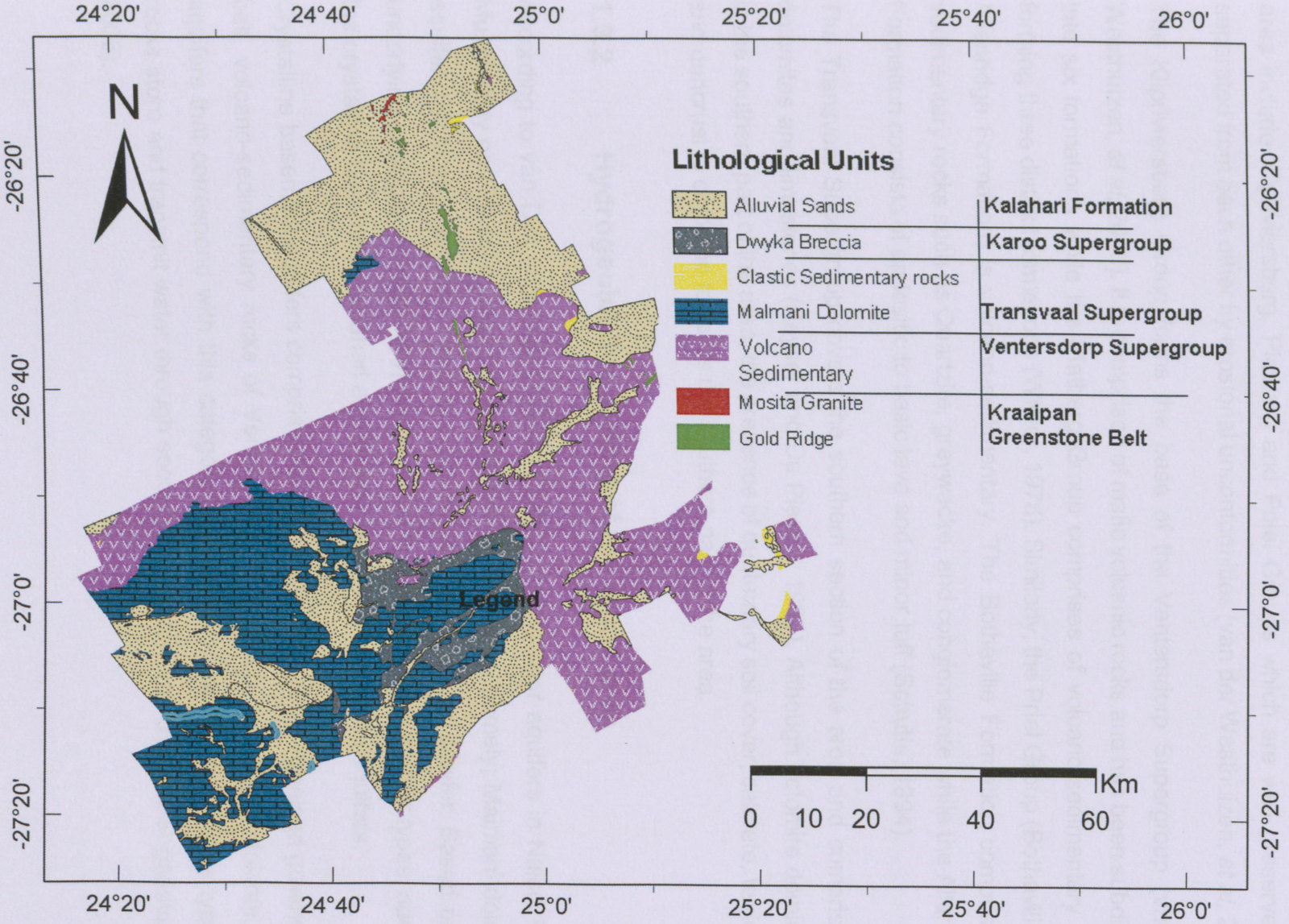

Figure 1. 3: The simplified geological map showing the lithological distribution in the area

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The Ventersdorp Supergroup covers the central part and extends in both north and southward direction. The stratigraphic sequence of the Ventersdorp Supergroup in this area include Klipriviersberg, Platberg and Pniel Groups which are well preserved but separated from each other by erosional unconformities (van der Westhuizen, *et al,* 2006).

The Klipriviersberg Group forms the base of the Ventersdorp Supergroup (van der Westhuizen, *et al,* 2006). It is comprised of mafic volcanic rocks and has been subdivided into six formations while the Platberg Group comprises of volcano-sedimentary rocks forming three distinct formations (Winter, 1976). Similarly, the Priel Group (Bothaville and Allanridge Formation) is volcano-sedimentary. The Bothaville Formation comprises of sedimentary rocks such as Quartzite, greywacke, and conglomerate while the Allanridge Formation consists of andesitic to basic lava and minor tuff (Schutte, 1994).

The Transvaal Supergroup covers the southern section of the area and comprises of dolomites and limestones (Keyser and Du Plessis, 1993). Although dolomite dominates in the southern part of the area, the presence of quaternary soil cover, calcrete, ferricrete, and duricrust is common towards the southern part of the area.

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1.3.2 Hydrogeological setting of the study area

According to van Dyk and Sagadevagan (2006), groundwater aquifers in Naledi Local Municipality can be subdivided into four broad aquifer types, namely; Malmani dolomite aquifer, fractured crystalline basement aquifer and intergranular aquifer. Based on the underlying geology, the aquifer types may be simplified into three aquifer types, namely; the crystalline basement, Kalahari aquifer and Transvaal carbonate aquifers.

Crystalline basement aquifers comprise the basement rocks of the Kraaipan greenstone belt, volcano-sedimentary rocks of Ventersdorp Supergroup, and Karoo dolerite. The aquifers that correspond with this category lacks primary porosity, i.e., these types of rocks store and transmit water through secondary porosity (van Dyk and Sagadevagan, 2006).

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Malmani dolomite aquifer

The Malmani dolomite aquifer comprises of sedimentary rocks, which do not possess primary porosity (van Dyk and Sagadevagan, 2006), but the flow and storage of water take place through dissolution channels and voids that developed within dolomite and limestone of the Transvaal Supergroup. The boreholes drilled within these rocks are recognized as high yielding in many parts of South Africa.

The Kalahari aquifers, which consist of aeolian sand, gravels, and quaternary deposits, are recognized as a primary aquifer because the storage of water takes place within the intergranular spaces of the unconsolidated granules (Keyser and Du Plessis, 1993).

In an attempt to understand the productivity of these aquifers, the Department of Water Affairs (DWA, 2008), conducted aquifer testing and established borehole-rating classes based on yields. The classification includes: extremely low potential development, very low potential development, low potential development, medium potential development and high potential development which correspond to 0.0-0.1 l/s, 0.1-0.5 l/s, 0.5-2.0 l/s, 2.0-5 l/s and >5 l/s, respectively (DWA, 2008).

Crystalline basement aquifer

According to Keyser and Du Plessis (1993), the crystalline basement aquifers comprise of Ventersdorp Supergroup and Kraaipan Greenstone belt. This type of aquifer corresponds to the oldest rock units in the area. The crystalline basement aquifer is recognized as a dual system aquifer in the study area, where the permeable layers consist the weathered upper regolith and the fractured rock layer overlying the fresh bedrock. The fracturing developed as a result of recurring tectonic events (Keyser and Du Plessis, 1993).

The borehole yields in basement aquifers are generally low (DWA, 2004). van Dyk and Sagadevan (2006) used the existing boreholes to evaluate the groundwater potential in these aquifer types in the area of study. The studies show that borehole yields in the basement aquifers are generally low particularly around Stella. The discharge rates of the boreholes range from 0.1 to 0.5 l/s. According to van Dyk and Sagadevan (2006),

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boreholes that are sited on the granitoid and gneiss of the Archean greenstone belt are most productive, with yields that often exceed 5 l/s.

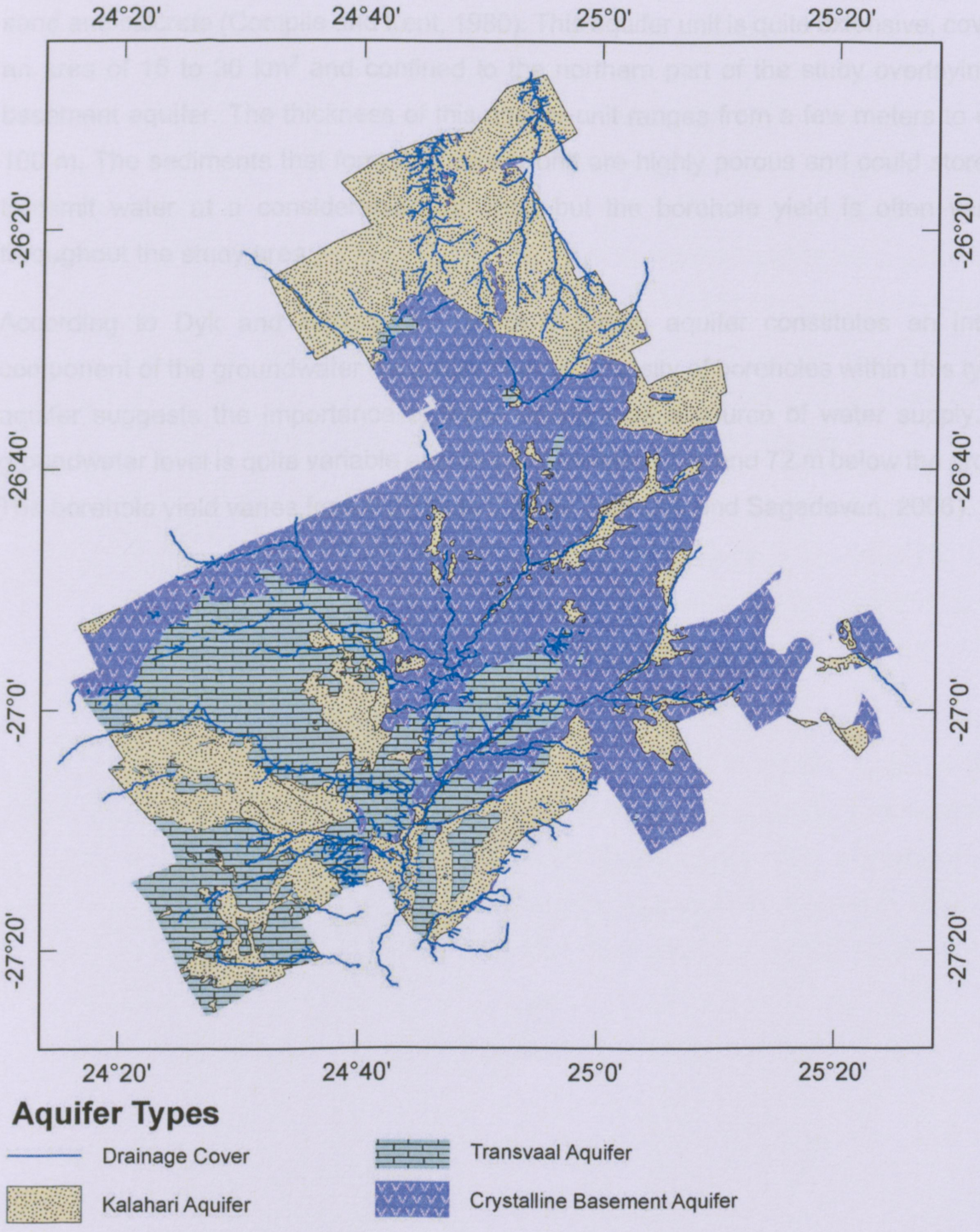

Figure 1. 4: Map showing simplified aquifer types in the study area.

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Kalahari Aquifer

Kalahari aquifer consists of unconsolidated sediments such as undifferentiated aeolian sand and calcrete (Compile and Kent, 1980). This aquifer unit is quite extensive, covering an area of 15 to 30 km^2 and confined to the northern part of the study overlaying the basement aquifer. The thickness of this aquifer unit ranges from a few meters to about 100 m. The sediments that form this aquifer unit are highly porous and could store and transmit water at a considerable high rate, but the borehole yield is often variable throughout the study area.

According to Dyk and Sagadevan (2006), Kalahari aquifer constitutes an integral component of the groundwater resource. The high density of boreholes within this type of aquifer suggests the importance of these aquifers as a source of water supply. The groundwater level is quite variable and ranges between 12 m and 72 m below the ground. The borehole yield varies from 0.27 l/s to 2.38 l/s (van Dyk and Sagadevan, 2006).

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1.4 Statement of the Problem

The deficiency of water resource in Naledi Local Municipality is one of the most significant socioeconomic challenges. The current water supply is inadequate to meet the current demand which is also escalating in proportion to the rate of industrialization, climate change, and population growth. As the results, there are numerous socioeconomic challenges that are emanating which include; the absence of adequate sanitary infrastructure (the lack of such basic infrastructure contributes to the contamination of the limited surface and groundwater through on-site sanitation and inappropriate waste disposal), poverty (as the inhabitants with low literacy level are restricted to participate in the agricultural sector at both subsistence and commercial levels), and there is a limitation of social and recreational facilities as the results of shortage of water. The issues outlined signifies that the scarcity of water resource presents a critical challenge.

The growing population, expanding agricultural sector and industrial growth exerts excessive pressure on the existing water resource that is already intensively stressed. The low annual rainfall, bare land, and high temperatures stimulate evapotranspiration that prohibits the development of surface water resources; hence, the streams are only periodic.

In the absence of surface water resource, the alternative is to explore for groundwater resources. However, the hydrogeological setting of the area is primarily composed of the crystalline basement rocks. These hydrogeological units are associated with heterogeneous conductivity and poor water quality. This study is, therefore, intended to fill the knowledge gap pertaining groundwater development potential in a crystalline basement setting.

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1.5 Aims and Objectives of the Research

The main aim of this study was to investigate the groundwater potential of the study area using the compilation of geological, hydrogeological and borehole data.

The specific objectives of this research were:

- To investigate the parameters that control borehole yield in the area.
- To assess the quality of the groundwater in the study area.
- To correlate the various physical and chemical parameters of groundwater in the area and investigate their sources.

1.6 Research Questions

- Which parameters controls the borehole yields?
- What is the quality of the groundwater?
- How do the physical and chemical parameters of water quality influence the groundwater chemistry?

1.7 Justification of the Research

The study area is largely covered by basement rocks, which are complex to comprehend, mainly because of their heterogeneous hydraulic properties. Although groundwater studies have been carried out previously, due to the limitation of the hydrogeological data, the groundwater potential and water quality in the area are still poorly known. The assessment of groundwater potential in complex hydrogeological environments such as the present study area requires the use of various data sets in order to minimize the uncertainty in the outcome of a project. The present study is therefore intended to shed light on the control of groundwater distribution and define potential areas based on interpretation of several datasets.

The assessment of groundwater potential of the area is important to regulate water use and ensure sustainable use of water resources.

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The study area largely falls in a crystalline basement terrain and the outcomes of this study will provide the basis for further research work. The hydrogeological database will be utilized to advance the knowledge and provide data input for related groundwater studies in the area. Furthermore, the study will serve as the basis for making sound and informed decision by the authority and stakeholders concerned.

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CHAPTER 2

LITERATURE REVIEW

Groundwater potential evaluation relies on the state of existing water supply and other related issues. Therefore, this chapter broadly synthesizes the existing literature regarding the state of water resources in the area. The key issues are covered in this chapter include the demand of water resources, the presiding groundwater aquifers, groundwater quality and some of the notable groundwater studies carried out in the area.

2.1 The Demand for Water Resource in the Study Area

One of the most critical issues affecting the people of North West Province is the availability of water resources. The existing water supply is insufficient to meet the escalating demand of the inhabitants (Sami, 2013). According to NWDACE-SoER (2008), approximately 1 million people are without access to basic water supply in the province. A further 19% of the total population do not have access to basic services or have services below basic standards (NWP-SoER, 2002). The water resource in the province is derived from the surface and groundwater sources (Sami, 2013). The surface water bodies comprise rivers, dams, pans, and wetlands that are spatially and temporary variable in correspondence with the semiarid climatic conditions (NWDACE-SoER, 2008). A significant portion of water supply is obtained from the large underground aquifers through the abstraction boreholes. Water in the province is regarded a key limiting factor for socioeconomic development (NWP-SoER, 2002).

According to Sami (2013), the principal source of water supply in the Naledi Local Municipality is the underlying groundwater aquifers, which are supplemented by the surface water resources. The groundwater resource account for 15.81 Mm^3/a which accounts for 72% of the bulk water supply, while the surface water which is drawn from the Vaalharts irrigation Canal accounts for 6 Mm^3/a (28%) (Sami, 2013). The two water

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sources are not sufficient to meet the escalating demand for the resource. This calls for the identification of additional groundwater resource to supplement the existing supply. DWA (2009), recorded a constant decline in groundwater level. However, Sami (2013) produced the groundwater potential harvest that suggests that there is underutilization of groundwater resources and the decline in water level is a rather compartmental response to groundwater abstraction, but not the depletion of the resource. These imply that additional water resources could be withdrawn from the aquifers, but to avoid declination of the water level, the factors controlling the groundwater potential should be clearly defined to ascertain proper locations for additional wells.

2.2 Groundwater Potential of the Area

The hydrogeological setting of Naledi Local Municipality is quite complex. It comprises of the three major aquifers which are namely; the plutonic aquifers of Venter'sdorp, Aeolian sands of Kalahari Formation, and the Malmani dolomite aquifer which exhibit highly variable storage and conductivity.

The groundwater potential along the Kalahari aquifers is considerably variable as the high and the low yielding boreholes coexist. According to van Wyk, (1987); Dziembowski and Appelcryn (1987), the pumping tests conducted in Kalahari Formation reveals that the boreholes are broadly grouped into two categories, the high yielding, and low yielding wells. Though these wells are appropriately categorized into two categories, hoever the causes of the discrepancies in the borehole yields in such classification are not well understood. The categorization of the two classes according to these authors indicate the low potential borehole yields ranges between 0.2 and 1 l/s, and the productive borehole output ranges between 2 l/s and 10 l/s. In exceptional cases, the discharge rates, in excess of 20 l/s are recorded within the optimal depth of 40 to 50 m, while in some cases the well deeper than 200 m where also encountered to be highly proficient (van Wyk, 2011). The proportionality that exists between the well depth and its productivity is not well outlined but it may be associated with the large volume of porous sands and the fractures along the underlying the sub-basement rocks.

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The Malmani dolomite aquifer is recognized as dual aquifer systems that comprise the fractured and the karst components. The fractured section of the aquifer, which comprises the Vryburg Formation, is considered a low to moderate yielding aquifer, as the majority of boreholes discharges less than 2 l/s, and only 10% liberates beyond 5 l/s (Barnard, 2000; van Dyk and Kirsten, 2006). The variations in the discharge of the two sub-units of this aquifer may easily be differentiated based on the mode of storage.

The karsified component of the Malmani dolomites (Ghaap dolomite rocks) is considered a moderate to a high yielding aquifer system because of the high frequency of the productive borehole yielding in excess of 5 l/s (Barnard, 2000). There are rare cases of extremely high discharge rates of up to 126 l/ reported (Barnard, 2000). The high yielding boreholes are generally associated with the chert-rich dolomite but only in areas with structural lineaments or the Karoo weathered dolerites (Kafri *et al,* 1986). According to Bredenkamp (1995), a significant portion of the water resources from the karst aquifers is mainly used for irrigation purposes because of high productivity.

According to Barnard (2000), the productivity of the boreholes in the crystalline basement rocks comprise of three distinct classes. The first class encompasses the low yielding boreholes that discharge less than 0.5 l/s, the second class consist of the borehole yields ranging between 0.5 l/s and 2 l/s, the boreholes in this category are considered moderately productive. The third class includes a few boreholes that yield in excess of 2 l/s (Barnard, 2000; Baran, 2003; van Wyk, 2011). Similarly, to the other aquifers, there are exceptionally high borehole yields of up to 20 l/s. These productive wells correspond with the fractured zones (Baran, 2003; van Wyk, 2011). Most of the borehole productivity studies in Naledi Local Municipality basement rocks was conducted by Barnard, (2000), Baran, (2003), van Wyk, (2011), the three authors managed to characterize the borehole productivity within the basement terrain, however, none of the three managed to outline the fundamental factors governing the yielding of the prevalent aquifers. This consequently necessitates a need for a study to address this mystery.

The groundwater level in the volcanic lava of Ventersdorp Supergroup is highly variable as it is intercepted between a depth of 5 and 40 m b.m.g.l (Barnard, 2000; Baran, 2003; van Wyk G, 2011). According to De Villiers (1961), the success of groundwater

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exploration in the crystalline basement is dependent on the underlying lithological units. The volcano-sedimentary has a success rate of 59%, followed by volcanic rocks at 56% and the subgroup has the success rate of 44% of the volcanic rocks. Although the studies by Barnard, (2000), Baran, (2003), van Wyk, (2011), outlined the existence of highly variable water level they do not account for the parameters responsible. However, this could be interpreted in accordance with Chilton and Foster (1995), who outlined that the crystalline bedrock aquifers are highly complex and groundwater occurrence is spatially variable over a short distance.

There are dykes of variable composition that are generally impermeable, which serve as barriers to groundwater flow. This has resulted in the formations of compartments (van Dyk and Kirsten, 2006). The individual compartments are generally characterized by variable groundwater level. The low groundwater level gradients are typical of areas with high transmissivities (Kafri *et al,* 1986). Outflow of groundwater from these compartments and its subunits generally occurs (Bredenkamp *et al,* 1986)

2.3 Groundwater Quality in the Study Area

According to Holland and Withüser (2011), the borehole yields in basement aquifers is temporary and spatially variable. The heterogeneous nature of the hydrogeological parameters renders each component of the aquifer to be unique in terms of borehole yield and water quality. Thus to say, neighboring villages abstracting from the same aquifer from different wells consume water of variable quality. Therefore, there should be considerable high water quality monitoring boreholes in this mode of an aquifer.

There is generally under-reporting of poor water quality throughout the entire country. In the rural areas of the Northwest province, a study conducted by Magowe (2000) reviews the water quality monitoring results. The findings of the study indicate that the quality of groundwater in the province is poor and still deteriorating. The poor water quality occurs in rural areas where groundwater is occurring in shallow aquifers. In such conditions, the groundwater is susceptible to nitrate contamination derived from mineralization, agricultural sector, and industrial effluents as well as pit latrines (Tredoux *et al*, 2000).

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These sources have the potential to yield chemical contamination (NWPG, 2002; Coetzee *et al,* 2006). The evidence of water contamination potential cannot be disputed; therefore, it is imperative that an assessment of the current state be conducted as failure to do so may result in critical health effects to the humans.

Although groundwater resource is believed to be of good quality according to Mpenyana-Monyatsi and Momba (2012), Momba *et al,* (2006); Ferguson *et al,* (2012) and Mackintosh and Colvin (2003). Mpenyana and Momba (2012) assessed the groundwater quality in rural settlements of the North West Province using the existing boreholes and the study indicates groundwater quality is posing health threats to the consumers as the following physicochemical parameters; TDS, NO_3, F^- and Mg were often found to exceed the regulatory standard. In spite outlining the existence of undesirable physiochemical parameters in water quality, the processes responsible for the liberation of such parameters remains unknown. This denote tha it is not only the assessment of the water quality that is crucial, but the underlying factors defining the hydrochemical composition of water is of similar significance.

The groundwater quality in the Kalahari aquifer is complex, it does not show any spatial trend or pattern. According to van Wyk (1987), there is variability of water quality parameters in the Kalahari aquifer. The variabilities are corresponding with the borehole depth and the spatiality. Similarly, van Wyk (2011) shows the EC values are erratic and highly inconsistent over a short distance. Wyk (1987); (2011) illustrates that the EC within the Kalahari is highly variable irrespective of the difference in monitoring period. Hence, the water quality of an area is not solely defined by the EC, the results may need to be updated with other physicochemical parameters to issue an informative water quality.

The groundwater quality in Malmani dolomite is often potable for human consumption. Karst aquifers are generally characterized by good water quality but the EC values suggest undesirable water quality also exist. According to Bernard (2000), there are significant spatial differences in the EC values of the Ghaap Subgroup. The EC values range between 63 mS/m and 397 mS/m. Du Toit and Leyveld (2006) shows the EC values along the escarpment of the dolomite ranges between 55 mS/m and 166 mS/m. In another study, Du Toit and Sonnekus (2010) show that the EC value ranges between 68 mS/m

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and 374 mS/m. All these studies cited in this brief review of the water quality within the Malmani dolomite aquifer point towards the existence of highly variable EC values that overlaps between the desirable and undesirable range.

The groundwater quality in Ventersdorp Supergroup is generally permissive for domestic consumption prior any treatment. The groundwater quality study by Barnard (2002) shows the EC value for the Klipriviersberg Formation ranges between 60 mS/m and 264 mS/m, the sulphate occasionally exceeds the maximum allowable limit with a maximum reported value of 1 038 mg/l. The elevated sulphate values within the Kameeldoorns Formation are associated with gypsum (Barnard, 2002). Baran (2003) assessed the suitability of groundwater resources in Platberg Group for domestic consumption. The investigation was based on groundwater monitoring data. The outcome of the study recommends that water resource should be avoided for human consumption. The water resources within the Ventersdorp Supergroup is not pristine water quality. However, the boreholes that were considered for such assessments were not outlined, these ultimately means assessing the groundwater in a more recent period may yield to updated results. Furthermore, the basement aquifers are associated with highly variable water quality over a short distance, therefore the resource may not necessarily be discarded based on these values.

2.4 Summary of Previous Studies

There are numerous case studies highlight the state of water resource in the study area. Such studies were primarily the works of the private companies and the government in an attempt to characterize the groundwater potential in the area. The methodology employed in such studies and their outcomes are summarised in this section and they are arranged in accordance to their spatial distribution.

Magowe (2000) investigated the groundwater quality pattern and trends in the northwest province using the time series water quality monitoring data. The study discovers that the groundwater quality in the province is poor and still deteriorating. The worst water quality occurs in rural areas where groundwater is occurring at shallow depth. Mpenyana-

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Monyatsi and Momba (2012), Momba *et al,* (2006); Ferguson *et al,* (2012) and Mackintosh and Colvin (2003) assesses the quality of groundwater in Northwest Province based on monitoring data. The study reveals the quality of the resource is often portable and is consumed without any prior treatment. Although Mpenyana-Monyatsi and Momba (2012), Momba *et al,* (2006); Ferguson *et al,* (2012) and Mackintosh and Colvin (2003) discover that the groundwater is suitable for consumption, groundwater monitoring should be done consistently since Magowe (2000) discloses that the quality of subsurface water resource is declining.

De Villiers (1961) evaluated the underlying factors controlling the borehole productivity in the crystalline basement aquifer. The study reveals that the significant parameter controlling the borehole productivity was the lithological units comprising the aquifer. The volcano-sedimentary shows the success rate of 59%, followed by volcanic rocks at 56% and the subgroup has the success rate of 44% of the volcanic rocks. The findings of these study imply that lithological characterization is key for groundwater potential assessment.

Motebe (2004) conducted groundwater potential assessment based on terrain mapping and integrated interpretation of the magnetic and gravity survey. The integration of the two approaches outlined 6 suitable drilling sites. Confirmatory drilling was conducted which revealed 5 of the sites were highly productive with water striking at the depth ranging between 17 and 80 m. Such a high success rate in basement aquifer hints that the approach should be tested elsewhere to evaluate the relative effectiveness of the approach.

van der Westhuizen and Hodgson (1981) investigated the groundwater potential in and around Vryburg town based on the hydrogeological parameters and the water quality data. The study suggests that the higher groundwater potential corresponds to the quartzite that is occurring at the depth ranging from 100 to 150 m. The authors propose detail exploration to validate this finding, but it can be deduced that the state of such quartzite should be of moderately fracturing to enhance groundwater potential.

During an attempt to increase groundwater abstraction in Vryburg, the DWA conducted the geohydrological survey. As a result, new boreholes were drilled to aid the domestic

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and industrial utilization (van Dyk, 1993). The results of the study indicate, variability in borehole productivity adheres to the proximity of the structures. The pumping test indicated a permanent decline in groundwater level as a result of over-pumping. It should be noted that the crystalline basement does not possess primary porosity, therefore it is not uncommon that the productive wells should be encountered within a close proximity to the structures.

Verhagen *et al,* (2011) assess the hydraulic conductivity of the basement aquifer in Vryburg. In the study, down-the-hole image logging was conducted to assess the structures. The results show two sets of fractures, the vertical and sub-vertical structures extending from the ground to the depth of about 45 m. Although such structures appear to be blocked by secondary minerals, the upper fracture, and the regolith are still intact and remain as hydraulic conduits during episodic recharge periods.

Monokofala (2011) evaluated the sustainability of groundwater using a constant discharge in Villages around Vryburg. Sustainable borehole yields were determined in the range between 0.3 l/s to 12.5 l/s for the basements in Vryburg wellfield and Armoedsvlakte farm respectively. The abstraction of the groundwater at the rate exceeding 12.5 l/s may result in sudden failure of the well.

Barnard (2000) assessed the groundwater quality of the Ventersdorp Supergroup using EC and sulphate. The study shows the EC value for the Klipriviersberg Formation ranges between 60 mS/m and 264 mS/m, the sulphate occasionally exceeds the maximum allowable limit with a maximum reported value of 1 038 mg/l. The elevated sulphate values within the Kameeldoorns Formation are associated with gypsum (Barnard, 2000).

Baran (2003) assessed the spatial variability of water quality parameters in Platberg Group. The study was based on the existing hydrochemical data obtained from the monitoring boreholes. The interpolated surface map of the significant parameters of the water quality shows important concentrations beyond human consumption exists. The study also advised that water resources for the entire Platberg Group should be avoided for domestic consumption.

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Nel (2001) assessed borehole productivity based on blow yields around Stella. The result of the study indicates efficient borehole yields are found in areas underlain by highly fractured granite rocks in Middlekop. Goldridge Formation also exhibits highly fractured rocks. Based on this study, Nel (2001) concludes that lineaments intersection, lineaments density and lineament length are critical conduits of the basement aquifer.

Dziembowski and Appelcryn (1987) evaluates the groundwater recharge mechanism within the Kalahari aquifer. The outcome of the study reveals the existence of three recharge mechanisms namely, the direct recharge from the rain during excessive rainfall periods, the excessive flooding, and the recharge where the formation outcrops. van Wyk (1987); Dziembowski and Appelcryn (1987) conducted the blow yield on a 72 hrs pumping tests to establish the sustainable discharge rates of the Kalahari aquifer. The study reveals that the efficient discharge rates can be broadly categorized into two classes, the high yielding boreholes discharging the excess of 20 l/s and the poorly productive boreholes that range between 0.2 and 1 l/s.

van Wyk (1987) investigated the groundwater quality within the Kalahari aquifer using EC water quality parameter measured from the monitoring wells. The findings of the study suggest the groundwater quality in Kalahari aquifer is complex and do not have a defined trend or pattern. The variabilities are evident along the horizontal and the vertical axis. In another study, van Wyk (2011) shows the EC values are erratic and highly inconsistent over a short distance.

Kafri *et al*, (1986) carried out the study aiming to assess the groundwater potential of the Malmani dolomite aquifer. The study discovers that the high yielding boreholes are generally associated with the chert-rich dolomite formations, but only in areas with structural lineaments or the Karoo Supergroup outliers.

The investigations to assess the suitability of water resource for human consumption within the Malmani dolomite aquifer was carried out by Barnard (2000). The outcomes of the study propose that the resource may be consumed prior any treatment. The follow-up investigation, by Du Toit and Sonnekus (2006) shows EC values ranging between 63

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mS/m and 397 mS/m. In another study, Du Toit and Sonnekus (2010) show the EC value ranges between 68 mS/m and 374 mS/m.

Nel and Wyk (1999) evaluate the productivity of the aquifers in Spitskop. The pump tests were conducted in 5 boreholes for a 72 hrs duration at a flat pumping rate of 11.6 l/s. The study indicates significant variability exists in hydrogeological parameters within the aquifers, the transmissivity of the fracture and matrix are 2000 m^2/d and 3 m^2/d respectively, and the storativity ranges from 0.02 to 0.002. Nel and Wyk (1999) evaluate the groundwater sustainability based on water level fluctuations, precipitation, and the aquifer test. The outcome of the study reveals that the abstraction exceeds the recharge; the authors then recommended the resources should be managed wisely.

Nel (2001) conducted geophysical logging using neutron, gamma ray, and resistivity logging. In some of the boreholes, camera logging was also used in Middlekop to characterize the permeability of the rocks and their thickness. The study revealed the presence of the granite and gneiss aquifer between the depth of 40 and 45 m, and the productivity of the boreholes is 25 l/s. The results of the study reveal that the effective depth of the fractures ranges between 20 m to 45 m below the surface.

Terblanche and Stroebel (2012) conducted electromagnetic and resistivity survey along Kraaipan to demarcate the potential drilling targets. Consequently, a target was defined based on geophysical anomalies and 66 new boreholes were developed. The productivity of such boreholes generally exceeded a lower limit of 360 l/s. Water strike was intercepted between the range of 3 m and 37 m depth. Higher productive boreholes were intercepted in highly fractured settings.

The water level fluctuation study was conducted by the DWA (2009). The Department base the study of the water level measurements taken for the previous four decades. The results show there is a declining trend of water level within the monitoring boreholes.

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CHAPTER 3

RESEARCH METHODOLOGY

This chapter presents a sequence of methods that were employed in data collection, handling, and processing of variable physicochemical parameters of water quality that are derived from existing monitoring data and primary field data in conjunction with the acquisition of different thematic layers which comprise the geology, structures, topography, drainage, soil type, land use and land cover, drainage, and elevation.

The study commenced with desktop study which provided the relevant information about the nature and state of the problem. Following the desktop study, the methodology of the research was outlined. This methodology is shown in a form of a flowchart in Figure 3.1. The research methodology comprises of two sections that deals with the delineation of groundwater potential zones and groundwater quality assessment.

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3.1 The Research Approach

Step 1: The desktop study characterized the initial phase of this study. This stage involved establishing the nature and the extent of the problem. Consequently, the appropriate methodology was designed such that the objectives of the study would be achieved. The initial phase of this research comprised of adoption of auxiliary data comprising of the geology, lineaments, drainage, rainfall, soil type, and topography for the assessment of the groundwater potential.

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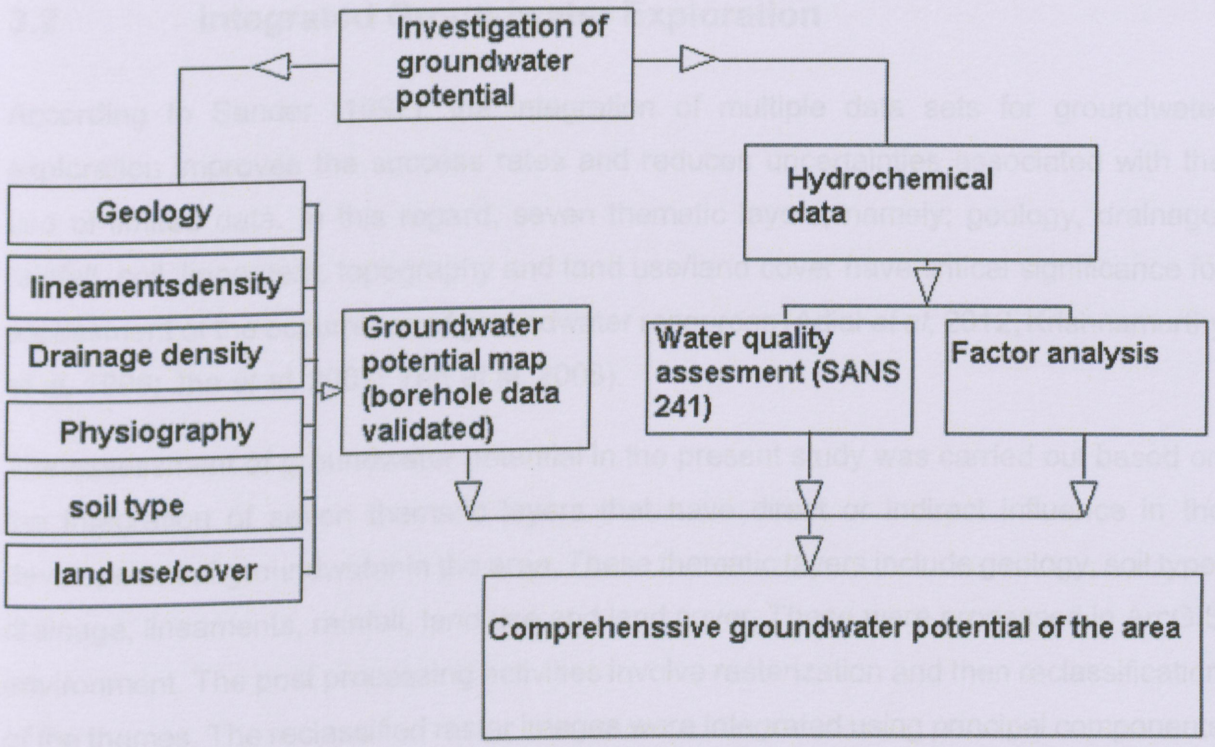

Figure 3. 1: Flowchart of generalized procedure used for assessment of groundwater potential in the area.

Step 2: The first thing to be conducted in step two was the creation of a workspace and a geodatabase in ArcGIS catalog to store the files. Immediately the thematic layers were obtained, they were georeferenced. In some special cases where the thematic layers were spatially extensive in relation to the study area, the data corresponding to the area was extracted. The processing aspect involves the incorporation of aforementioned auxiliary datasets to demarcate the different groundwater potential zones. Secondly, the secondary water quality data was obtained from the National Groundwater Archive. These data were used to investigate the groundwater quality in the area

Step 3: The third step involved fieldwork to gather additional data to supplement the secondary data. This includes the groundwater sampling from the existing boreholes that were having a supporting facility for sampling and the absence of casing for ease access. Both on-sight and laboratory analysis was conducted. The study was concluded with the writing of the thesis.

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3.2 Integrated Groundwater Exploration

According to Sander (1997), the integration of multiple data sets for groundwater exploration improves the success rates and reduces uncertainties associated with the use of limited data. In this regard, seven thematic layers, namely; geology, drainage, rainfall, soil, lineament, topography and land use/land cover have critical significance for assessment of the occurrence of groundwater resources (Adial *et al,* 2012, Krishnamurthy *et al,* 1996; Jha *et al*, 2007; Yeh *et al*, 2008).

The assessment of groundwater potential in the present study was carried out based on the integration of seven thematic layers that have direct or indirect influence in the development of groundwater in the area. These thematic layers include geology, soil type, drainage, lineaments, rainfall, land use and land cover. These were processed in ArcGIS environment. The post processing activities involve rasterization and then reclassification of the themes. The reclassified raster images were integrated using principal components analysis to delineate the groundwater potential.

3.2.1 Lithological data

According to Teixera *et al*, (2008), the lithology type and the thickness of weathered layer have significant influence in the development of groundwater aquifer. According to El-Baz *et al*, (1995), CFCFF (1996); Shaban *et al,* (2006), Jha *et al,* (2007); lithological domains, structural development, the intensity of weathering, and the thickness of the regolith enhances the groundwater development in the basement terrains.

The ArcGIS software was used to group the lithologies with similar hydrogeological parameters. The lithological layer was rasterized then reclassified into five ranks based on the hydrogeological attributes. According to van Dyk and Sadagavan (2006) and Neil (2001), the crystalline basement rocks in the study area are characterized by a lack of primary porosity; they exhibit poor storage and conductivity. The majority of the boreholes that were drilled in this geological terrain where either dry or low yielding (van Dyk and Sadagavan, 2006). In view of these hydrogeological parameters, the basement rocks

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comprising the Venterdorp Supergroup and Kraaipan Greenstone belt were assigned a rank of one.

According to Boocock and Van Straten (1962), in spite of the porous nature of the Kalahari, there is calcareous clay that crams the intergranular pore spaces of the Kalahari sediments that ultimately reduces the porosity and the conductivity of this formation. According to van Dyk and Sadagavan (2006), there is a considerable high rate of borehole failure within this rock unit. In view of these factors, the Kalahari Formation was allocated a ranking of two.

According to Keyser and Du Plessis (1993), the clastic sedimentary rocks of the Transvaal Supergroup comprise conglomerates and siltstone. These lithological units exhibit primary porosity which may be regarded as good groundwater aquifer. In this regard, the lithological units corresponding to this classification were assigned a rank of three.

The Ghaap dolomite aquifers comprise the most significant aquifers in the area (Bredenkamp, 1995). According to Barnard (2000), the highest borehole yields are located in chert-rich dolomites. In correspondence with this, the chert-poor and the chert-rich dolomites were assigned a rank of four and five respectively. The high borehole productivity is associated with the underground caves that are developed through karstifications (Kafri *et al,* 1986).

3.2.2 Lineaments data

According to Lattman and Parizek, (1964); Krishnamurthy *et al,* (1996) and Sander (1997), lineaments are one of the important factors that control the development of groundwater in crystalline basement rocks. Previous studies indicate the spatial correlation between lineament density correlate with high borehole yield (Yeh *et al,* 2008).

The lineaments were derived from the interpretation; of aeromagnetic data covering the study area. Lineament map was prepared from aeromagnetic imagery through on-screen manual digitization in ArcGIS. Manual digitization was preferred over automatic

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lineaments extraction, to ensure that only lineaments of tectonic significance are selected. The resultant structural map was transformed into lineaments density using line density tool in Spatial Analyst which is an add-on programme in ArcGIS. The following equation was used to calculate lineament density:

$$LD = \frac{\Sigma l_0}{A} \ldots\ldots\ldots\

3.2.4 Soil map

The soil has a significant influence on groundwater recharge as it determines the volume of infiltration and runoff. The physical parameters of the soil that control the hydrogeological attributes are, texture, grain size, packing, cracking, sorting, clay and silt content, mineralogical composition, and particle size distribution. The soil friability in unconsolidated sands promotes groundwater infiltration and recharge, which prompts the chances of intercepting water, such areas were assigned higher groundwater occurrences.

The soil type map was derived from the pedological atlas map. There are five generic soil types in the area; arenosols, plinthosols, cambisols, vertisols and liptosols were reclassified based on hydrogeological parameters into five classes.

The plinthosols has limited hydrogeological parameters to enhance groundwater development. The soil is characterized by high iron content, poor mixture of clay minerals and quartz granules. The iron, humus and clay, reduce the porosity that ultimately prohibits infiltration and percolation, which results in soil water retention that prohibits recharge. In view of all these, the plinthosols was assigned a rank of one.

The arenosols were assigned a rank of two, in view of the poor hydraulic parameters (conductivity and porosity). This soil type comprises the loamy-sandy particles. The coarse texture of the soil provides higher storage capacity at low suctions that decreases as suctions increase. The aerosols are highly permeable, but hydraulic conductivity is significantly variable.

The vertisols soil exhibit ideal physical properties that promote groundwater development. These attributes include strongly developed structures, cracking and swelling clays. The highly developed cracks in the surface extend downward, which provide pathways for groundwater recharge in rapid rates. The aquifers underlying the vertisols are constantly recharged during rainfalls. The moisture is reserved in mineral grains through the swelling property of the soil. Based on the hydrogeological attributes, the vetisols were assigned a rank of four.

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Leptosols is a group of soil that is classified under minimal pedological development. It is usually shallow occurring and overlays the crystalline basement and/or the weathered country rock which often comprises calcareous materials. They also comprise deeper soils that are extremely gravelly and stony. This soil group is characterized by poor water holding capability. However, it enhances groundwater development through intensive recharge. This soil type was assigned a rank of five.

3.2.5 Topographic map

According to Jha *et al,* (2007) and Yeh *et al,* (2008) the topographic setting relates to the local and regional relief and gives an idea about the general direction of groundwater flow and its influence on groundwater recharge. The steepness of the slope of topographic relief is one of the factors that determine the infiltration and recharge of the groundwater, consequently the nature of the slope alongside other geomorphic features can give an indication of the groundwater prospect of an area. In the gentle topographic relief, there is a minimal surface runoff, which consequently facilitates infiltration of rainwater. While high slope area enhances high runoff with short residence times for infiltration and recharge.

The topographical relief and physiography of the area control groundwater recharge. The areas with steep terrain correspond to the high rate of runoff while flat topographical reliefs and low-lying areas exhibit low runoff and rainwater have prolonged time to recharge the underlying aquifer. Such areas are of paramount importance for groundwater development (Solomon, 2003). Similarly, the topographic relief is a critical component for evaluation of groundwater table elevation (Sener *et al,* 2005).

The topographical relief map was prepared from the ASTER global Digital Elevation Model (DEM) with a spatial resolution of 30 m by 30 m. The DEM was rasterized and classified into five. The elevated and steep slope areas were assigned low ranks while low-lying areas are assigned high ranks.

The ranking was established in relation to the overall altitude that ranges between 1107 m to 1800 above mean sea level (a.m.s.l). The rank of five is allocated to gentle

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topographic relief in a low-lying area, the altitude corresponding to this class ranges between 1107 and 1198 m a.m.s.l. The rank of four is also a low-lying area with elevation ranging from 1198 to 1249 m. The moderate topographic relief has a rank of three, the altitude in this class ranges between 1249 m and 1288 m. The areas of high topographic relief are prominent towards the northern, eastern, and western escarpment with altitude exceeding 1800 m a.m.s.l.

3.2.6 Land use and land cover

Different land uses and land cover have a certain degree to either promote or prohibit the development of groundwater. Certain land uses have a significant influence on groundwater occurrences. These include agricultural crop production, irrigation, and human settlements. Cultivation directly increases the permeability of the underlying soil, which may increase the percentage of moisture in the soil leading to recharge of groundwater. In a similar scenario, crop production increases the permeability of the soil and reduces the surface retention of the water. For example, areas that are covered by forest commonly associate with high groundwater resources, though the type of trees determines the rate of recharge.

The land use map was reclassified into five groups based on the influence to groundwater occurrence. The dry bare land covers a significant portion of the northern part of the area which hampers groundwater development. It enhances runoff and transpiration, as such, it is assigned a rank of one. The grassland and the bushland, which are occurring adjacent to each other, ranked two and three, respectively in response to their effect on groundwater development. The areas assigned a rank of four is shown by semi-irrigated land and some wetland. The highest rank is assigned to the well-irrigated areas; these areas are occupying the southern margin that corresponds to the dolomitic rocks located in the southern part of the area.

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3.3 Integration of the Rasterized Thematic Layers

The groundwater potential was established based on the integration of the thematic layers. The principal component analysis was applied to seven layers to minimize the biases associated with the subjectivity of assigning the scores to each layer.

The reclassified thematic layers were overlaid using principal component analysis to avoid bias allocation of the weights on the involved thematic layers for the prediction of the groundwater potential. The principal component is thus given by the formula:

$$Z_{ij} = a_{i1}X_{ij} + a_{i2}X_{j2} + a_{i3}X_{j3} + \cdots \ldots \ldots \ldots \ldots a_{in}Z_{nj} \ldots \ldots (3.2)$$

Where, z is the component score, a is the component loading, x is the measured value of the thematic layer, i is thematic layer number, j is the sample number, and n is the total number of layers.

3.3.1 The significance of the parameters

There are uncertainties associated with a manual ranking of the themes as other layers are preferred over others. In order to overcome this, the Principal Component Analysis (PCA) was used to determine the weighting coefficient of the thematic layers. This was achieved through overlaying of reclassified thematic layers using PCA in ArcGIS spatial analyst. The following equation was used to overlay thematic layers to determine their weighting coefficient

$$WC\%_{tl} = \frac{\sum_i^6 ev_i}{\sum_j^6 . \sum_i^6 ev_i} * 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.3)$$

The weight allocated to a specific layer was a function of the Eigenvector of a particular theme divided by the sum of all Eigenvectors, where *evi* is the Eigenvalue of any of the seven thematic layers.

The resultant correlation table revealed the relationship between the loaded parameters concerning their influence to groundwater occurrence. The covariance matrix indicated

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how the rasters were interrelated. The Eigenvalues and Eigenvectors were derived from the covariance matrix. The former was used to outline the dimensionality of the spatial data while the latter was significant for the indication of how much the component was influencing the distribution of groundwater. The ratio of the sum of the Eigenvectors was used to assign the weighting of each classified rasterized thematic layer towards an explanation of groundwater potential in the area.

3.3.2 Establishing the groundwater potential map

The weighted sum functionality in the ArcGIS spatial analyst tool was used to establish the integrated groundwater potential map of the area using multi-datasets. Equation 3.3 illustrates how reclassified synoptic rasters were summed to yield the groundwater potential map of the area.

$$GWP(\%) = \sum_{6}^{n} \frac{\sum_{i}^{6} ev_i}{\sum_{j}^{6} \cdot \sum_{i}^{6} ev_i} * RTL \quad \text{.....(3.4)}$$

Where GWP is the groundwater potential of the area, which is given by the product of the weight of the thematic layer and the reclassified thematic layer (RTL).

3.4 Groundwater Quality Assessment

The evaluation of groundwater quality was conducted based on primary and auxiliary datasets. The pre-existing data was obtained from the National Groundwater Archive (NGWA) of the Department of Water Affairs. Figure 3.2 indicates the locations of the boreholes used in this study. The data comprises the major physicochemical parameters of water such as EC, TDS, TAL, pH, Cl^-, SO_4, F^-, NO_3, Na, Mg, Ca, and K.

In order to supplement the existing borehole data, samples were collected from 18 wells and streams that are currently supplying water in the study area. The rationale for boreholes selection for sampling was accessibility and the availability of the sampling support facilities, particularly boreholes with no construction.

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Prior to the collection of the water samples, water level measurements were taken using water level meter designed for borehole monitoring. The probe was inserted into the borehole, the metallic head of the instrument upon coming into contact with water makes a beeping sound, the depth units on the thread-tape holding the probe was recorded as the water level.

The water level measurements were followed by borehole purging. This was conducted to reduce the effect of stagnant water that might have undergone chemical transformations, which as a result would not reflect the chemical composition of groundwater in the aquifer. Manual purging was executed using the Teflon bailers tubes. These cylindrical tubes have an inlet valve at the bottom that opens when submerged in water to fill it up. The process was repeated multiple times until the suspended particles were entirely minimized.

The properly rinsed Teflon bailers were used to collect water samples from the boreholes. Water samples were transferred to properly numbered, well-rinsed airtight clean high-density polyethylene (HDPE) bottles. The bottles were rinsed with the same water prior to sampling. They were filled completely to the top for major ions analysis and capped tightly to avoid evaporation and exchange of sample water with atmospheric materials such as oxygen and CO_2. Two sample bottles, one each for cations and anions were required for sampling. The third bottle was used for sampling water for isotope analysis. The samples for the cations were filtered on site using 0.45 micrometer filter and acidified with concentrated nitric acid (HNO_3) to give a pH <2 that preserves the metals dissolved and prevent precipitation. Immediately after sampling, the bottles were stored in a cooler box (< 5°C) till the samples were being delivered to the laboratory. The physical parameters pH, EC, TDS, redox potential (Eh) and alkalinity were measured on site using an Aquaread GPS Aquameter 200 multi-parameter water quality meter. The measurements of the physical parameters of water are important to carry out on the site because they can easily be subjected to alter soon after sampling from the aquifer. The equipment was calibrated using three know standard solutions prior to measurement of the physical parameters.

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3.5 Laboratory Analysis of Water Samples

The water samples were analyzed at the Water Lab in Pretoria using inductively coupled plasma optical emission spectrometry (ICP-OES). The equipment used was a Perkin Elmer Optima 2100 DV ICP-OES spectrometer. The major anions composition (Cl^-, SO_4^{2-}, NO_3^-, and Cl^- were analyzed using a Thermo Scientific Aquakem 250 photometer analyzer. Fluoride (F^-) was analyzed using the ion selective electrode (ISE) methods with a Radiometer Analytical ION check 45 ion analyzer. The concentration of HCO_3^- anion was determined by titrating hydrochloric acid (HCl) with each sample.

The ISE is sometimes referred to as the specific ion electrode (SIE). This sensor translates the activity of a specific ion dissolved in a solution into an electrical potential. This potential is measured by either a voltmeter or a pH meter unit. According to Nernst equation, the electrical potential theoretically relies on the logarithmic of the ionic activity. The sensing part of the electrode is usually made os an ion-specific membrane, along with a reference electrode. The ion selective electrodes are mainly used for hydrochemistry, biochemical, and biophysical research, where the measurements of the ions are performed in aqueous solution and on a real-time basis.

Inductively coupled plasma atomic emission spectroscopy (ICP-AES) is sometimes referred to as the inductively coupled plasma optical emission spectrometry (ICP-OES). It is a very common technique for the assessment of the trace metals. This instrument relies on the inductively coupled plasma to excite atoms, which when excited emit electromagnetic radiation with waves that correspond to a specific element (Meyers, 2000). This technique is considered a flame based on the temperature of the flame that ranges between 6000 and 10 000 K (Meyers 2000), It is also referred to as the aqueous approach hence standard silicate dissolution methods are employed. The intensity of this emission is indicative of the concentration of the element within the sample (Meyers, 2000).

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3.5.1 Stable isotopes of hydrogen and oxygen

The stable isotopes ratio of $^{2}H/^{1}H$ and $^{18}O/^{16}O$ were analyzed at the iThema Labs in the Gauteng Province. The $^{18}O/^{16}O$ ratio was analyzed by equilibrating a small aliquot of water with CO_2 gas which is then introduced into an isotope ratio mass spectrometer (IRMS). The $^{2}H/^{1}H$ ratio was analyzed by equilibrating water with H_2 gas in the presence of a platinum catalyst. The analytical results were reported as $\delta^{2}H$ and $\delta^{18}O$ relative to Vienna Standard Mean Ocean Water (SMOW) as described by Gonfiniatini (1981) and Patermoster (2007). Los Gatos Research (LGR) Liquid Water Isotope Analyzer with the precision of 0.5‰ for oxygen and 1.5% of hydrogen was used for the analysis of the isotopes.

The analysis of stable isotopes of the water molecules involves water gasification of the water molecule. The laser spectroscopic technique measures the water molecule in real time without external sample preparation systems; hence, both the H and O are measured simultaneously and at a high time resolution (Han *et al.*, 2006).

According to Sturm and Knohl (2010), this instrument illuminates a laser through the light emitting diode, this ray was directed off-axis into an optical cavity, and the cavity is an absorption cell with reflective mirrors at both ends. This mirrors prolonged the beam path length into kilometres, this adjusted the laser beam and results in increased sensitivity. The mixing ratios of the isotopic species of oxygen and hydrogen are determined by the measured spectrum which is combined with the measured effective path length (determined by switching off and measure the time taken for the light to leave the cavity) Sturm and Knohl (2010). The measured gas temperatures and pressure in the cell and spectroscopic parameters from the high-resolution transmission molecular absorption database Sturm and Knohl (2010).

3.5.2 Analysis of tritium radiogenic

The samples were distilled and then enriched by electrolysis. The electrolysis cells consist of two concentric metal tubes, which are insulated from each other. The outer anode, which is also the container, is of stainless steel. The inner cathode is of mild steel with a

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special surface coating. Some 500 ml of the water samples, having first been distilled and containing sodium hydroxide, is introduced into the cell. A direct current of some 10–20 amperes is then passed through the cell, which is cooled because of the heat generated. After several days, the electrolyte volume is reduced to some 20 ml. The volume reduction of some 25 times produces a corresponding tritium enrichment factor of about 20. Samples of standard known tritium concentration (spikes) are run in one cell of each batch to check on the enrichment attained.

For liquid scintillation, counting samples are prepared by directly distilling the enriched water sample from the now highly concentrated electrolyte. Ten ml of the distilled water sample was mixed with 11 ml ultima gold, placed in a vial in the analyzer, and counted 2 to 3 cycles of 4 hours. Detection Limits is 0.2 tritium unit (Tu).

3.6. Data Accuracy Checking

The groundwater quality data often contain errors as the results of mishandling and contamination of water samples at any stage of data generation. The post-analysis errors are usually generated during data capturing. Therefore, data accuracy check was conducted to eradicate such errors and mistakes in two successive phases.

The initial phase of data editing comprised of visual inspection of the datasets. During this phase, all erratic values that are mostly the results of data capturing were manually excluded from the data set for post processing. This was comprehended by basic descriptive statistical analysis, which was equally meant for outlining erratic physiochemical values.

The second phase of data editing was performed in accordance with the standard requirement for water quality assessment, which was proposed by Freeze and Cherry (1979). The principle behind this approach states that, in a large-scale electrolytic solution, the sum of anions should be equal to the sum of the cations. In aligning to this principle, Rockworks software was used to assess charge balance error% (CBE). The Equation 3.5 illustrates how CBE was computed, the threshold of 15% CBE was considered for the assessment of the groundwater quality. Since monitoring was

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conducted and recorded in mg/l, the monitoring data were converted to meq/l prior to CBE using rockworks software.

$$CBE\% = \left(\frac{\sum z.m_c - \sum z.m_a}{\sum z.m_c + \sum z.m_a}\right) * 100 \quad \text{.....(3.5)}$$

Where c is the total cation in milliequivalents per litre (meq/L) and a, is the total anions (meq/L).

3.7 Data Presentation

The rationale behind the selected mode of data presentation was suitability, simplicity in reading and interpretation. The descriptive statistical graphs were often found to be highly literate. The graphical presentation of the physiochemical data was also plotted to interpret the groundwater quality, these primarily consisted of piper and durov diagrams for the major three aquifer types in the area. The gridded hydrochemical data were also produced to illustrate the spatial distribution of selected parameters.

3.7.1 Descriptive statistical analysis

The water quality data that have been screened and edited to comply with CBE was divided into four groups based on the underlying geology. The descriptive statistical analysis of the hydrochemical data comprising the maximum value, the minimum, mean, standard deviation, the coefficient of correlation (R) were conducted using JMP statistical package The statistical assessment was conducted to gain a broader spectrum of the distribution of various populations of the chemical data.

3.7.2 Graphical presentation

Piper (1940), proposed an approach for presenting water quality in terms of dominant ions. The chemical components (major ions) such as Ca, Mg, Na, K, HCO_3, CO_3, SO_4, and Cl were imported to Rockworks software to produce the piper diagram. The design of this diagram consists of the triangles that indicate the level of anions on the right and

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cations on the left. A diamond-like quad is projected from the two triangles to indicate an overall chemistry of groundwater as well as different water types. The Piper Diagram also conveniently reveals similarities and differences among groundwater samples. Those samples with similar qualities will tend to plot together as groups (Todd and Mays, 2005).

3.7.3 Interpolated physical parameters

One of the most common approaches for presenting groundwater quality data is an interpolation technique of the water quality parameters. The advantage of this mode of presentation relies upon simplicity to interpret. This mode of data presentation yields an unparalleled advantage with the issuing of patterns and a spatial trend that would have otherwise been unrevealed. In this regard, the following critical components of water quality, TDS, EC, TAL, NO_3, F, TH, and SAR were interpolated using IDW gridding approach.

The WGS84 coordinate system the data were retrieved in was converted into UTM (35). The Inverse Distance Weighting (IDW) spatial interpolation technique opted in order to maximize the spatial variability in spatial trends. This process was conducted in Oasis Montaj 7.5. The grid cell size of 600 m was used to ensure the gridded image cover the entire study area. The outcomes of these processes were the production of the maps indication the spatial distribution of the physiochemical parameters. The following IDW equation was used for interpolation of the values.

$$V = \{\sum_{i=1}^{n} \frac{1}{d_1} v_1)/(\sum_{i=1}^{n} \frac{1}{\cdot d^p{}_1})\} \quad (3.6)$$

Where v is the estimated value, v_i is the known value, $d^p{}_i \ldots d^p{}_n$ is the distance from then points to the power of p of the point estimated

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3.8 Factor Analysis

Factor analysis is an informative statistical approach that is used to study the dimensionality of a set of variables and deduce their association. In factor analysis, latent variables represent unobserved constructs and are referred to as factors or dimensions. Factor analysis attempts to explain the correlations between the observations in terms of the underlying factors, which are not directly observable nor measurable (Yu *et al.*, 2003). Factor analysis was used to investigate the control of groundwater quality. The suitability of the physiochemical data for factor analysis was evaluated using a significance test in the JMP statistical package. R-mode factor analysis was used to extract principal components governing the hydrochemistry. The components with Eigenvalues exceeding one were outlined as the response of water chemistry to the factors controlling the water composition while the number of factors generated indicating the possible sources of variation.

The first step in factor analysis (FA) was the standardization of the raw data. This procedure is vital for water quality study since the measurements of the physicochemical parameters are recorded in different units of measurement. Therefore, to minimize the influence of a certain parameter, the standardization is carried out. The following standardization equation was used:

$$Z_{ij} = \frac{(X_{i.j} - x_m)}{S_i} \quad \ldots\ldots\ldots\

The following equation was used to determine the coefficients of correlation amongst any pair of the physicochemical parameters:

$$r_{x.y} = \{\frac{[\Sigma(x-x_m)(y-y_m)]}{\{[(\Sigma x-x_m)]^2 * [\Sigma\Sigma(y-y_m)]^2\}^{1/2}}\} \quad \text{.....(3.8)}$$

The coefficient of correlation $r_{x.y}$ are the sum of chemical species over all samples of the same physicochemical species of the deviations of the x measurements and the y measurements of each sample from the mean value of x and y respectively for the complete set of samples (Liu *et al.*, 2003). The factors were ranked in order of their merit, where the first factor has the highest Eigenvector and is responsible for maximum variation in the data set. Similarly, the last factor contributes less to the compositional variation of the.

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CHAPTER 4

RESULTS AND DISCUSSION

The groundwater potential was evaluated based on a set of the primary and auxiliary data sets. The following chapter focuses of the interpretation of the reclassified thematic layers and their weighted overlay to produce the groundwater potential map. The spatial map of the physicochemical parameters was also interpreted and the factor analysis and isotopic data of water molecule.

4.1 Interpretation of the Reclassified Thematic Layers

The characterization of the groundwater potential was established based on the integration of the multi-datasets. The significant parameters examining the groundwater potential comprise the geology, lineaments, soil type, drainage cover, topography, rainfall, and land use and land cover (LU/LC) that were rasterized and then reclassified into five ranks based on the physical parameters that influence the recharge and development of the groundwater resource in the area.

4.1.1 Interpretation of lithological map

Different lithological domains exhibit variable hydrogeological attributes in relation to their formational environment. The influence of the lithological units on the development of the groundwater was assessed based on the hydrogeological attributes that influence the flow and the storage of water in a rock unit (primary porosity and transmissivity). Figure 4.1 shows the spatial distribution of the different lithologies and their ranking in the study area. The ranking sequence from one to five successively corresponds to the crystalline basement, Kalahari formation, Karoo sediments, chert-poor dolomite, and the chert-rich dolomite respectively.

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The lithological rank of one represents the lowest groundwater potential, which covers the central part of the area and consists of crystalline basement rocks of the Ventersdorp Supergroup and the Kraaipan greenstone belt. The rock units in this category lack primary porosity.

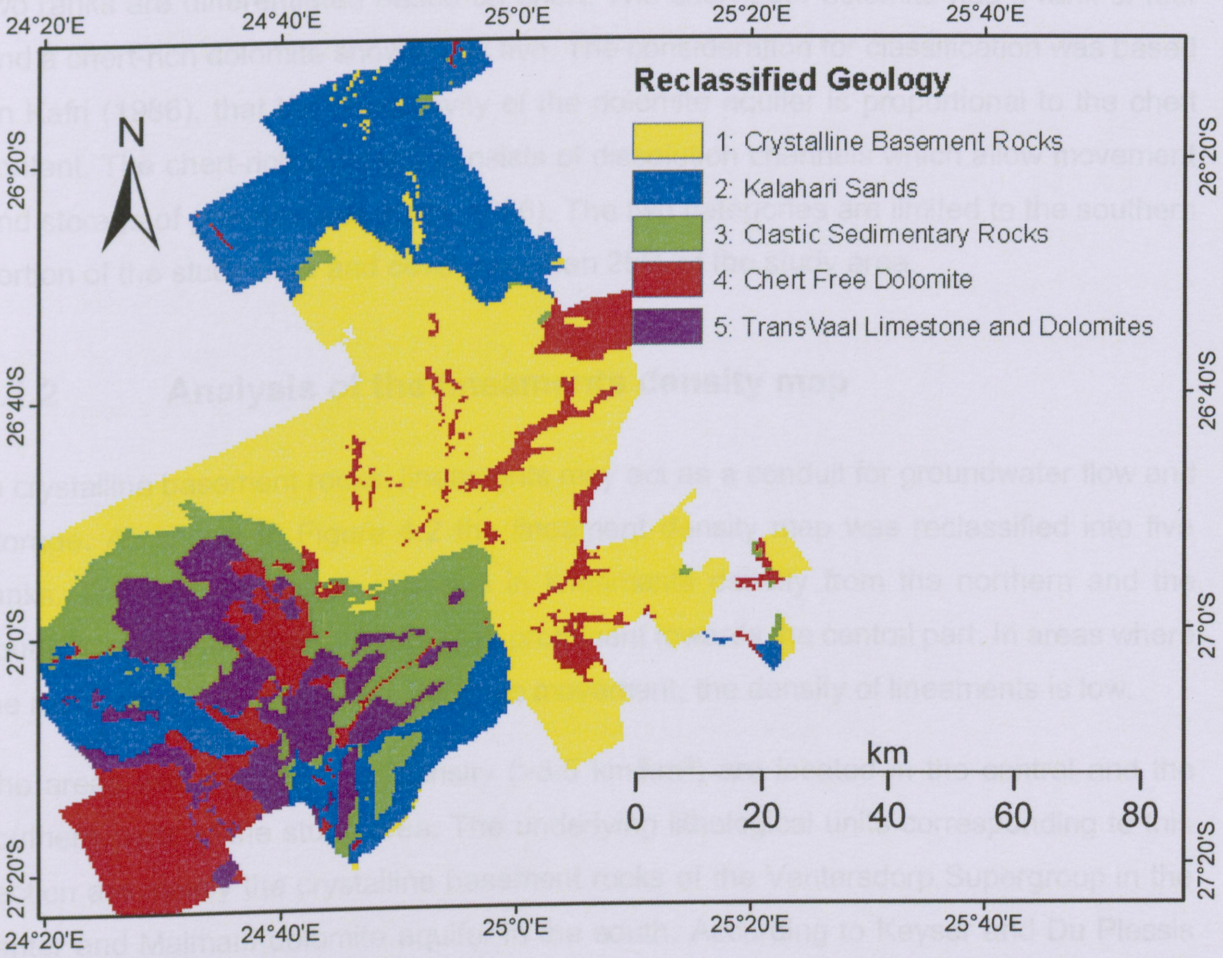

Figure 4. 1: Interpretation of the Lithological map.

Rank two corresponds to the Kalahari Formation. It covers the northern part of the area with outliers in the central and the south part. This formation encompasses 23% of the entire surface extent. According to Boocock and van Straten (1962), the aeolian sands and basal gravels in this geological terrain are crammed by the calcareous clay, which ultimately eliminate the pore spaces that consequently reduce the porosity.

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The clastic sedimentary rocks of the Transvaal Supergroup have a rank of three. The rocks composing this category are located in the southern part of the study area. The lithological units consist of conglomerates, siltstone, and sandstones.

The Malmani dolomite comprises rank four and five. The dolomites corresponding to the two ranks are differentiated based on chert. The chert-poor dolomite has a rank of four and a chert-rich dolomite shows rank five. The consideration for classification was based on Kafri (1986), that the productivity of the dolomite aquifer is proportional to the chert content. The chert-rich dolomite consists of dissolution channels which allow movement and storage of groundwater (Kafri, 1986). The two categories are limited to the southern portion of the study area and cover less than 25% of the study area.

4.1.2 Analysis of the lineaments density map

In crystalline basement rocks, lineaments may act as a conduit for groundwater flow and storage. As shown in Figure 4.2 the lineament density map was reclassified into five ranks. The map shows an increase in lineaments density from the northern and the southern edges and the structures are prominent towards the central part. In areas where the rocks were less affected by tectonic movement, the density of lineaments is low.

The areas with high fracture density (>3.5 km/km^2) are located in the central and the southern parts of the study area. The underlying lithological units corresponding to this section are mainly the crystalline basement rocks of the Ventersdorp Supergroup in the center and Malmani dolomite aquifer in the south. According to Keyser and Du Plessis (1993), the fracture zones are the results of multiple episodes of tectonic events that resulted in the formation of crosscutting structures. Whereas, the high lineaments density in Malmani could be interpreted in terms of the underground opening that are left as the results of dolomitic dissolution.

The lineaments density corresponding to rank four varies from 3.0 to 3.5 km/km^2. The lineaments in this class are prominent in the central part of the area which is striking in the northeast-southwest direction. There are patches of similar patterns of lineaments in the northern part of the area.

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The area shown by rank one is characterized by lineaments density of <0.5 km/km^2, and it is situated in the northern part of Stella town. The underlying rocks consist of the Kalahari Group. The area that is shown as moderate structural density (1.5-2.5 km/km^2) covers a large area extending from the north to the south.

4.1.3 Reclassified soil types map

The soil is one of the most significant factors that control groundwater recharge. In spite of the hydrogeological attributes of the rocks (porosity, transmissivity and the permeability of the underlying rocks), if the residual soil restricts groundwater recharge, the development of the groundwater resource is less likely to occur. The map in Figure 4.3 illustrates the ranking assigned to the different soil types based on their influence on groundwater development.

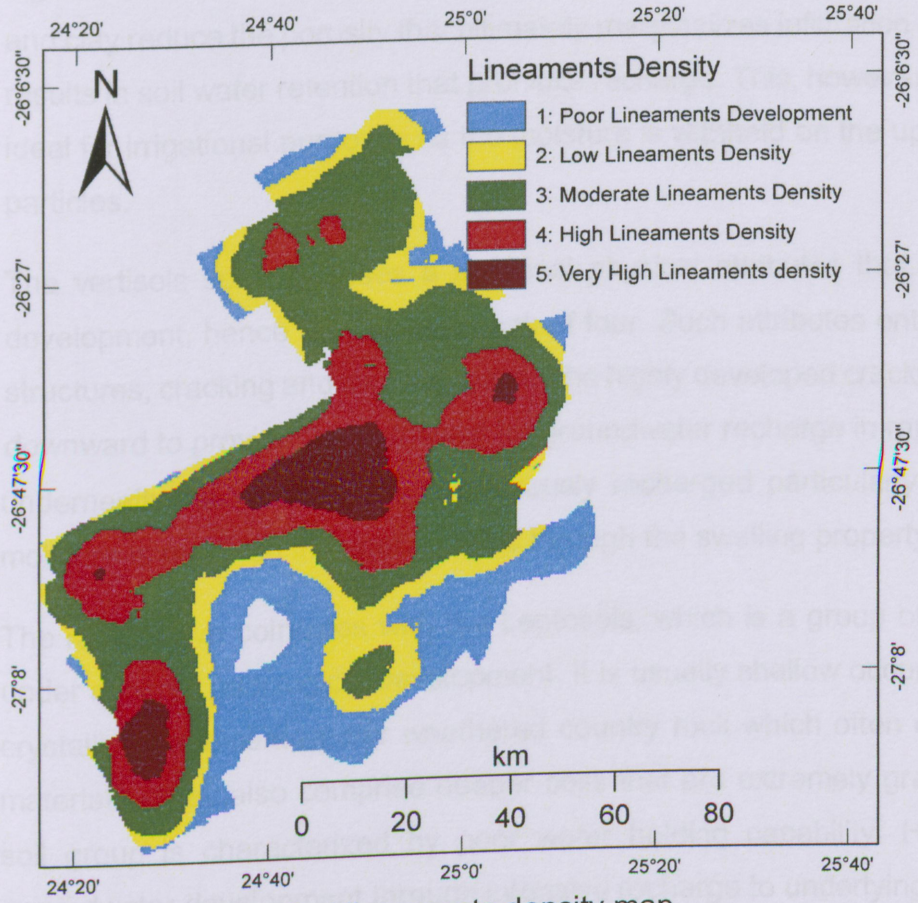

Figure 4. 2: Reclassified lineaments density map.

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The northern portion is covered with the arenosols that have a rank two. The surface cover comprising this rank corresponds to the Kalahari Formation. The rank value assigned corresponds with the poor hydraulic parameters (conductivity and porosity) of this soil. The loamy-sandy particles and some coarse fragments comprise this rank. According to Boocock and Van Straten (1962), the pore spaces of the Aeolian sands are often blocked with calcareous clay and the storage within the coarse fragments is inversely proportional to the suctions. These factors reduce the rate of infiltration in this soil. The aerosols are highly permeable, but hydraulic conductivity and storativity are significantly variable (Schulze, 1984).

The ranks of one and two are located adjacent to each other and are restricted to the northern segment of the area. These two ranks share a common boundary. The influence of rank two in groundwater development is minimal because the soil is characterized by high iron content, poor mixture of clay minerals and quartz granules. The iron, humus, and clay reduce the porosity that ultimately marginalizes infiltration and percolation, which results in soil water retention that prohibits recharge. This, however, renders this soil type ideal for irrigational purposes as the moisture is withheld on the upper surface of the soil particles.

The vertisols soil expresses a set ideal physical attributes that promote groundwater development, hence they show a rank of four. Such attributes entail strongly developed structures, cracking and swelling clays. The highly developed cracks in the surface extend downward to provide the pathways for groundwater recharge in rapid rates. The aquifers underneath the vertisols are continuously recharged particularly during rainfalls. The moisture is reserved in mineral grains through the swelling property of the soil.

The rank of five coincides with the Leptosols, which is a group of soil that is classified under minimal pedological development. It is usually shallow occurring and overlays the crystalline basement and/or weathered country rock which often comprises calcareous materials. They also comprise deeper soils that are extremely gravelly and stony. This soil group is characterized by poor water holding capability. However, it enhances groundwater development through intensive recharge to underlying aquifers.

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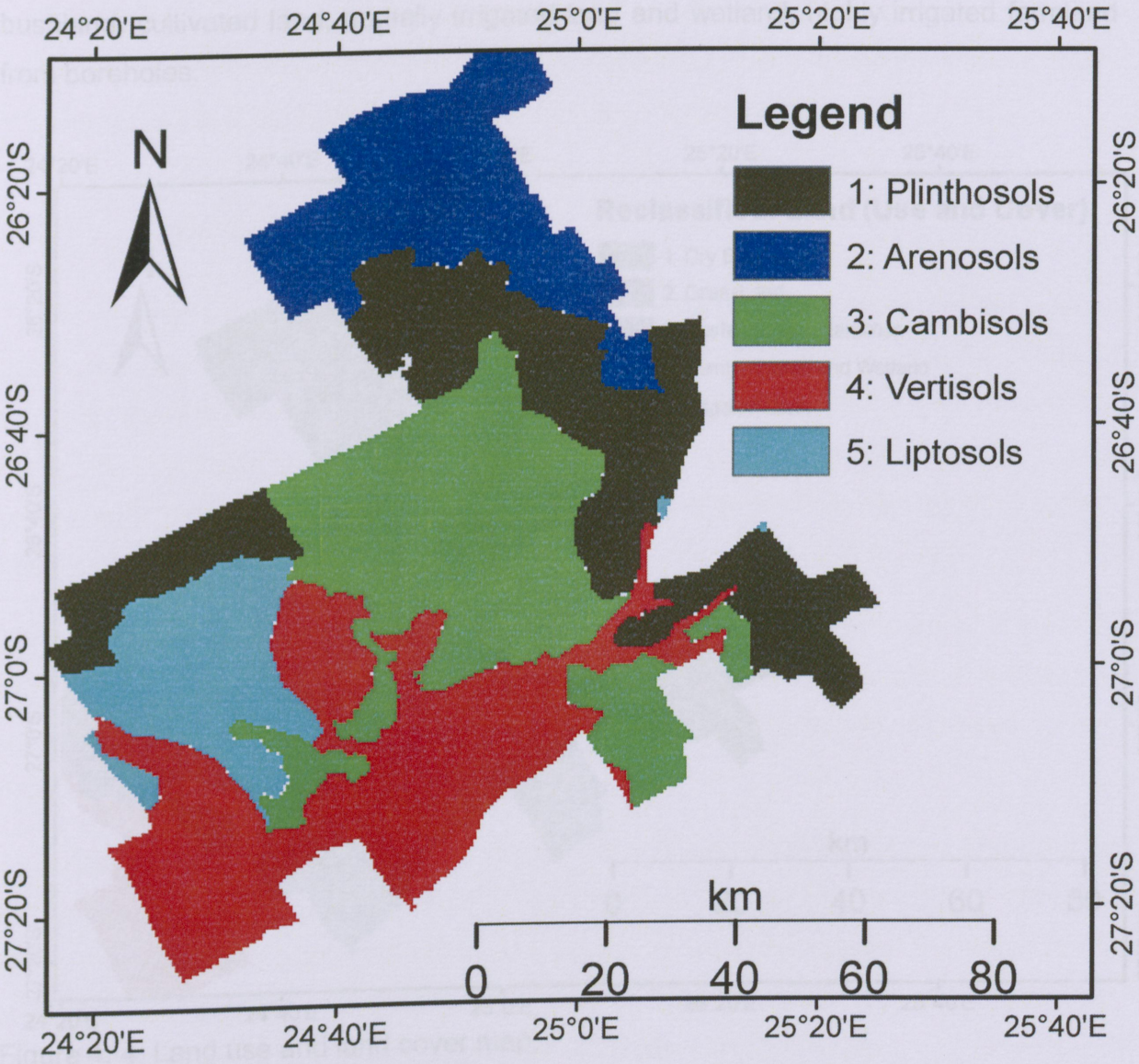

Figure 4. 3: Reclassified soil type map.

4.1.4 Land use and land cover map

The different land uses and land cover (LU/LC) have a diverse influence towards groundwater development. The logical assessment of the LC/LC was the key to the systematic allocation of the ranks. Consequently, the LU/LC map was reclassified into five groups based on the influence of each factor on groundwater occurrence. Figure 4.4 shows the existing land practices and their respective ranks. The proposed ranking classifies the existing land use into the following groups: bare land, grassland, and

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bushland, cultivated land, partially irrigated land and wetland, highly irrigated farmland from boreholes.

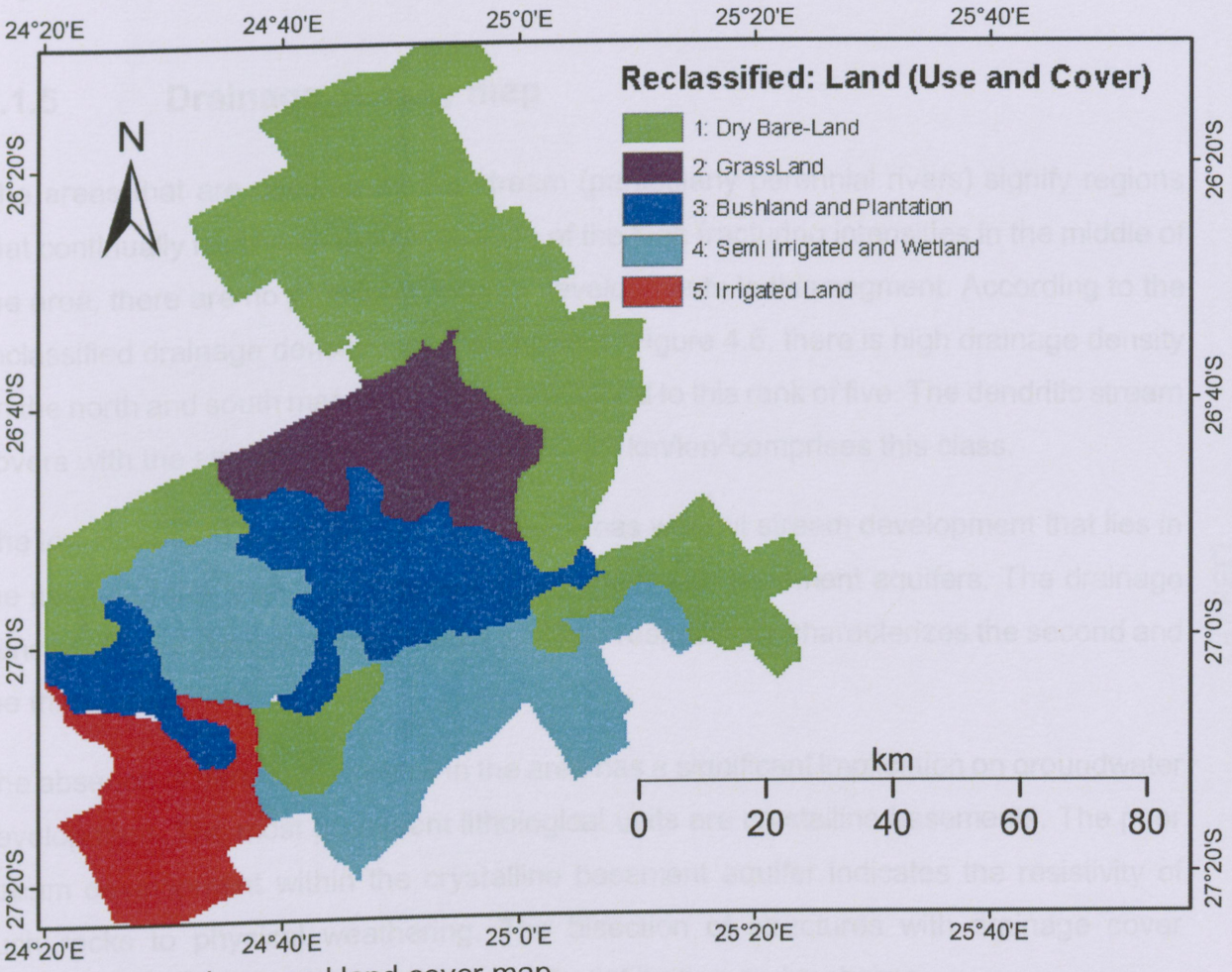

Figure 4. 4: Land use and land cover map.

The physiography in the study area depicts that of a typical arid to the semiarid environment. The significant portion of the study area, which comprise the entire northern region, the eastern, and western flanks are completely dry bare land. A rank of one corresponding to this area indicates that the area is most likely dry, and if by any chance there is water is should be occurring at considerably high depth. The bare land is also believed to limit groundwater occurrence, as it influences runoff and direct transpiration.

Rank two and three have a moderate connotation with groundwater occurrence, as they comprise the grassland, and the bushland respectively. The two ranks occupy the middle

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section of the area. The marginal irrigation and low-density forests denote the rank of four. The rank of five is characterized by the presence of pans, wetlands and the highly irrigated areas that are occurring in the south along the dolomitic rocks.

4.1.5 Drainage density map

The areas that are covered by the stream (particularly perennial rivers) signify regions that continually receive recharge. In spite of the high fracturing intensities in the middle of the area, there are no prominent stream developments in this segment. According to the reclassified drainage density map, as shown in Figure 4.5, there is high drainage density on the north and south margins, which correspond to this rank of five. The dendritic stream covers with the stream density in excess of 4.0 km/km^{2}comprises this class.

The low ranking of one corresponds to the areas without stream development that lies in the middle of the area. Such areas are underlain with basement aquifers. The drainage density of 1.0-2.0 km /km^2 and 2.0-3.1 km /km^2 respectively characterizes the second and the third ranks.

The absence of perennial streams in the area has a significant implication on groundwater development. The most prominent lithological units are crystalline basements. The poor stream development within the crystalline basement aquifer indicates the resistivity of such rocks to physical weathering. The bisection of structures with drainage cover provides improved estimates of groundwater infiltration and recharge.

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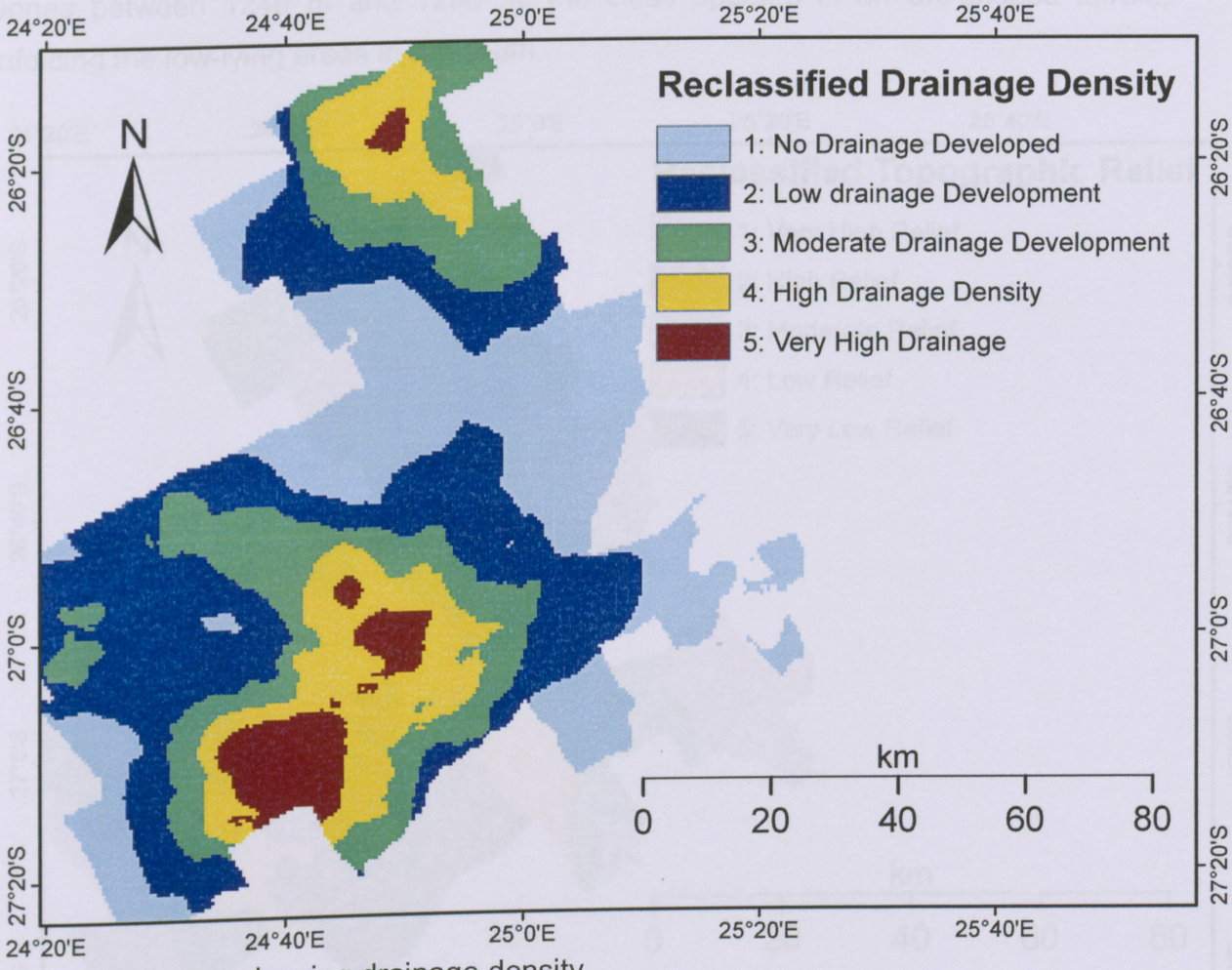

Figure 4. 5: A map showing drainage density.

4.1.6 Topographic relief map

The reclassified raster of the topographic relief is shown in Figure 4.6. In spite of the categorization of the elevation into five rankings, the physiographical setting is predominantly categorized by the gentle landscapes. The ranking was established in relation to the overall altitude that ranges between 1107 and 1800 m above mean sea level (A.M.S.L). The rank of five aligns with the gentle topographic relief in a low-lying area, the altitude corresponding to this class ranges between 1107 and 1198 m (A.M.S.L). The area is also characterized by the high rank of drainage density. Rank four consists of a low-lying area with minor undulations, the elevation in this part ranges between 1198-1249 m. The moderate topographic relief has a rank of three, the altitude in this class

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ranges between 1249 m and 1288 m, the class appears in an arc-shaped terrain, enfolding the low-lying areas in the south.

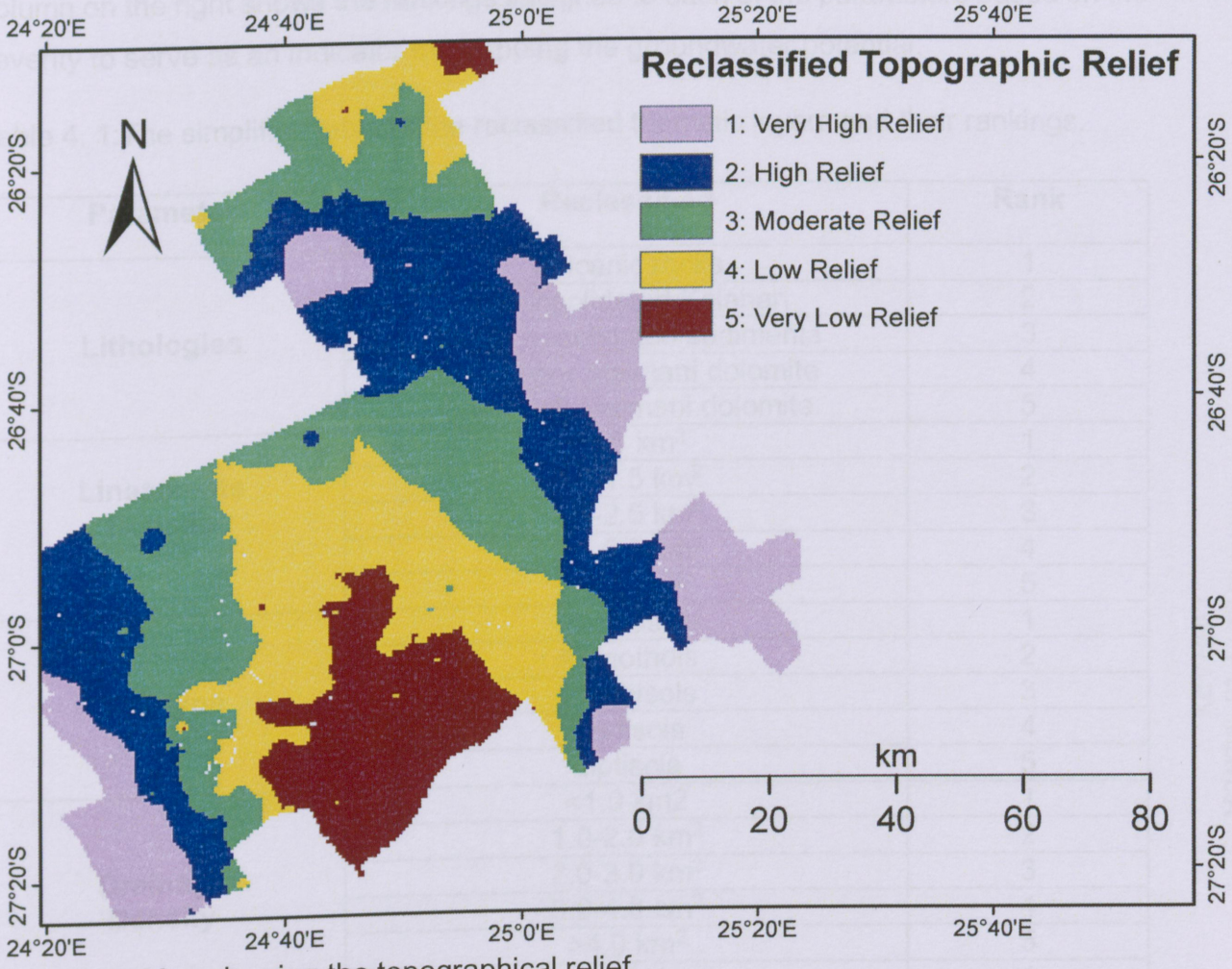

Figure 4. 6: Map showing the topographical relief.

The areas of high topographic relief are prominent towards the northern, eastern, and western escarpment. The topographic relief in this area surpasses 1800 m. The rank matching with this terrain is one. The locations adjacent to the rank of one are considerably high relief areas with a rank of two. The ranks four and five comprise the low-lying areas; rationally, water flows from high topographic relief to low-lying areas. The logical comprehension that groundwater development favors flat terrains is rational. Such areas are characterized by high drainage density, which also enhances groundwater development.

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Table 4.1 illustrates the simplification of the seven reclassified thematic layers that were considered significant for the control of groundwater resource in the study area. The column on the right shows the rankings assigned to each of the parameters based on the severity to serve as an indicator for mapping the groundwater potential.

Table 4. 1:The simplified table of the reclassified thematic layers and their rankings.

Parameter	Reclassified	Rank
Lithologies	Volcanic rocks	1
	Unconsolidated Kalahari	2
	Semi-consolidated sediments	3
	Chert-poor Malmani dolomite	4
	Chert-rich Malmani dolomite	5
Lineaments Density	<0.5 km^2	1
	0.5-1.5 km^2	2
	1.5-2.5 km^2	3
	2.5-3.5 km^2	4
	>3.5 km^2	5
Soil type	Plinthosols	1
	Arenothols	2
	Cambisols	3
	Vertisols	4
	Liptisols	5
Drainage Density	<1.0 km2	1
	1.0-2.0 km^2	2
	2.0-3.0 km^2	3
	3.0-4.0 km^2	4
	>4.0 km^2	5
Land Use/Cover	Bare Dryland	1
	Grassland	2
	Grass and Bushland	3
	Agricultural-Semi irrigation	4
	Borehole Irrigation	5
Topography	>1800 m	1
	1288-1800 m	2
	1249-1288 m	3
	1198-1249 m	4
	1107-1190 m	5

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4.2 Principal Component Analysis

Principal Component Analysis (PCA) is a dimension reduction technique that was invented in 1901 by Karl Pearson. It was developed as a useful approach for summarizing a set of factors which interprets a large number of variables. The factors are linear combinations of the original variables. The approach can handle only quantitative variables. The principal component analysis was applied to 6 thematic layers that include geology, soil cover, lineaments, land use, drainage density, and elevation to assess the relative importance of each in controlling the occurrence of groundwater in the area. The Eigenvectors derived from the covariance matrix of the principal components are shown in Table 4.2.

Table 4.2: Eigenvectors derived from the covariance matrix of the principal components.

Parameters	PC1	PC2	PC3	PC4	PC5	PC6
Linear	-0.20557	0.38363	0.82036	0.02136	0.36872	-0.03422
LU/LC	0.59508	0.39451	-0.25091	-0.41878	0.49807	-0.06185
Drainage	0.29777	-0.53965	0.16417	0.20966	0.40752	0.61897
Geology	0.46159	0.18105	0.01720	0.80864	-0.04519	-0.31293
Elevation	-0.28306	0.58283	-0.33447	0.28077	0.02157	0.62372
Soil	0.47092	0.18302	0.35346	-0.2179	-0.66887	0.35346

According to Table 4.2, PC1 is dominated by the high loading of LU/LC, soil, and the rock units. Elevation and drainage dominate PC2 with the Eigenvectors of 0.58283 and -0.53965 respectively. The lineaments and the lithologies have a high Eigenvector of 0.82036 and 0.80864 in PC3 and PC4 successively. PC5 is characterized by the significant loadings of LU/LC, drainage cover, and soil. The drainage and elevation have similar Eigenvectors of -0.61897 and 0.62372.

The Eigenvectors shown in Table 4.2 illustrates that, each of the six principal components is characterized by a unique set of loadings that correspond to different parameters. This explains that, each of the signatures of the principal component is dominated by different

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parameters. The high Eigenvectors in each of the six principal components are contributed to different factors. This outlines that the groundwater control in the area is not a factor of a single parameter but the integration of different factors.

Table 4.3 shows the correlation matrix of the groundwater controlling parameters. This matrix indicates the significance of the coefficient of correlation between any pair of the groundwater controlling factors, how strong is the association between two factors. This table is imperative for data integration and interpretation of the groundwater potential.

Table 4. 3: The correlation matrix of the groundwater potential parameters.

CORRELATION MATRIX						
Parameters	**Linear**	**LU/LC**	**Drainage**	**Geology**	**Elevation**	**Soil**
Linear	1	-0.24701	-0.28836	-0.17193	0.21506	-0.04069
LU/LC	-0.24701	1	0.21788	0.53498	-0.18947	0.60828
Drainage	-0.28836	0.21788	1	0.35606	-0.63683	0.28831
Geology	-0.17193	0.53498	0.35606	1	-0.17426	0.52985
Elevation	0.21506	-0.18947	-0.63683	-0.17426	1	-0.37186
Soil	-0.04069	0.60828	0.28831	0.52985	-0.37186	1

The correlation matrix in Table 4.3 shows the structures do not have a significant correlation with other parameters. The lineaments density is prominent in the middle of the study area, that is underlain by the volcanic lava of Allanridge Formation. According to Figure 4.2, the lineaments density in this particular area corresponds to rank five and no other parameter shows a significant ranking in this region to warrant improved groundwater potential. It is on this basis that the structures illuminate poor coefficient of correlation with all other factors.

The LU/LC shows moderate significance coefficient of correlation with the lithological units (r=0.53) and the soil type (r=0.60). The basis for this correlation could be interpreted in terms of the association of the two parameters. Generally, land-uses are allocated based on the soil type, and soil is derived from rocks, hence the two have similarity in spatial coverage. Drainage cover correlate with the elevation (r=0.63). The maximum

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drainage density is located in the south where the topographic relief is low, and streams flow from higher altitude to low level.

4.3 Integration of the Thematic Layers

The previous section outlined that the groundwater potential in the area may be interpreted based on the integration of the thematic layers. However, the relative importance of each parameter was not defined. Prior to the incorporation of the thematic layers to establish the groundwater potential map, the weights of the parameters were derived from the sum of Eigenvectors corresponding to a single parameter in the 6 principal components, ratio of the total sum of Eigenvectors was then used to compute the weights. The ratios of the weights of the parameters are shown in Table 4.4.

Table 4. 4: The weight assigned to each reclassified thematic layer.

Lineaments	LU/LC	Drainage	Geology	Topography	Soil
23.57%	13.16%	20.16%	19.33%	15.52%	8.25%

According to Table 4.4, the parameters with high weight are the lineaments, drainage, and the geological setting. These parameters individually contribute 23.57%, 20.16%, and 19.33% respectively. This suggests that the principal parameters controlling the groundwater potential are the lineaments, drainage, and the geology which collectively account for 63% of the overall groundwater potential. The significance of the lineaments has been globally recognized, particularly in the basement aquifer (Krishnamurthy *et al,* 1996; Sener *et al,* 2005; Sander, 2007).

The present results support the outcomes of some of the key groundwater studies that outlined the significance of lineaments. Such studies include Lattman and Parizek, 1964; Krishnamurthy *et al,* 1996; Sener *et al,* 2005; Sander, 2007. The general conclusion in those investigations is that the groundwater resource in basement rocks correlate with the proximity to the structures.

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The weights established through PCA (in Table 4.4) show the significance of the lineaments as the prime groundwater potential indicator. These results conform to the classical concept of the basement aquifer that outlines, 'the occurrence of water resource in the hard-rock terrain correlate with the structures and displacements on the rock units' (lineaments) (Detay *et al,* 1989).

Although Table 4.4 illustrates relative supremacy of lineaments as a groundwater potential indicator, it does not comprise a significant portion of the total weight. This implies that the groundwater potential in the area is not merely dependent to the lineaments, hence the spatial distribution of the structures is restricted to the center of the study area. In fact, the groundwater potential can proficiently be demarcated based on the integration of a set of spatial parameters. According to Rao and Jugran (2003), the delineation of the groundwater potential based on one parameter is more likely to fail, and the integrated groundwater exploration approach helps to increase the accuracy of results and reduce the subjectivity towards a particular theme.

4.3.1 The groundwater potential map of the study area

The integrated groundwater potential map was developed based on the incorporation of the weighted-reclassified thematic layers. The map in Figure 4.7 illustrates the prospective areas are categorized into three classes, namely; the low groundwater potential (LGWP), moderate groundwater potential (MGWP), and high groundwater potential (HGWP). Table 4.5 indicates the three groundwater potential categories and their respective areal extent in percentage.

According to the map in Figure 4.7, the groundwater potential classes significantly correspond to the underlying lithological domains. The low groundwater potential conforms to the crystalline basement aquifer, the Kalahari sediments and the clastic sediments of the Transvaal Supergroup correspond to the moderate groundwater potential and the high groundwater potential correlate with the Malmani dolomite aquifer.

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Table 4.5: Groundwater potential classes and relative coverage in percentage.

Groundwater Potential Category	Areal coverage in (%)
Low groundwater potential (LGWP)	43.30%
Moderate groundwater potential (MGWP)	40.09%
High groundwater potential (HGWP)	16.61%

The LGWP comprises 43.30% of the entire surface. It is prominent in the epicenter of the study area. This class corresponds to the volcanic lava of the Allanridge Formation. According to Sadagawan and van Dyk (2011), the lithologies comprising this water potential class lack primary porosity for storing and transmitting water resource at a significant level (van Dyk and Sadagavan, 2006).

The lithologies within the LGWP class are resistive to physical weathering. This category is characterized by the absence of prominent stream development, bare land with minimal vegetation cover and inclined topographic relief. According to Keyser and Du Plessis (1993), the Ventersdorp Supergroup comprises of some of the oldest lithologies in the area. Consequently, they have developed different sets of joints and fractures in response to the eventual recurring tectonic events. In this regard, the only logical mode of porosity is provided by the structures. Figure 4.2 indicates the lineaments density is excessive within the Allanridge Formation.

Nevertheless, there are patches of the MGWP within the LGWP that are striking in the southwest-northeast direction that bulges within the crystalline basement rocks along the epicenter of the study area, which is along the lineaments orientation. According to Sami (2009), the productive boreholes have close proximity with the lineaments that are striking in that particular direction. The recurring transition of the two prospective classes may be interpreted based on Holland and Withüser, (2011) who states that a basement aquifer is a heterogeneous unit, where the hydraulic conductivity varies over a short distance.

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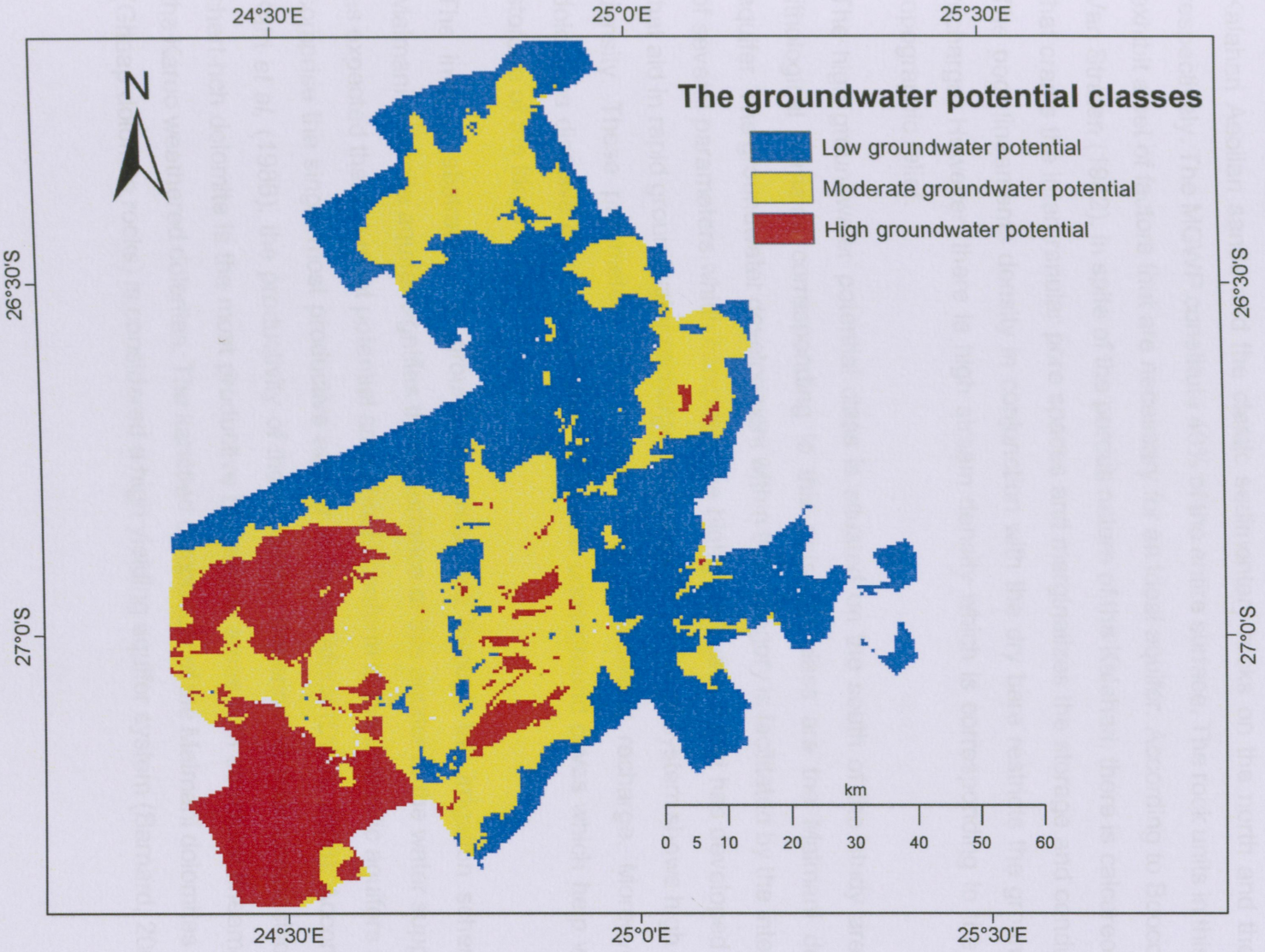

Figure 4. 7: Groundwater potential map of the area.

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The moderate groundwater potential is situated in the north and the south of the study area. The geological domains corresponding with this groundwater potential area are the Kalahari Aeolian sands and the clastic sedimentary rocks on the north and the south respectively. The MGWP constitute 40% of the entire surface. The rock units in this group exhibit a set of factors that are necessary for an ideal aquifer. According to Boocock and Van Straten (1962), in spite of the porous nature of the Kalahari, there is calcareous clay that crams the intergranular pore spaces and marginalizes the storage and conductivity. The poor lineaments density in conjunction with the dry bare restricts the groundwater recharge. However, there is high stream density which is corresponding to the gentle topographic relief.

The high groundwater potential class is situated on the south of the study area. The lithological domains corresponding to this potential class are the Malmani dolomite aquifer. The groundwater development within this category is facilitated by the integration of several parameters which comprise; the highly porous soil that has developed cracks that aid in rapid groundwater recharge, the dendritic drainage system shows high stream density. These parameters yield to improved groundwater recharge. Moreover, the dolomites dissolve in water to forms voids and underground caves which help with the storage of the large volume of water.

The intense abstraction of groundwater resource through the irrigation schemes in Malmani dolomite aquifer signifies the importance of this aquifer in the water supply. It is as expected that the most potential area should conform to the dolomitic aquifers as they comprise the single most productive aquifer in South Africa (DWA, 2008). According to Kafri *et al,* (1986), the productivity of the dolomites depends on their composition. The chert-rich dolomite is the most productive but only in areas with structural lineaments or the Karoo weathered dolerites. The karsified component of the Malmani dolomites aquifer (Ghaap dolomite rocks) is considered a high yielding aquifer system (Barnard, 2000).

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4.3.2 Superimposing of borehole yield on groundwater potential-prediction map

The reliability of the groundwater potential map is tested with the integration of the borehole data, particularly of the borehole yields. The map in Figure 4.9 shows the graduated symbols of the borehole yields superimposed on the groundwater potential map.

Figure 4.8 indicates that both the low and the high borehole yields are present throughout the three groundwater potential classes. However, the ratio of the productive wells inclines towards the higher groundwater potential class. In spite of the occurrence of the poor borehole yields of <2.63 l/s in all classes, they are quite significant from LGWP to the MGWP. Therefore, this suggests that the categorization of the potential areas could not necessarily avoid low borehole yields; but rather improves the chances of sitting highly productive boreholes.

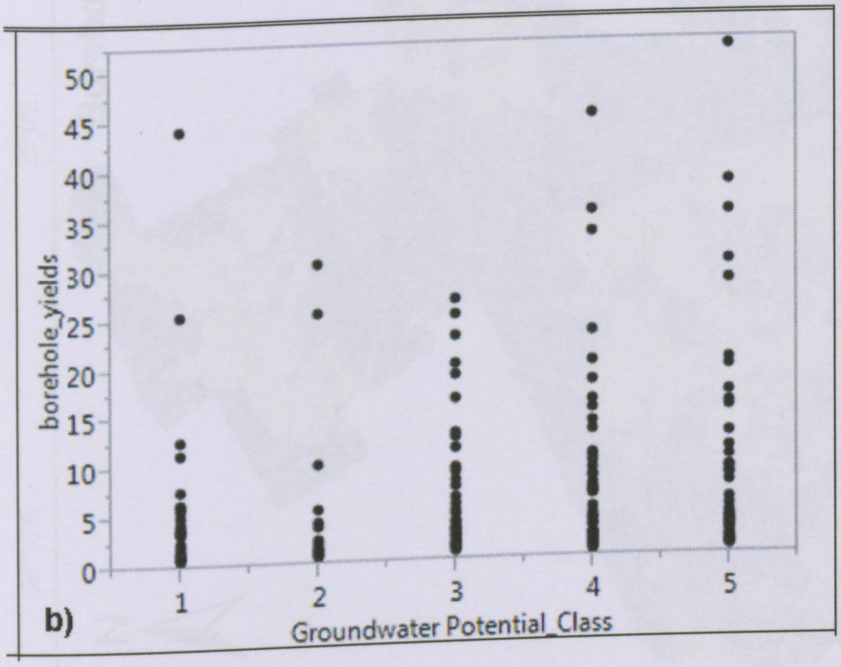

Figure 4. 8: Borehole yields in groundwater potential classes

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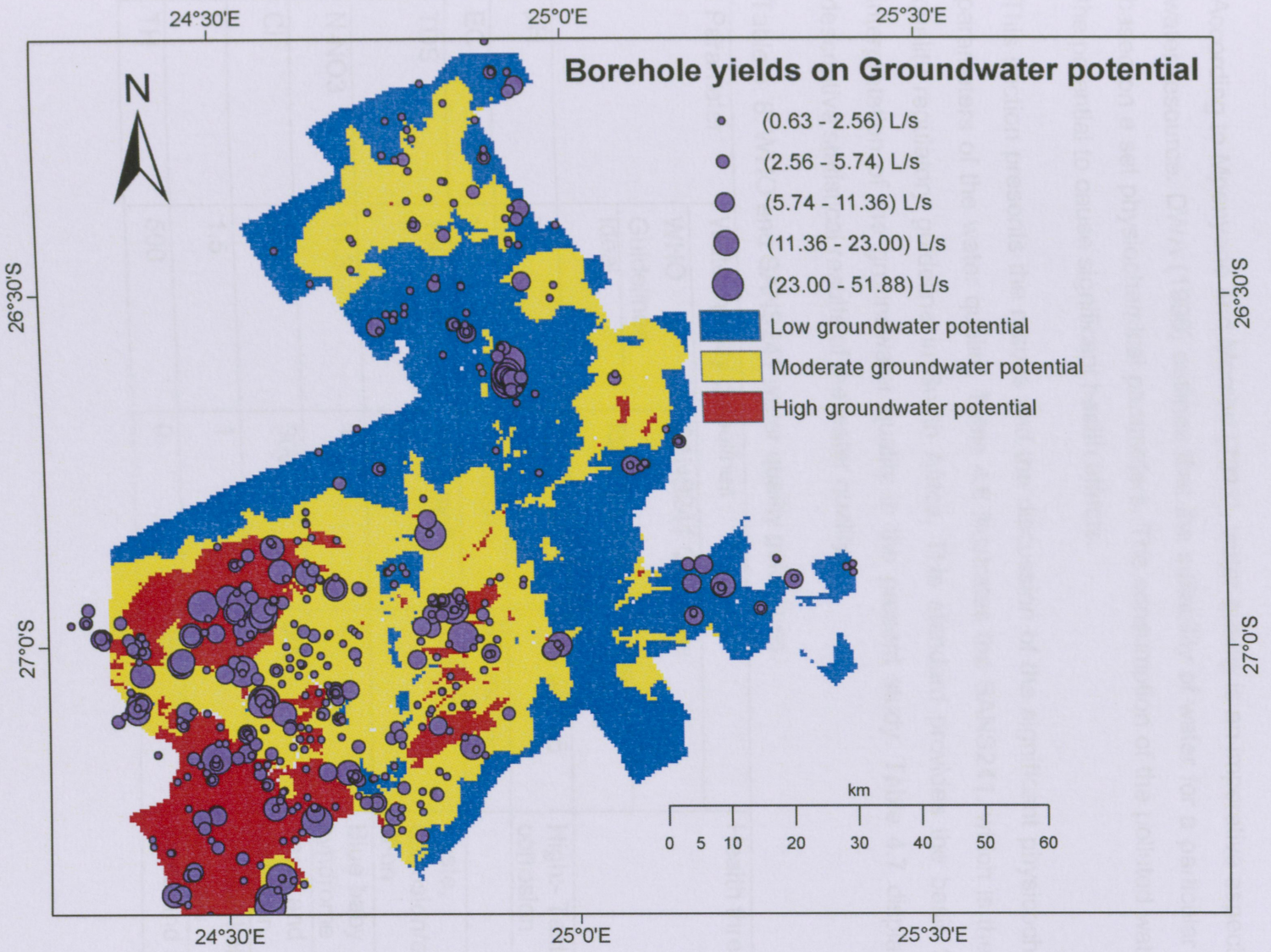

Figure 4. 9: Borehole yields superimposed on groundwater potential map.

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4.4 Water Quality Parameters

According to Mpenyane and Momba (2012), water quality is an imperative aspect of the water resource. DWA (1996) outlines that the suitability of water for a particular use is based on a set physiochemical parameters. The consumption of the polluted water has the potential to cause significant health effects.

This section presents the results and the discussion of the significant physicochemical parameters of the water quality. Table 4.6 illustrates the SANS241, which is the water quality regulatory guideline in South Africa. This standard provides the basis for the interpretation of the groundwater quality in the present study. Table 4.7 displays the descriptive statistical results of the water quality.

Table 4. 6: WHO and SANS241 water quality guidelines.

Parameter	Water quality guidelines			Health threats
	WHO Guidelines	SANS241 Guideline		
	Ideal	Ideal Values	Maximum Tolerable	
pH	-	5 < pH > 9.7	>10 and <5	High:- Taste; low corrosion
EC	-	170 mS/m	370 mS/m	
TDS	1500 mg/l	1200 mg/l	2500 mg/l	Taste, corrosion/encrustation
N-NO3	11.3	11	20	Blue baby syndrome
Cl	250	300	600	Taste and corrosion
F	1.5	1	1.5	Dental/skeletal fluorosis
TH	500	0	450	Scale and scum

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Table 4. 7: The descriptive statistical analysis of critical water quality parameters.

Statistics	pH	EC	TDS	NO_3	Cl	F	TH	SAR
Mean	7.97	91.16	609.87	11.25	67.12	0.51	379.42	1.20
Std. Deviation	0.36	48.48	278.32	17.31	98.05	0.35	166.03	1.22
Range	4.64	543.72	2513.90	198.77	949.50	4.28	1687.36	9.08
Minimum	4.18	10.78	142.40	0.02	0.50	0.03	100.57	7.76
Maximum	8.82	554.50	2656.30	198.79	950.00	4.30	1787.93	9.21

4.4.1 Distribution of the pH in Groundwater

The pH is one of the most significant indicators of the water quality (DWA, 1996). It is defined as the inverse logarithmic concentration of hydrogen ion in the water. This parameter is considered as an indicator, because it explains the underlying factor of the water quality, for instance, the pH ranging between 3.5 and 5 does not pose any health effects but has the capability to dissolve heavy metals, which are highly detrimental in the body (DWA, 1996).

According to Table 4.7, the pH values ranged from 7 to 9. The histogram in Figure 4.10a indicates that the pH values are scattered between 7 and 8.6. The parameter is characterized by the minimum (min) of 4.18, maximum (max) of 8.82, the mean and the standard deviation of the pH are 7.97 and 0.36 respectively. Based on SANS241 (2011), the pH reflects that the water in the area is potable. These results support the earlier findings of Mpenyana-Monyatsi and Momba (2012), which indicates the resource, is suitable for consumption.

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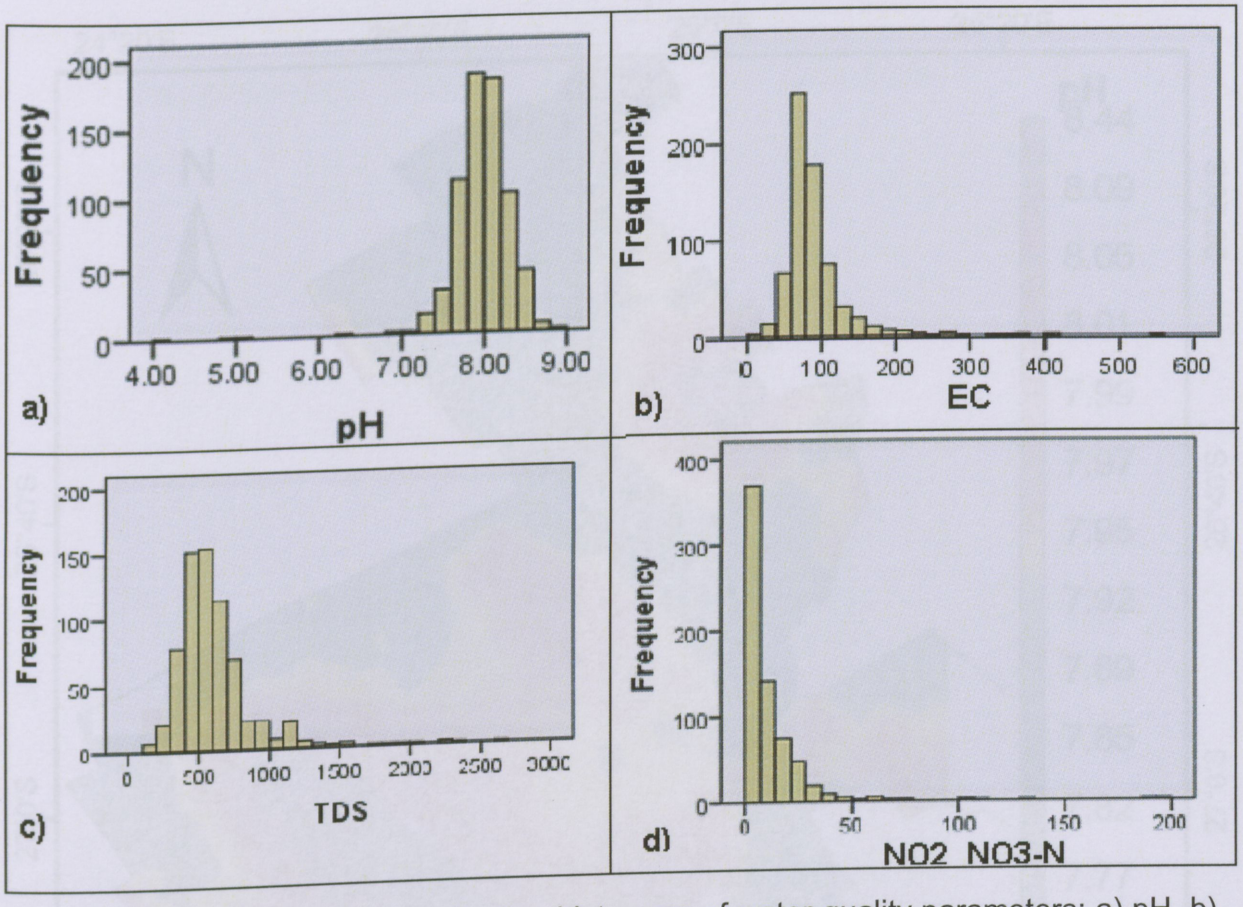

Figure 4. 10: The frequency distribution histogram of water quality parameters: a) pH, b) EC, c) TDS and d) NO_3.

The map in Figure 4.11 signifies that the pH distribution in the study area is normal. Nevertheless, there were high pH values on the southern part. This could be interpreted based on the underlying lithological units. This section is underlain by the Malmani dolomite that has the capability to neutralize the acidity of water. According to Barnard (2000), the Malmani dolomite is highly karsified, which means the resource is neutralized by the dissolved carbonates minerals.

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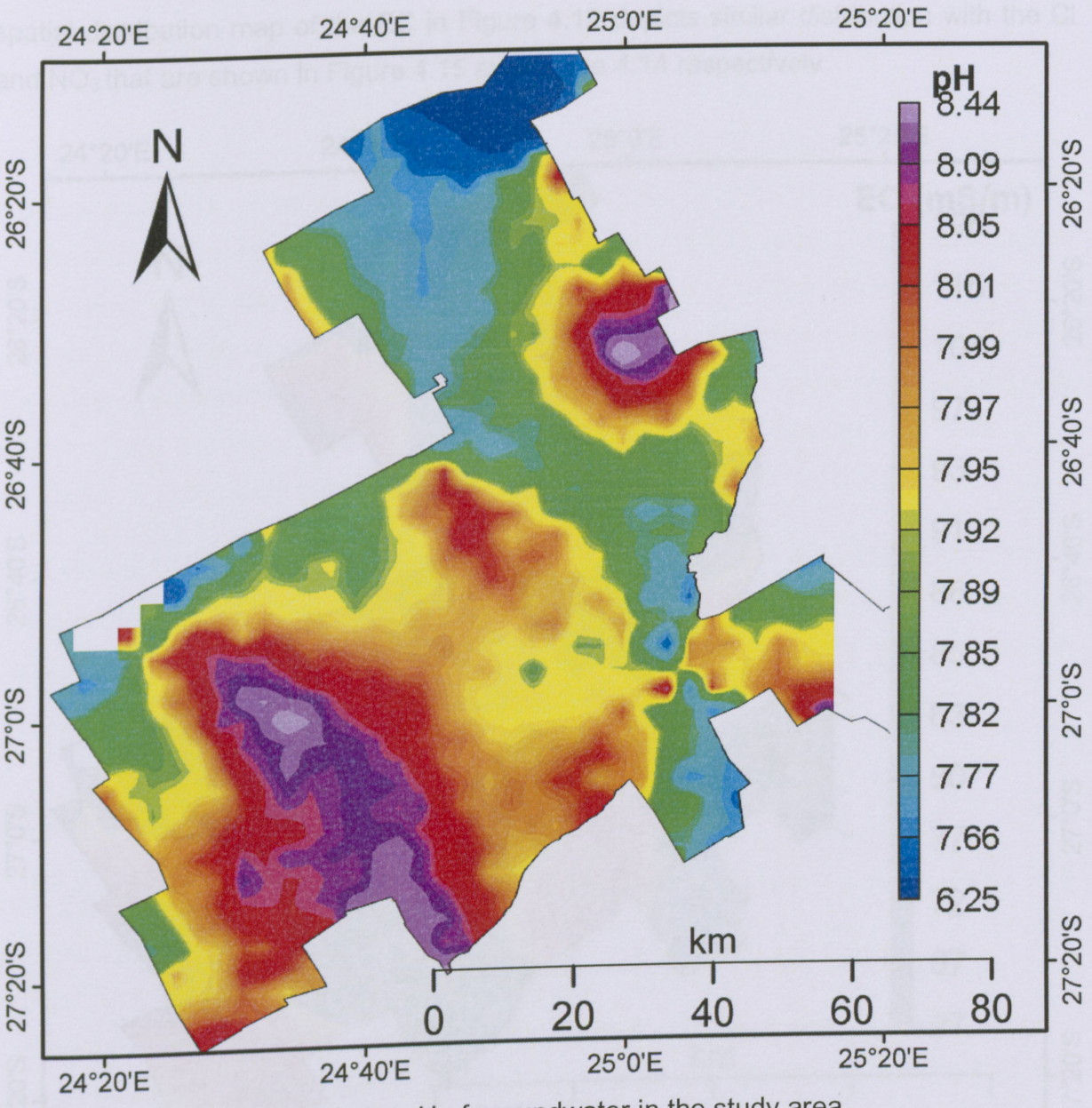

Figure 4. 11: A map showing the pH of groundwater in the study area

4.4.2 Electrical conductivity

Electrical conductivity (EC) defines the ability of water to transmit electrical charge based on dissolved ions and mineral salts (DWA, 1996a). According to Table 4.6, the World Health Organization (WHO) does not have a standard water quality guideline for EC. The

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spatial distribution map of the EC in Figure 4.12 depicts similar distribution with the Cl and NO_3 that are shown in Figure 4.15 and Figure 4.14 respectively

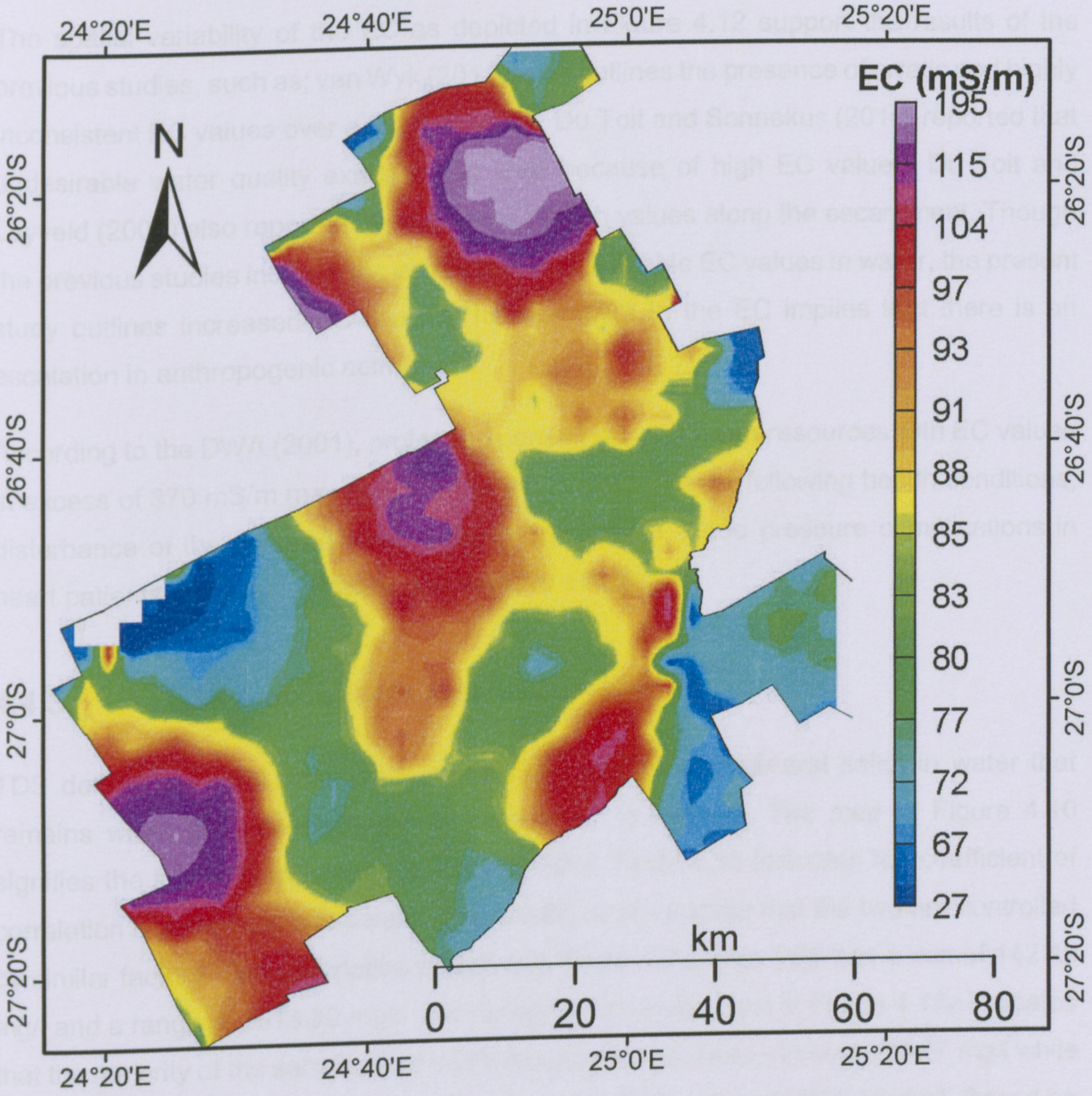

Figure 4.12: The spatial distribution trend map of the EC.

The coefficient of correlation between EC and Cl is 0.67, and between EC and NO_3 is 0.92. This suggests that the spatial variations in EC are controlled by the concentration of Cl and NO_3. On the basis of significant R with NO_3 and Cl, the high EC values may be

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attributed to anthropogenic sources that include; the domestic effluents, sanitation, and agricultural activities.

The spatial variability of the EC as depicted in Figure 4.12 support the results of the previous studies, such as; van Wyk (2011), who outlines the presence of erratic and highly inconsistent EC values over a short distance, Du Toit and Sonnekus (2010) reported that undesirable water quality exists in the area because of high EC values. Du Toit and Leyveld (2006) also reported the existence of high values along the escarpment. Though the previous studies indicate the existence of undesirable EC values in water, the present study outlines increased EC levels. The increment in the EC implies that there is an escalation in anthropogenic activities.

According to the DWA (2001), prolonged consumption of water resources with EC values in excess of 370 mS/m may result in the development of the following health conditions; disturbance of the salt and water balance in children, blood pressure complications in heart patients and renal patients, and laxative effects.

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4.4.3 TDS distribution in groundwater

TDS defines the total amount of solids dissolved (usually mineral salts) in water that remains when the water sample is evaporated to dryness. The map in Figure 4.10 signifies the similarity between the EC and TDS. Table 4.10 indicates the coefficient of correlation between the two parameters is 0.87, which implies that the two are controlled by similar factors. The descriptive statistics in Table 4.7 shows TDS has a min of 142.40 mg/l and a range of 2513.90 mg/l. The histogram frequency plot in Figure 4.12c indicates that the majority of the samples are scattered around the mean value of 609.87 mg/l while fewer samples are scattered around the maximum TDS value of 2656.30 mg/l. Based on the concentration of TDS, groundwater in the area is not entirely potable. Table 4.9, indicates that TDS has a relationship with Na, Cl, Ca and HCO_3.

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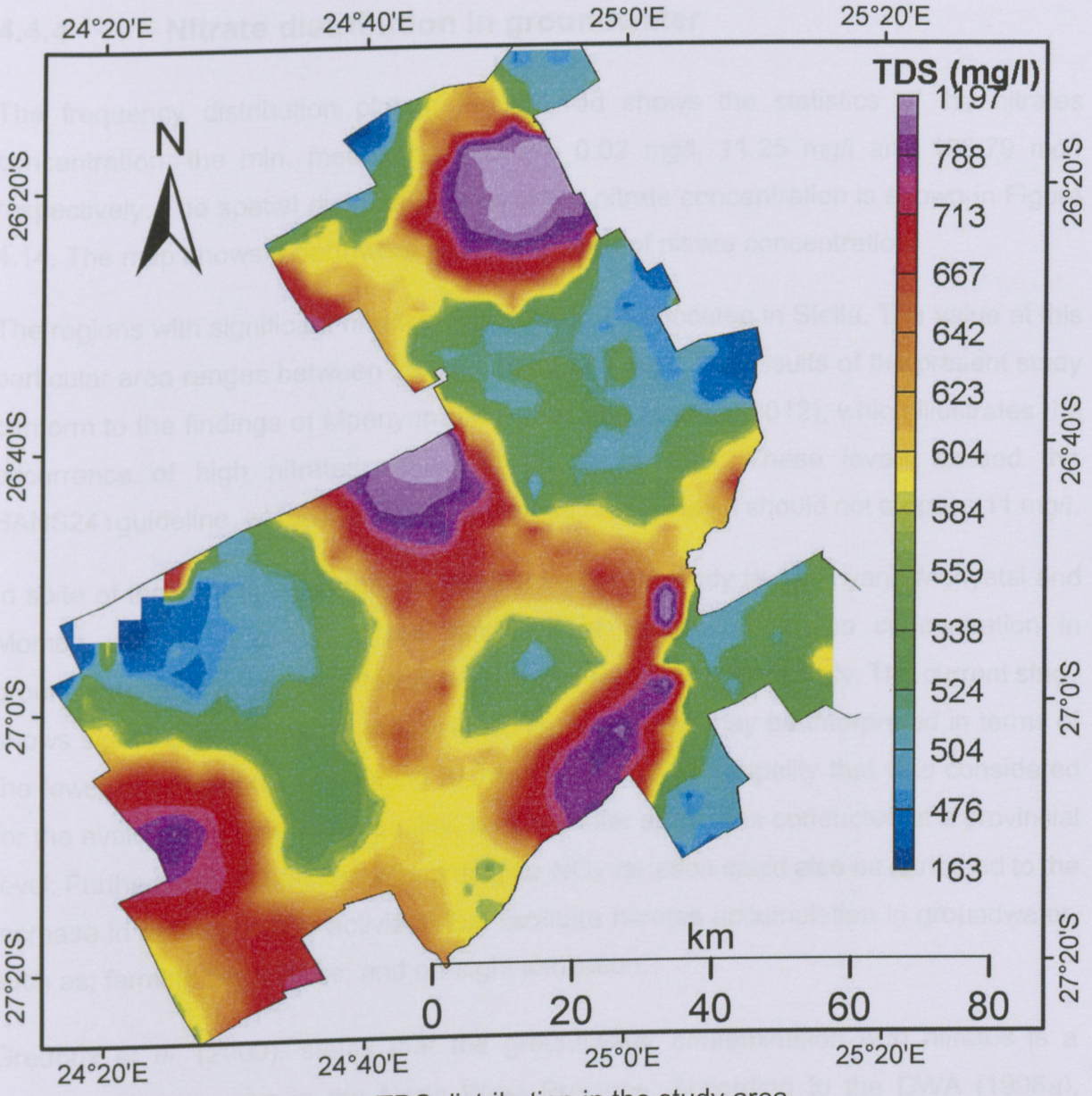

Figure 4. 13: Map showing the TDS distribution in the study area.

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4.4.4 Nitrate distribution in groundwater

The frequency distribution plot in Figure4.10d shows the statistics of the nitrates concentration, the min, mean and max are 0.02 mg/l, 11.25 mg/l and 198.79 mg/l respectively. The spatial distribution map of the nitrate concentration is shown in Figure 4.14. The map shows a northward increment trend of nitrate concentration.

The regions with significant nitrates concentration are located in Stella. The value at this particular area ranges between 23 mg/l and 47.76 mg/l. The results of the present study conform to the findings of Mpenyana-Monyatsi and Momba (2012), which illustrates the occurrence of high nitrates values of up to 14 mg/l. These levels exceed the SANS241guideline, which indicates the desired nitrates level should not surpass 11 mg/l.

In spite of the conformity in the results of the present study to Mpenyana-Monyatsi and Momba (2012), in outlining, the existence of excessive nitrates concentration in groundwater, the values reported in the two studies varies imperatively. The current study shows significantly higher nitrates values. The variations may be interpreted in terms of the fewer boreholes corresponding to the Naledi local Municipality that was considered for the evaluation of the water quality, as the earlier study was conducted at a provincial level. Furthermore, the factors accounting for NO_3 variation could also be attributed to the increase in anthropogenic activities that facilitate nitrates accumulation in groundwater, such as; farming, agriculture, and on-sight sanitation.

Gredoux *et al*, (2000), states that the groundwater contamination with nitrates is a common phenomenon in the North West Province. According to the DWA (1996a), excessive nitrate levels are derived from the oxidation of vegetable and animal debris and of animal and human excrement. Treated sewage wastes also contain elevated concentrations of nitrate (DWA, 1996a). The high nitrate concentrations in the northern part of the study area could be associated with human defecation from the informal settlement in Stella, poor sanitary infrastructure (sewage) (Barrett *et al*, 1999) and commercial game farming (cattle in particular).

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According to the SANS241 (DWA, 2011), the water resources that are characterized by the nitrates levels that exceed 10 mg/l are not fit for consumption, as this may yield to adverse health effects such as Methaemoglobinaemia on the infants, and mucous membrane irritation on the adults (DWA, 1996). According to Zingoni *et al,* (2005) the higher nitrates concentrations are often accompanied by microbial contaminants.

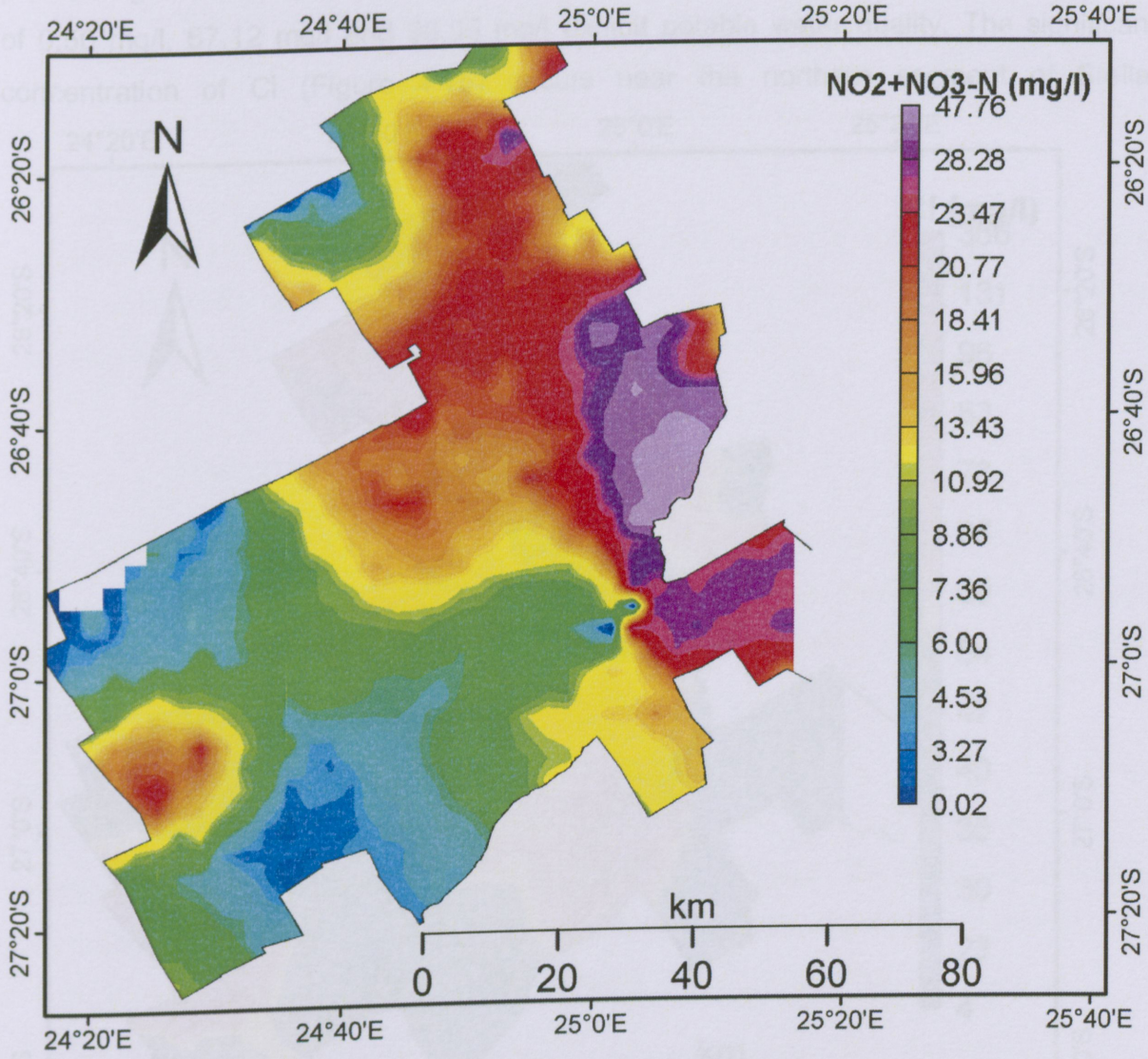

Figure 4. 14: Map showing nitrate content in groundwater.

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4.4.5 Distribution of chloride

Table 4.7 indicates the presence of excessive Cl concentration in the water. The max level of 950 mg/l is extremely beyond the prescribed limit of 600 mg/l as stipulated by SANS241 (DWA, 2011). In spite of the high Cl values, these statistical parameters do not provide significance insight of the Cl distribution, the min, mean and standard deviation of 0.50 mg/l, 67.12 mg/l and 98.05 mg/l exhibit potable water quality. The significant concentration of Cl (Figure 4.15) occurs near the northern segment of Stella.

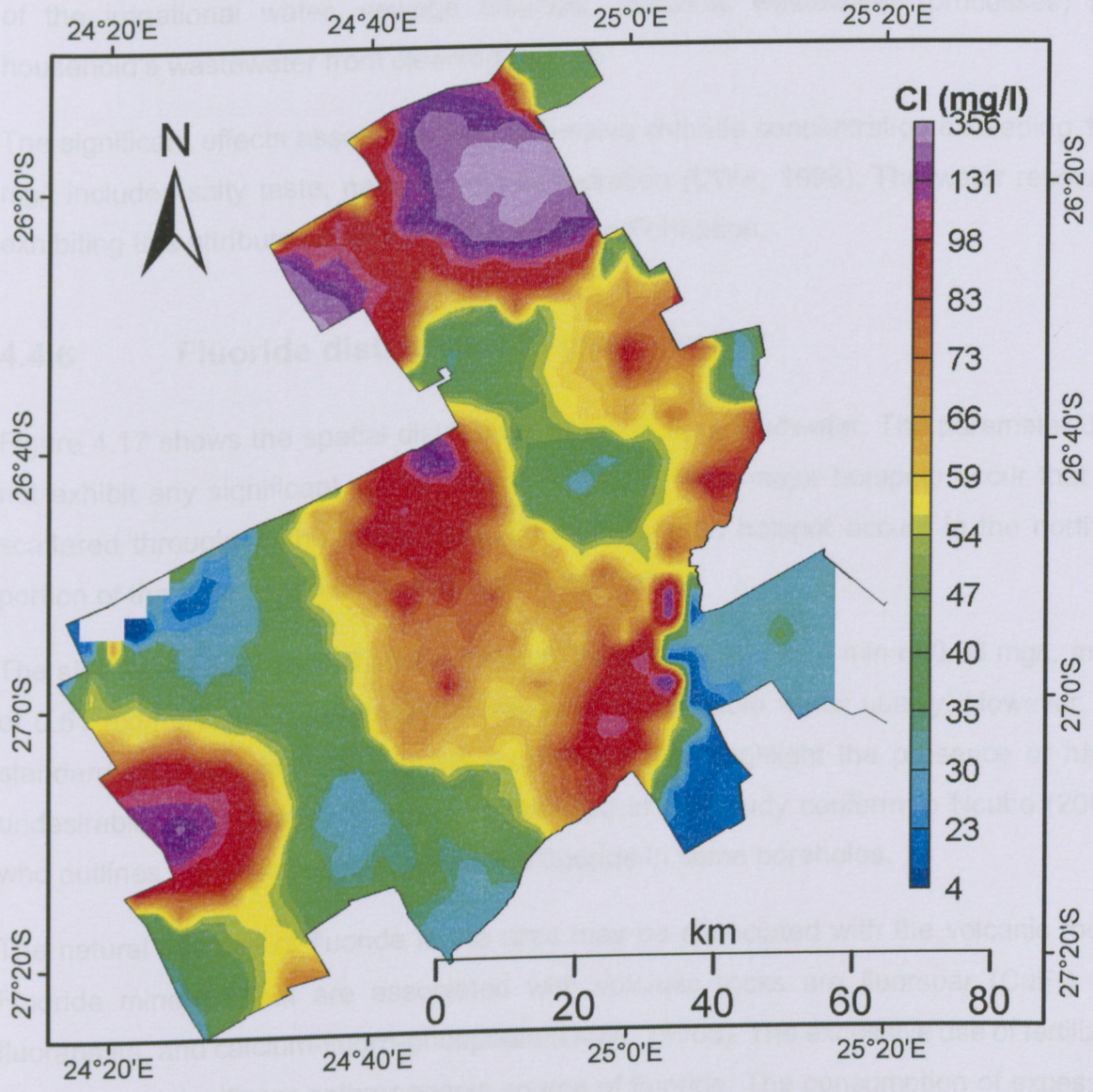

Figure 4. 15: The map illustrating the Cl content in groundwater.

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Table 4.10 shows that Cl has a coefficient of correlation (R) of 0.73 and 0.66 with Mg and Na respectively. Therefore, excessive Cl can be attributed to the dissolution of the chloride salts such as (NaCl) and (MgCl). The Cl enrichment in groundwater can be explained in terms of high evaporation rate where the rocks are poorly porous preventing recharge of groundwater.

According to Barrett *et al*, (1999); and Yang *et al,* (1999), the significant anthropogenic sources of the chloride concentration in groundwater consist of factors such as; infiltration of the irrigational water, sewage effluents, industrial wastewater (processes) and, household's wastewater from cleaning agents.

The significant effects associated with excessive chloride concentration exceeding 1200 mg/l includes salty taste, nausea, and dehydration (DWA, 1996). The water resources exhibiting this attribute occur along the Kalahari Formation.

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4.4.6 Fluoride distribution in groundwater

Figure 4.17 shows the spatial distribution of the F^- in groundwater. The parameter does not exhibit any significant spatial trend. However, three major hotspots occur that are scattered throughout the entire area. The first fluoride hotspot occurs in the northern portion of the area occupied by Kalahari Formation.

The statistical summary in Table 4.7 shows the parameter has a min of 0.03 mg/l, mean of 0.51 mg/l show the parameter correspond to desirable water quality. However, the standard deviation of 0.35 and the max of 4.3 mg/l highlight the presence of highly undesirable groundwater. The results obtained in this study conform to Ncube (2000), who outlines the occurrence of excessive fluoride in some boreholes.

The natural sources of fluoride in the area may be associated with the volcanic rocks. Fluoride minerals that are associated with volcanic rocks are fluorspar (CaF_2) and fluorapatite, and calcium-fluoro-phosphate (DWA, 1996a). The excessive use of fertilizers comprises a significant anthropogenic source of fluoride. The consumption of excessive

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fluoride beyond 1.5 mg/l for a prolonged period can result in a chronic condition known as fluorosis, which deforms the skeletal and dental structures (DWA, 1996).

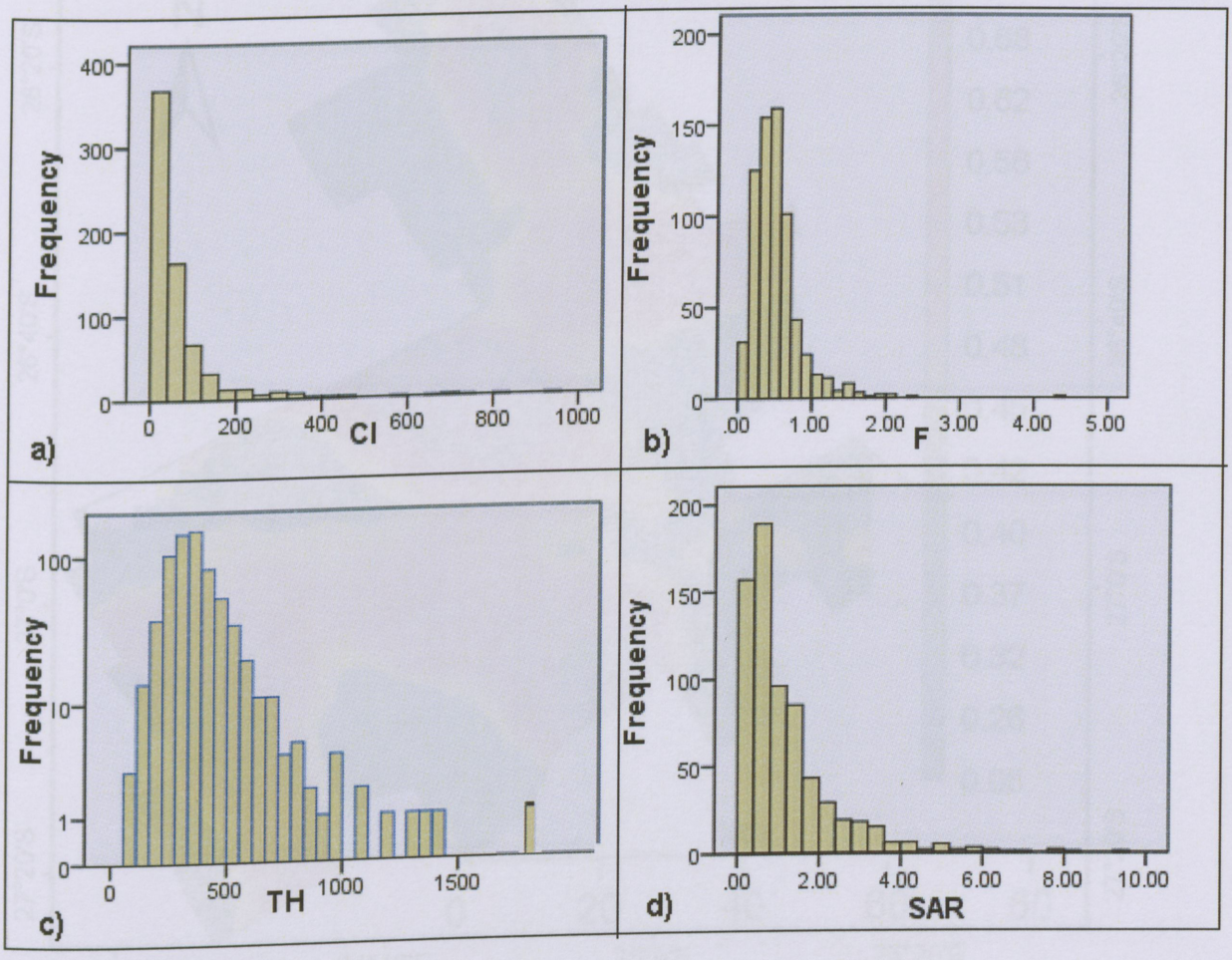

Figure 4. 16: Shows the frequency distribution histogram of: a) Cl, b) F, c) TH and d) SAR.

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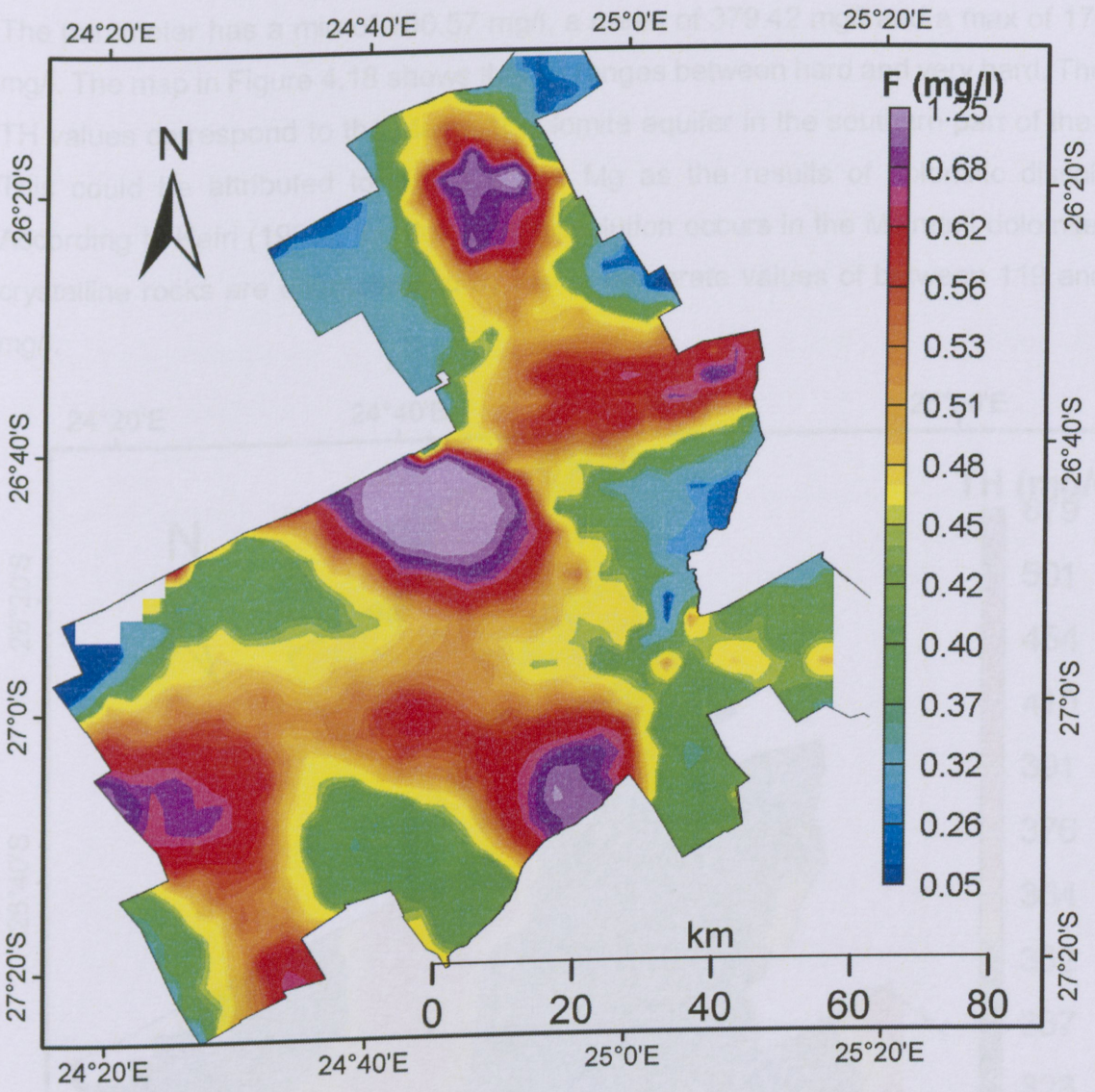

Figure 4.17: Concentration of fluoride in groundwater.

4.4.7 Spatial distribution of the total hardness

The total hardness (TH) is the capacity of water to react with soaps to produce lather. At present, there are no hazardous effects associated with human health based on TH (DWA, 1996). The importance of the parameter lies on the corrosive action to copper utensils, electrical appliances, and plumbing pipes.

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The parameter has a min of 100.57 mg/l, a mean of 379.42 mg/l and a max of 1787.93 mg/l. The map in Figure 4.18 shows the TH ranges between hard and very hard. The high TH values correspond to the Malmani dolomite aquifer in the southern part of the area. This could be attributed to high Ca and Mg as the results of dolomitic dissolution. According to Kafri (1986), the dolomitic dissolution occurs in the Malmani dolomite. The crystalline rocks are characterized by low to moderate values of between 119 and 364 mg/l.

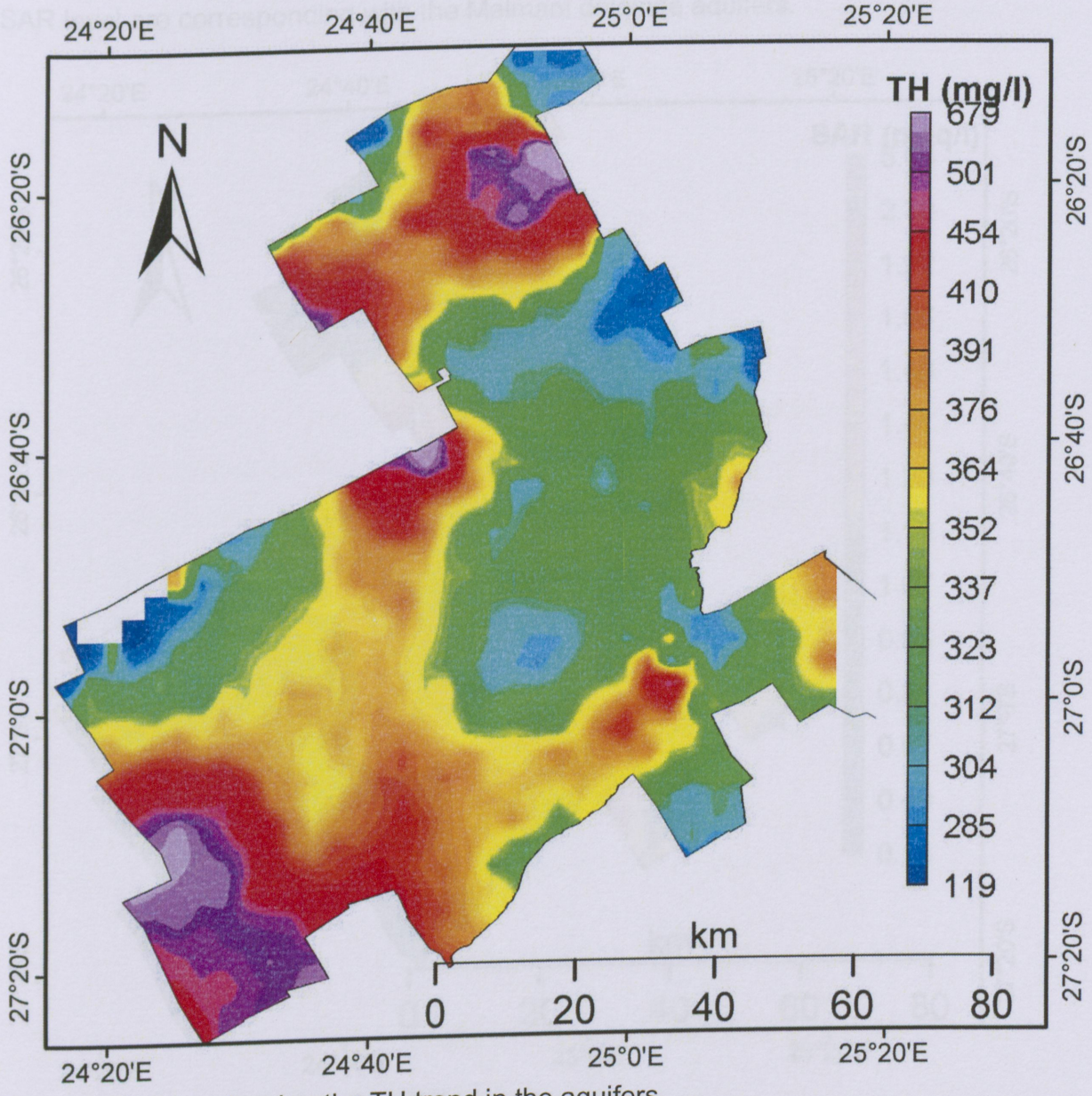

Figure 4.18: Map showing the TH trend in the aquifers.

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4.4.8 Suitability of water for irrigation

The suitability of water resources for irrigation purposes is primarily based on the concentration of Na in relation to the sum of Ca and Mg (Hem, 1985). According to the SAR hazard chat proposed by the Agricultural council of America, the suitable water resource for irrigation is characterized by the SAR value of <3 meq/l.

Figure 4.19 portrays the spatial distribution of SAR. The areas that constitute an ideal SAR level are corresponding with the Malmani dolomite aquifers.

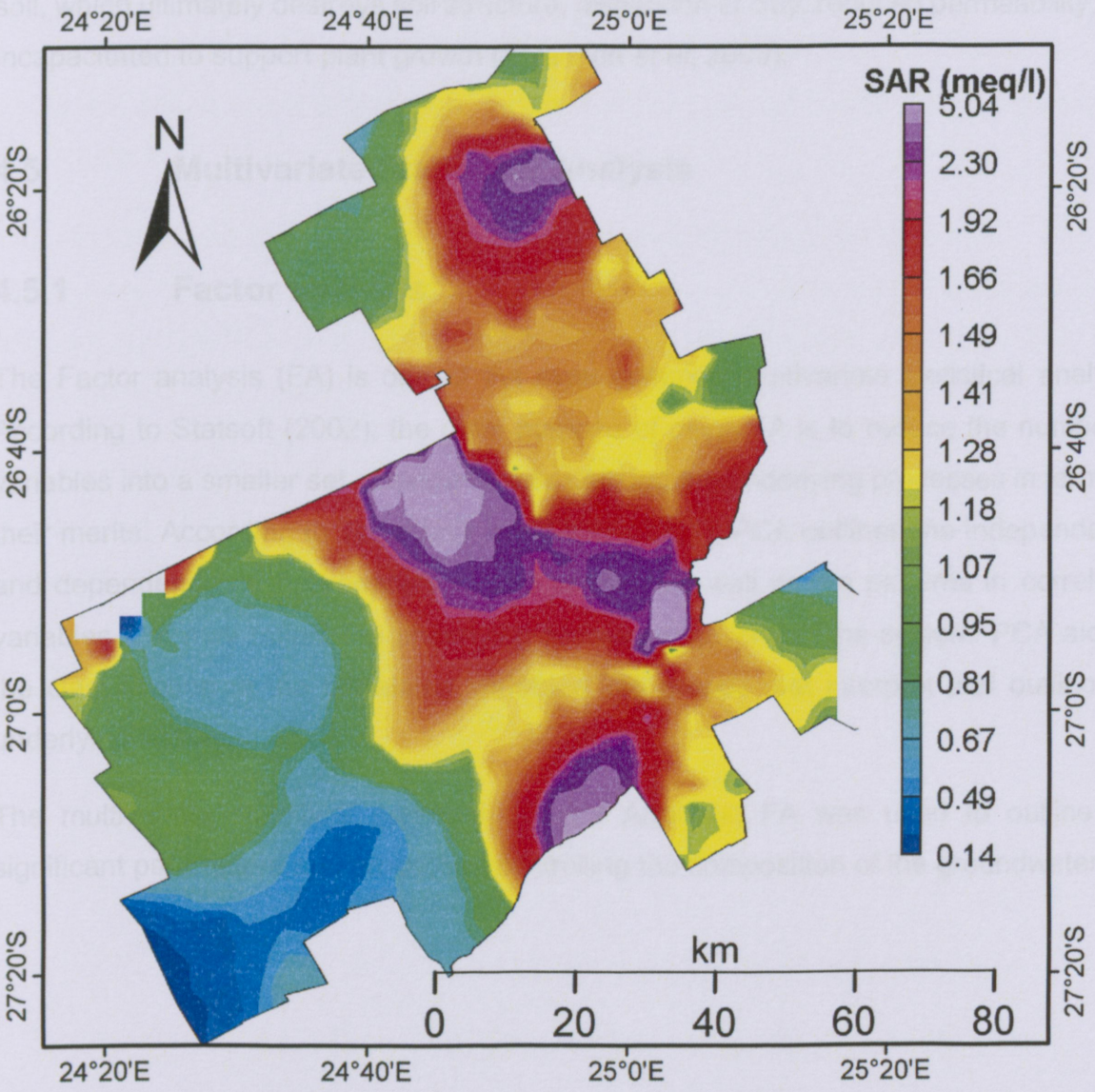

Figure 4. 19: Map of SAR in the study area.

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According to Swanson *et al*, (2003) gypsum which is a Ca-rich compound, when added to the water, it minimizes the effect of SAR. In this regard. The Low SAR in the Malmani dolomite may be attributed to the dissolution of the dolomites which are Ca-Mg rich compound, so when they dissolve in water they reduce the SAR in water.

The significant nitrates level occurs between 5 and 9 meq/l. The areas corresponding to this category are evident in the middle of the study area which is underlain by the crystalline basement rocks. The Na in this case exceeds the ratio of the sum of Ca and Mg. As the results, the ionic substitution may occur, resulting in sodic enrichment in the soil, which ultimately destroys soil structure, dispersion of clay, reduced permeability, and incapacitated to support plant growth (Swanson *et al*, 2003).

4.5 Multivariate Statistical Analysis

4.5.1 Factor analysis

The Factor analysis (FA) is one of the most common multivariate statistical analysis. According to Statsoft (2002), the main purpose of using FA is to reduce the number of variables into a smaller set of latent factors defining the underlying processes in terms of their merits. According to Tabachnik and Fidell (2001), PCA outlines the independence and dependence of the variables to one another as well as the patterns in correlated variables that may reflect the underlying processes governing the system. PCA aids in the classification of the correlated variables into groups that interpret and outline the underlying factors.

The multivariate statistical approach (Factor Analysis) FA was used to outline the significant parameters and processes controlling the composition of the groundwater.

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Table 4.8 depicts the communalities, which illustrate the proportion that the extracted components explain in correspondence to the original data. The communalities represent the index of efficiency to reduced set of factors. The principle governing the adequacy of the factor solution state that the extracted factors should explain at least 50% of the original variables variations.

Table 4.8: The communalities assessment of the water quality.

Parameter	Ca	Mg	Na	K	Cl	SO_4	HCO_3	TDS	NO_3	EC
Initial	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Extraction	1.00	0.95	1.00	0.15	0.92	0.82	1.00	1.00	0.60	0.99

Table 4.9 shows the Kaiser-Meyer-Olkin (KMO), which is an index for comparing the magnitude of the existing coefficient of correlation.

The Bartlett's test checks if the observed correlation matrix R=(rij)(p x p) diverges significantly from the identity matrix (theoretical matrix under H0: the variables are orthogonal). The PCA can perform a compression of the available information only if we reject the null hypothesis.

In order to measure the overall relation between the variables, we compute the determinant of the correlation matrix |R|. Under H0, |R| = 1; if the variables are highly correlated, we have |R| of 0.

The Bartlett's test statistic indicates to what extent we deviate from the reference situation |R| = 1. It uses the following formula.

$$r^2 = \left(n - 1 - \frac{2p+5}{6}\right) * \ln. |R| \quad \text{.....(4.1)}$$

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Table 4.9: KMO and Bartlett significance test.

Significance Test			
Test	DF	ChiSquare	Prob>ChiSq
H0: no common factors	65	8807.939	<.0001*
HA: at least one common factor			
Test	DF	ChiSquare	Prob>ChiSq
H0: 5 factors are sufficient	10	606.665	<.0001*

A Bartlett's sphericity test indicates the water quality parameters are correlated (Bartlett χ^2 = 606.665 df, $p \leq 0.001$). This is critical for the explanation of the variance in the hydrochemical data using a low number of variables. Additionally, the Kaiser Meyer Olkin method (KMO) showed that the measure of sampling adequacy (MSA) was indicating that the degree of correlation between the variables and the appropriateness of factor analysis was ordinary.

4.5.2 Correlation of the physicochemical parameters

The correlation matrix generated through covariance of water quality parameters indicates the relationship amongst the physiochemical parameters. Table 4.10 indicates the positive correlation amongst the following parameters; Ca, Mg, Na, K, Cl, SO4, NO_3, F, EC, pH, HCO_3, and TDS exist. The TDS shows a strong coefficient of correlation (r) with the major ions of water quality except K. Similarly, the EC also exhibits a strong correlation with major ions except K and Ca. Ca and Na exhibit similar r of 0.8 with TDS, Cl, and SO_4 shows a very strong r with TDS of 0.82 and 0.85 respectively. TDS and EC also show significant r=0.87. These imply that TDS is controlled by the major ions of water quality excluding K.

Ca does not show any significant r with any of the physicochemical parameters but TDS. Mg strongly correlates with the major cations (Cl and SO_4), r=0.73 and r=0.69 respectively. Na exhibits a similar coefficient of correlation with the two anions of r=0.66 and r=0.74 with Cl and SO_4.

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Table 4.10: The correlation amongst the physio-chemical parameters.

	Ca	Mg	Na	K	Cl	SO_4	NO_3	F	EC	pH	HCO_3	TDS
Ca	1.00	0.39	0.15	0.05	0.46	0.31	0.42	0.03	0.46	-0.1	0.23	0.52
Mg	0.39	1.00	0.39	0.3	0.73	0.69	0.47	0.15	0.81	0.06	0.37	0.8
Na	0.15	0.39	1.00	0.12	0.66	0.74	0.36	0.37	0.67	0.01	0.34	0.8
K	0.05	0.3	0.12	1.00	0.24	0.24	0.32	0.02	0.31	0.04	0	0.24
Cl	0.46	0.73	0.66	0.24	1.00	0.71	0.57	0.13	0.92	-0.1	0.05	0.82
SO_4	0.31	0.69	0.74	0.24	0.71	1.00	0.34	0.27	0.74	0.05	0.25	0.85
NO_3	0.42	0.47	0.36	0.32	0.57	0.34	1.00	0.06	0.67	-0.1	-0.11	0.46
F	0.03	0.15	0.37	0.02	0.13	0.27	0.06	1.00	0.26	0.25	0.33	0.31
EC	0.46	0.81	0.67	0.31	0.92	0.74	0.67	0.26	1.00	-0	0.23	0.87
pH	-0.1	0.06	0.01	0.04	-0.1	0.05	-0.1	0.25	-0	1.00	0.25	0.05
TAL	0.23	0.37	0.34	0	0.05	0.25	-0.11	0.33	0.23	0.25	1.00	0.52
TDS	0.52	0.8	0.8	0.24	0.82	0.85	0.46	0.31	0.87	0.05	0.52	1.00

Cl strongly correlates with the following parameters; Mg, (r= 0.73), Na, (r= 0.66), SO4-, (r = 0.71), NO_3, (r= 0.57) EC, (r= 0.92) and TDS, (r=0.82). NO_3 has a significant correlation (r=0.67) with EC. In the other hand, F and pH do not exhibit any significant correlation with any other parameter.

4.5.3 Factors loading

Table 4.11 shows the five factors controlling groundwater composition. Similarly, Table 4.12 shows the variance explained by such factors. The physiochemical parameters with significant loadings in Factor 1 are Na=0.962, TDS=0.703, SO_4=0.698 and Cl=0.545. The chemical species controlling the concentration of TDS are Na, SO_4, and Cl. Table 4.11 shows factor one accounts for 46% of the total variance. Table 4.9 shows Na has r of 0.74 and 0.66 with SO_4 and Cl^- successively. Factor 1 can be explained in terms of the dissolution of the chloride salts, namely Na-SO_4 and Na-Cl. The dominance of Na could be explained in terms of the weathering and dissolution of the plagioclase minerals that then liberate Na, which is ionically substituting other cations in the groundwater. The

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water composition dominated by the two chloride salts characterizes an intermediate to sub-modern hydrochemical facies (Ishaku, *et al*, 2011).

Table 4.11: Factor loading of groundwater quality.

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
Na	0.962	0.130	-0.008	0.110	0.212
TDS	0.703	0.528	0.365	0.280	0.124
SO_4	0.698	0.548	0.163	0.042	-0.049
Mg	0.240	0.867	0.243	0.275	0.068
EC	0.494	0.679	0.245	0.049	0.472
Cl	0.545	0.653	0.263	-0.158	0.321
K	0.061	0.371	-0.021	-0.012	0.063
Ca	0.115	0.146	0.971	-0.021	0.148
HCO_3	0.251	-0.001	0.222	0.942	0.007
pH	-0.016	0.034	-0.071	0.281	-0.042
NO_3	0.236	0.370	0.266	-0.243	0.530

Factor 2 shows the strong positive loading of Mg=0.867, EC=0.679, Cl=0.653 and TDS=0.528. Table 4.10 shows a very strong r between TDS and EC of 0.87. The similarity in the loadings of K and NO_3 of 0.370 shows homogeneousness in the origin of the two parameters, which could be attributed to the agricultural activities, in spite of the low loadings. According to the DWA (1996a), a strong correlation between the two parameters exists that is associated with composts origin. TDS is a significant parameter for explaining the groundwater quality because of high loadings in the first two factors. The high Cl loading explains the effects of both the anthropogenic and the natural sources. The former entails sewage, domestic wastewater, and agricultural effluents while the latter entails saltpan dissolutions. Factor 2 explains 14.22% of the total variance. This can be explained in terms of dominant ions, which are Mg-Cl water type.

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Table 4.12: Shows the Eigenvalues and the Variance explained by the factors.

Component	Initial Eigenvalues			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	5.622	46.850	46.850	5.489	45.745	45.745
2	1.707	14.224	61.074	1.736	14.467	60.212
3	1.056	8.799	69.872	1.159	9.661	69.872
4	.977	8.141	78.013			
5	.748	6.236	84.249			

The variance explained by Factor 3, Factor 4 and, Factor 5 are 8.7%, 8.1%, and 6.2% respectively. The three Factors are characterized by the loading of a single significant parameter each in the following sequence; Ca, HCO_3 and NO_3 respectively. Factor 3 and Factor 4 may be attributed to the recent recharge and probably the dolomitic dissolution because of high Ca and HCO_3 loadings. On the other hand, Factor 5 shows high loading of nitrates, perhaps this explains the effects of anthropogenic activities such as cattle farming, and human excreta.

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4.6 Hydrochemical Facies

The concept of hydrochemical facies has been used by Back (1960, 1966) to denote the chemical character of groundwater in hydrologic systems. According to this author, the composition of water transforms as it flows along a particular direction, irrespective of the uniformity in chemical composition of the medium. This process is known as hydrochemical facies, which reflects the effects of chemical processes in the lithologic environment. The transformations result from chemical reactions and the residence time in a particular aquifer. Factors such as temperature, pH of water, oxidation state, and solubility of the groundwater flow patterns. The trilinear piper diagram is commonly used for mapping such facies based on major ions.

4.6.1 Water types in Kalahari aquifer

The piper diagram in Figure 4.20a indicates the hydrochemical facies of the Kalahari Formation. The figure shows that Mg was the most dominant cation in some boreholes, but the rest do not signify any dominant facie. The anion triangle shows that the HCO_3 was the major anion though some considerable boreholes showed high Cl levels. In all the boreholes, the concentrations of SO_4 did not exceed 20 meq/l%.

The four generic water types describing the hydrochemical facies of the groundwater in Kalahari Formation are Ca-Mg-HCO_3, Ca-Mg-HCO_3-Cl, Ca-Cl-HCO_3, and Na+K-HCO_3-Cl. According to Bartolino and Cole (2003), the existence of Ca, Mg and HCO_3 signify the occurrence of recent groundwater recharge. According to Back (1960 and1961). This facies indicates water that is in the early phase along the hydrochemical facie, which has not undergone any significant hydrochemical evolution. However, this facie does not correspond with the composition of the Kalahari Formation. The logical explanation for the occurrence of this water type could be interpreted in terms of the underlying Malmani dolomite aquifer resting underneath the Gordonia Formation. van Wyk (2011) indicates the boreholes in this aquifer extends deeper than 50 m, which is consistent with the depth of most boreholes drilled in the Kalahari aquifer.

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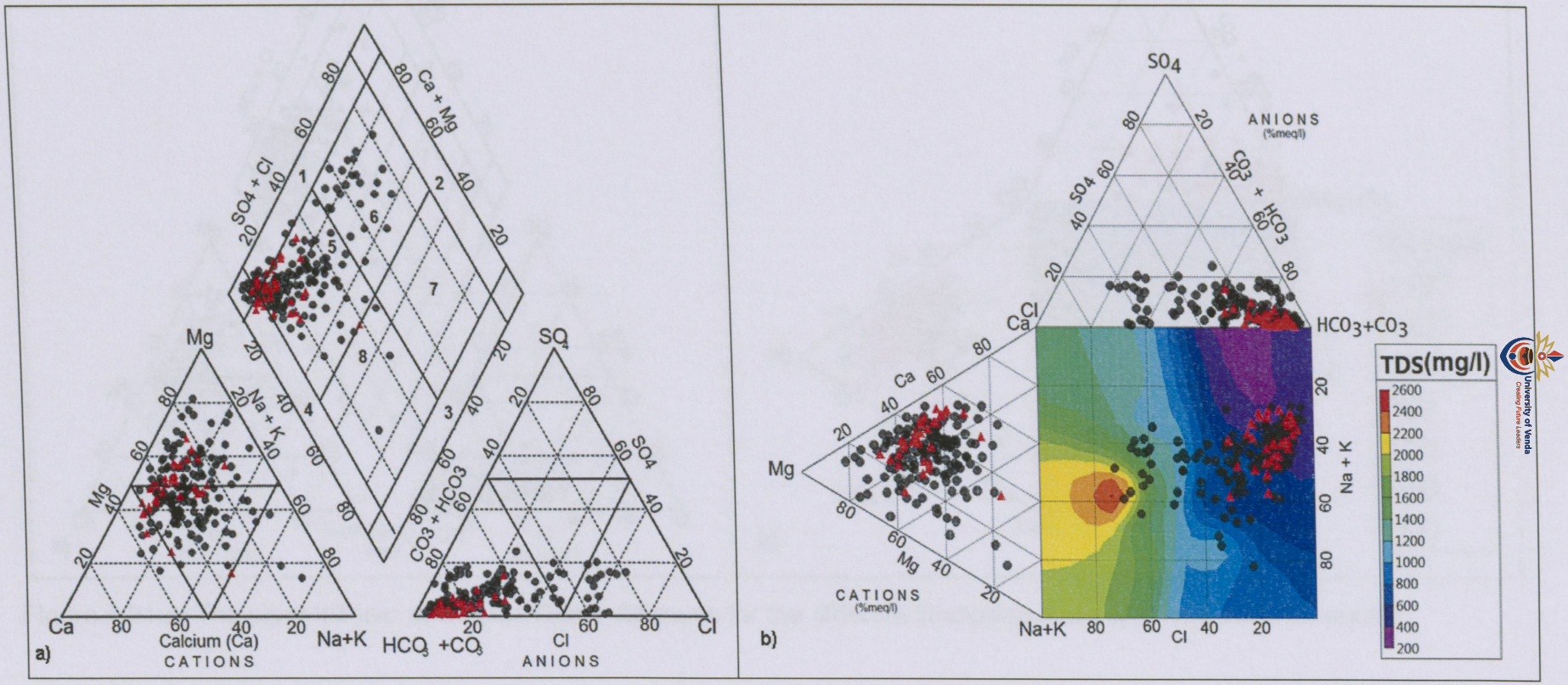

Figure 4. 20:a) The piper, and b) the Durov diagrams for the Kalahari Formation.

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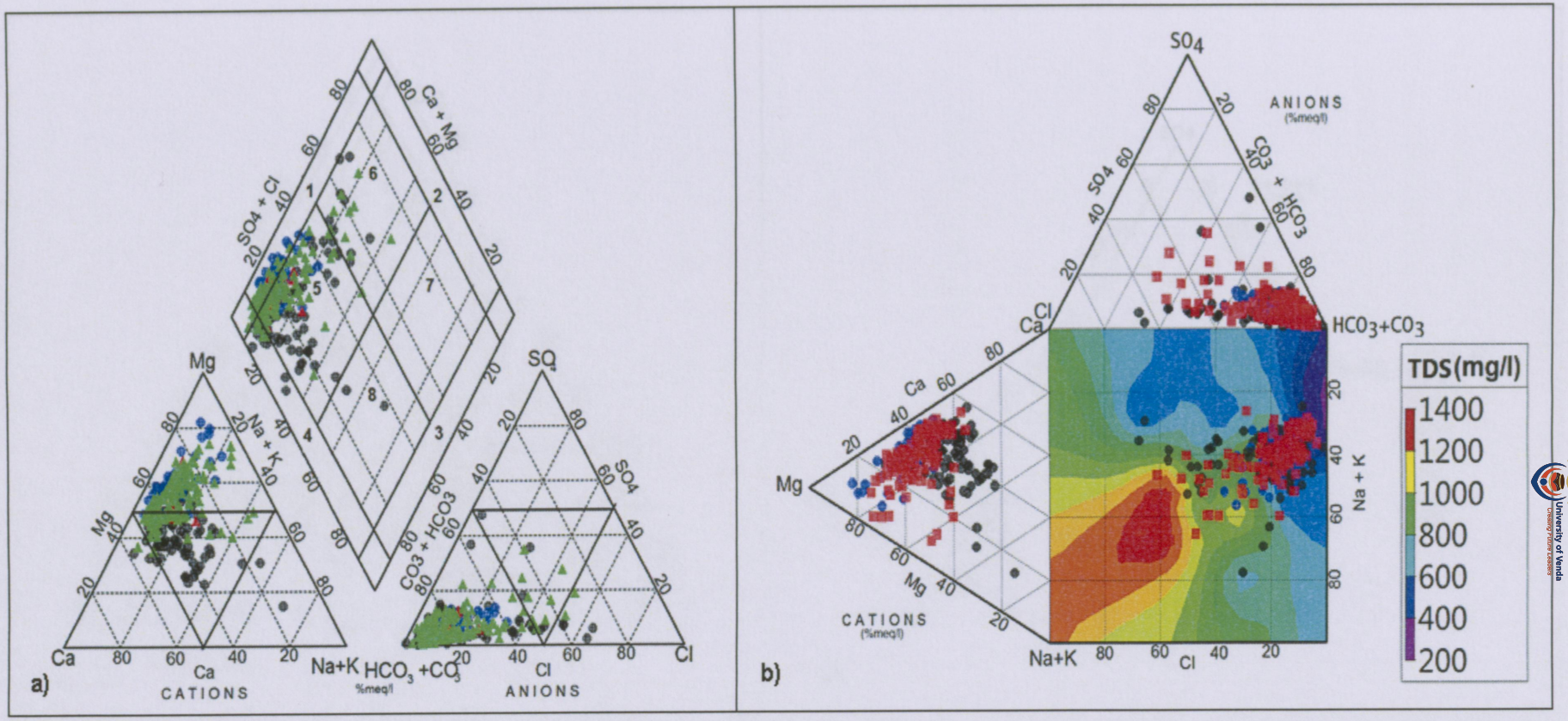

Figure 4.21:a) The piper trilinear and b) the Durov diagrams for the different lithologies in the Malmani dolomite aquifer.

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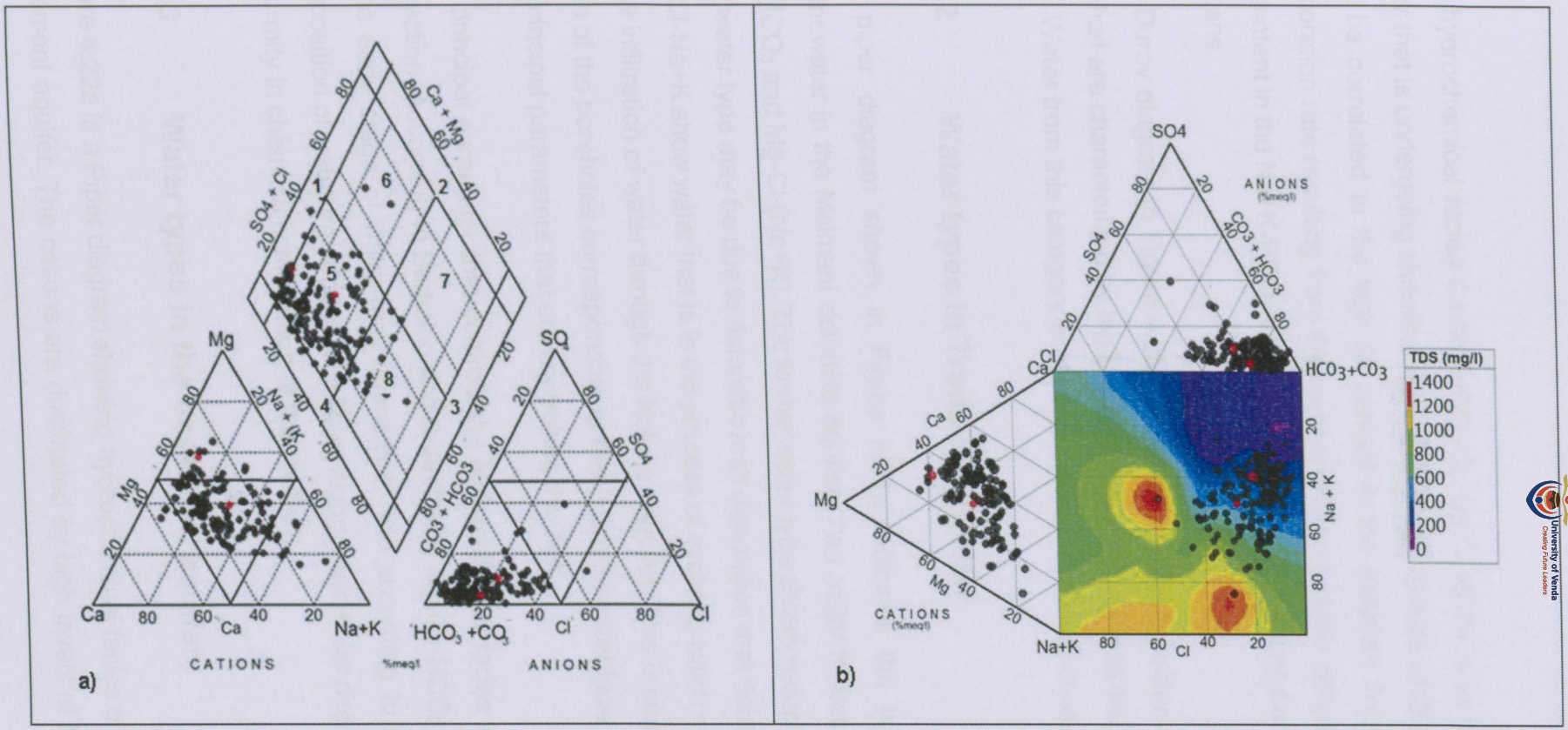

Figure 4. 22:a) The piper and b) the Durov diagrams for the Ventersdorp volcanic rocks.

The hydrochemical facies Ca-Mg-HCO_3-Cl, Ca-Cl-HCO_3, and Na+K-HCO_3-Cl illustrate water that is undergoing chemical evolution. The presence of Cl in the three water types may be correlated to the high Cl content in the Kalahari Formation due to the high evaporation rate resulting from the semi-arid nature of the climate. However, the Cl and Na content in the Na+K-HCO_3-Cl may be related to the dissolution of salt from the nearby saltpans.

The Durov diagram in Figure 4.20b shows a significant portion of the boreholes in the Kalahari are characterized by high TDS values which exceed the prescribed vale of 1000 mg/l. Water from this category is not desirable for domestic consumption.

4.6.2 Water types in Transvaal aquifer

The piper diagram shown in Figure 4.21a indicates the hydrochemical facies of groundwater in the Malmani dolomite aquifer. Two major hydrochemical facies are Mg-Ca-HCO_3 and Mg-Cl-(Na+K). The former water type shows recent groundwater recharge. This water type may be due to dolomitic rock dissolution that contains Ca, Mg and HCO_3. Mg-Cl-Na+K show water that is in the process of evolving which may as well be attributed to the infiltration of water through the Kalahari aquifer. This is consistent with the shallow depth of the boreholes corresponding to this hydrochemical facie. The Mg and HCO_3 are the principal parameters that are controlling the TDS.

The principal parameter that controls the hydrochemical facies is the groundwater-rock interaction. According to Bartolino and Cole (2003) Mg-Ca-HCO_3 signify water that is still in the early stage of water-rock interaction, and according to Back (1960; 1966) the composition of water transforms as it flows along a particular direction, irrespective of the uniformity in chemical composition of the medium.

4.6.3 Water types in the basement aquifer

Figure 4.22a is a Piper diagram showing hydrochemical facies of groundwater within the basement aquifer. The cations are dominated by high levels of Mg and Na. The anions

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triangle shows the dominance of the HCO_3. The major water types in the area include; Ca-Mg-HCO_3, Na-HCO_3-Cl-SO_4, Mg-Na+K-Cl, and Ca-Mg-HCO_3-Cl.

According to the Durov diagram shown in Figure 4.22b, the TDS shows that the water in the basement rock is generally suitable for human consumption. However, there are few boreholes showing significant Cl values beyond the consumption range. The water types Na-HCO_3-Cl-SO_4, Mg-Na+K-Cl, and Ca-Mg-HCO_3-Cl signify the prevalence of Cl in the groundwater. This parameter may be attributed to the mixing of recent and relatively old groundwater that has slightly undergone chemical evolution to enrich Cl. The same chemical component may also be correlated with the anthropogenic activities that comprise agricultural effluents and domestic wastewater disposal that contributed to an increase in this element.

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4.7 Groundwater Isotopes

Table 4.13 shows the concentration of the environmental isotopes of the water molecule. The samples were collected from the 12 boreholes.

Table 4.13: The results of the environmental isotopes of the water molecule.

SITE	^{2}H (dD‰ SMOW)	^{18}O (dO‰ SMOW)	TU	±
ARV 01	-27.80	-5.26	1.10	0.30
BV 01	-28.50	-5.66	1.00	0.20
BV 04	-22.00	-4.46	1.20	0.30
DTK 01	-27.40	-5.25	0.50	0.20
DTKR 01	-25.70	-4.39	0.90	0.20
MDK 01	-28.60	-5.08	1.00	0.20
ST 02	-29.00	-5.23	0.60	0.20
ST 03	-27.90	-5.23	0.90	0.20
STGC 01	-28.30	-4.60	0.40	0.20
STGC 04	-29.60	-4.74	0.70	0.20
SWF 01	-30.10	-5.23	1.10	0.30
SWF 06	-27.50	-4.16	1.30	0.30

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4.7.1 Tritium concentration in groundwater

The environmental isotopes of the water molecule ($\delta^{18}O$, $\delta^{2}H$ and ^{3}H) are significantly considered as the groundwater fingerprints (Sami, 1992; Adams, 2001). This is because they provide invaluable information regarding the groundwater flow, groundwater recharge and corresponding recharge condition. In the present study, the isotopes were employed to characterize the groundwater potential of the area.

The bar graph in Figure 4.23 illustrates the distribution of the tritium values in the groundwater. The blue and the red longitudinal bars in the same figure indicate the tritium concentrations corresponding to the crystalline basement aquifer and Transvaal aquifer (Malmani dolomite aquifer) respectively.

The tritium concentration in basement rock aquifer ranges between 0.4 and 1.0 TU. The mean concentration in this area is 0.72 TU. The MDK 01 and STGC 01 respectively correspond to the highest and lowest values of 1.0 and 0.4 TU. ST 02 and ST 03 are located adjacent to each other, but they show variability in tritium concentrations of 0.6 and 0.9 TU respectively. Similarly, STGC 03 and STGC 04 show variable concentrations of 0.7 and 0.4 TU respectively.

The Transvaal aquifer generally shows high TU values. In spite of the low min value of 0.5 TU, the mean and the max are 1.1 TU and 1.3 TU respectively which signifies a narrow range of TU values. Out of the five borehole corresponding to the Transvaal aquifer, only two have TU less than 1.0 and their concentration are 0.9 and 0.5 which correspond to DTKR 01 and DTK 01 respectively. The two sampling points are only a few metres apart. The max value of 1.3 TU is in SWF 06. SWF 01 that is located nearby, also exhibit high TU of 1.1. The other boreholes that are located in the same area are BV 01 and BV 04 that shows slightly similar TU of 1.0 TU and 1.2 TU. Lastly, ARV 01 has the TU of 1.1.

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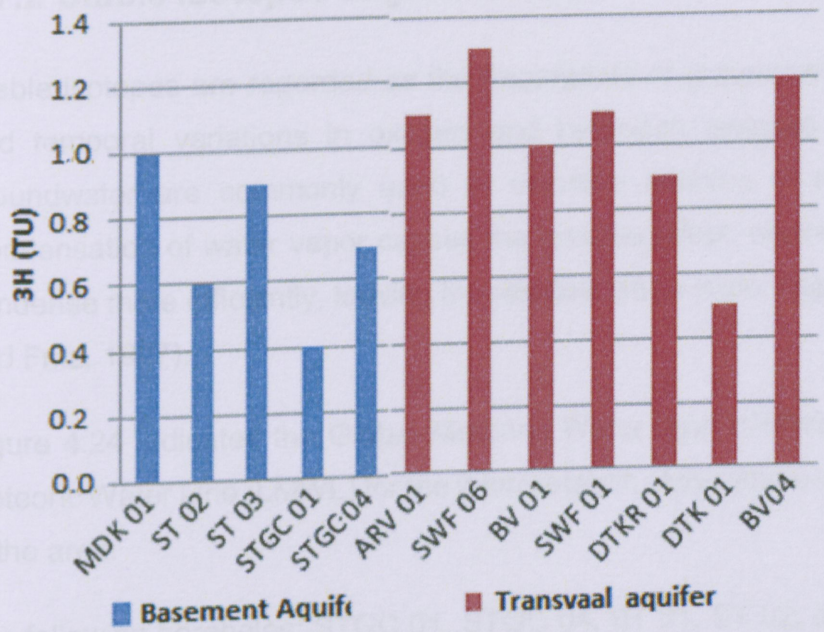

Figure 4. 23: The tritium concentration in the groundwater (Basement and Transvaal aquifers).

Clark and Fritz (1997) provide the guideline for the interpretation of the groundwater Isotopes (TU). This classification outlines that the TU of less than 0.8 signifies the occurrence of sub-modern groundwater resources. Based on this guideline, the water resources within the crystalline basement is strictly classifying under the sub-modern recharge (prior to 1950s). This implies suggest there is the minimal occurrence of groundwater recharge. The decline in water level, within the current study area, particularly in the hard rocks reported by the Sami (2013), may be interpreted in terms of over abstraction in the absence of groundwater recharge. Contrary to the basement rocks, the Malmani dolomite presents the mixing of modern and sub-modern water resource due to the TU ranging between 0.8 and 4.0 (Clark and Fritz, 1997). The high stream density and the porous nature of the medium comprising this aquifer promote groundwater infiltration.

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4.7.2 Stable isotopes of groundwater

Stable isotopes are regarded as the fingerprints of groundwater resources. The spatial and temporal variations in oxygen and hydrogen isotopes in the precipitation and groundwater are commonly used to examine sources of recharge (Coplen, 1993). Condensation of water vapor causes the reverse effect, whereby the heavier molecules condense more efficiently, leaving the residual water vapor depleted in ^{18}O and ^{2}H (Clark and Fritz, 1997).

Figure 4.24 indicates the Global Meteoric Water Line (GMWL) plotted along the Local Meteoric Water Line (LMWL) for the interpretation of the stable isotopes of $^{2}H‰$ and $^{18}O‰$ in the area.

The following boreholes: STGC 01, STGC 04, ST 01, ST 02, and MDK 01 are underlain by the crystalline basement rocks of the Ventersdorp Supergroup. They are located on the northern portion around Stella town. The isotope concentrations in the basements have the following ranges, -5.5 ‰ to -4.5 ‰, and -30 ‰ to -27 ‰ for the $\partial^{18}O$ and, $\partial^{2}H$ respectively. The $\partial^{18}O$ shows a very narrow range of values in the basement rocks.

The MDK 01, ST 02, and ST 03 plots along the local meteoric water line, which suggests that the infiltration was rapid immediately after the precipitation without undergoing any significant fractioning (Craig, 1961). The percolation of water resources in basement terrains is generally a gradual process due to the absence of primary porosity. In this regard, the rapid recharge in groundwater in this geological setting may be facilitated by the underlying structures that provide enhanced storativity and conductivity. Another logical explanation could be the recharge occurring during the cold winter where the rates of recharge are insignificant, but the precipitation is strictly received during the warm summer. But STGC 01 and STGC 02 plots on the right of the PLMWL. According to Craig (1961), this signifies the water that is depleted in ^{2}H and enriched in ^{18}O as the results of evaporation on the isotopic composition of groundwater. This could be explained in terms of the gradual infiltration of the results of poor primary porosity in the absence of structures.

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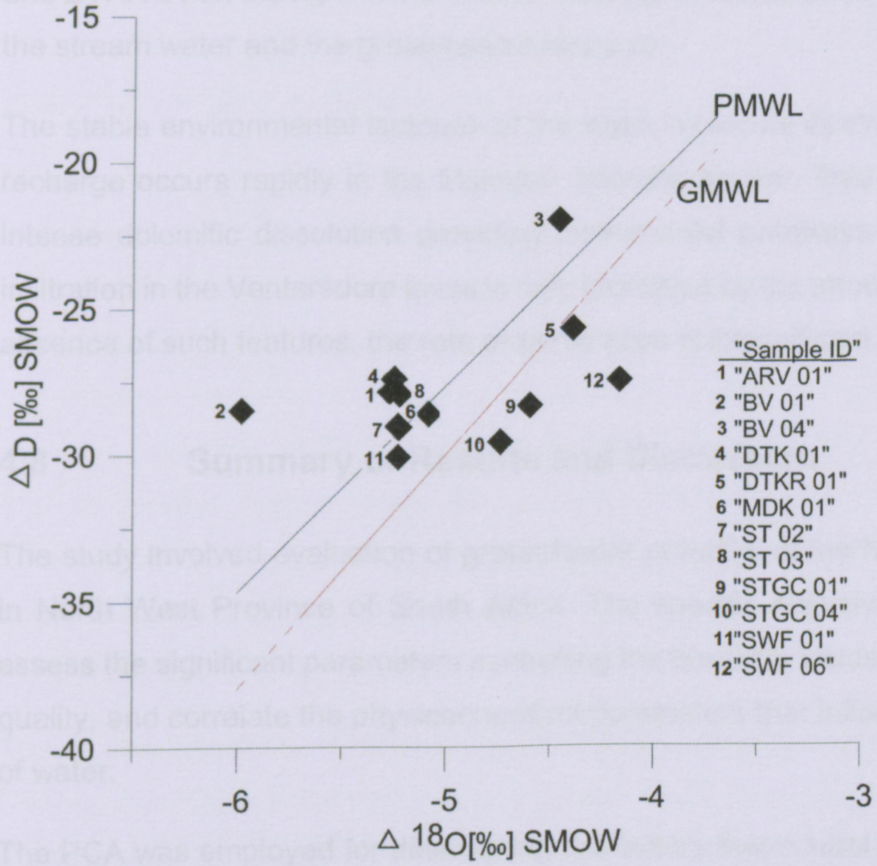

Figure 4. 24: Stable isotopes plot depicting the relationship between groundwater.

In comparison with the basement aquifer, the Malmani dolomite aquifer shows a wide array of $\partial^{18}O$ values that ranges between -4 ‰ and -6 ‰ and $\partial^{2}H$ that ranges between -22 ‰ and -30.1 ‰. All the boreholes that are underlain by the Malmani dolomite aquifer are plotting either on the PMWL or on the left. Only DTKR 01 which was acquired from the river is plotting on the right of the global meteoric water line. This signifies that the groundwater recharge in this aquifer unit occurs rapidly, immediately after the precipitation (Craig, 1961). According to Kafri (1986), the Malmani has undergone significant dissolutions. Consequently, there are voids, skarns, and underground cave providing immediate porosity.

The samples labeled DTK 01 and DTKR 01 were obtained adjacent to each other from the well and a stream respectively. In spite of the adjacency of the two collection point,

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they show significant variable isotopic signatures. DTK 01 locates on the left of the PMWL and DTKR 01 on the right of the GMWL. This signifies that there is no interaction between the stream water and the groundwater resource.

The stable environmental isotopes of the water molecule illustrate that the groundwater recharge occurs rapidly in the Malmani dolomite aquifer. This occurs as the results of intense dolomitic dissolution providing instrumental pathways for water. Whereas the infiltration in the Ventersdorp lavas is only facilitated by the structural development, in the absence of such features, the rate of percolation is insignificant.

4.8 Summary of Results and Discussion

The study involved evaluation of groundwater potential of the Naledi Local Municipality, in North West Province of South Africa. The specific objectives of the study were to assess the significant parameters controlling the borehole yields, to investigate the water quality, and correlate the physicochemical parameters that influence the hydrochemistry of water.

The PCA was employed for determining the factors that control the borehole yields. The 6 reclassified thematic layers comprising the geology, lineaments, LU/LC, drainage, soil, topography were used as input layers. The importance of the thematic layers was derived from the ratio of the sum of Eigenvectors corresponding to a single parameter to the total sum of eigenvectors across the all thematic layers. The resultant weights signified that the most imperative parameters that control the groundwater potential in the area are lineaments, drainage, and the geology. The supremacy of the weighting coefficient that is corresponding with the lineaments within the crystalline basement is common as the following authors observed the same outcome (Sener *et al*, 2005, Sander, 2007, Detay *et al*, 1989).

The groundwater potential of the area established consists of three groundwater potential classes that correspond to the spatiality of the underlying lithological domains. These prospective areas were as follow, the low groundwater potential (LGWP), moderate groundwater potential (MGWP), and high groundwater potential (HGWP). The three

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groundwater potential classes correspond with the crystalline basement rocks, sedimentary units of Kalahari Formation, and the Malmani dolomite rocks respectively. The superimposing of the borehole yields over the GWP class indicated that there is direct proportion relationship between the two parameters.

The groundwater within the crystalline basement is generally sub-modern. The decline in water level, within the current study area, particularly in the hard rocks reported by the Sami (2013), reflects over abstraction due to limited recharge. The poor conductivity and storativity are the major reasons behind poor recharge hence, the area receives a considerable high amount of precipitation. On the other hand, the Malmani dolomite presents the mixing of modern and sub-modern water resource. The high stream density and the porous nature of the medium comprising this aquifer promote groundwater infiltration. The recent recharge in the dolomitic rocks interprets the uniformity in hydraulic conductivity and intense karstification that enhances groundwater recharge and the mixing of water resources.

The most dominant water type in the study area is the Ca-Mg-HCO_3. The prevalence of Ca, Mg, and HCO_3 in the water facie indicates the freshness of water. This indicates that the rate of groundwater is quite significant and water is of the modern age. The areas characterized by this water type are often regarded as the recharge zones. The Na+K-HCO_3-Cl water type shows the water that is stagnant and as the results, Na+K has substituted Ca and Mg entirely but Cl is still facilitating HCO_3 precipitation. This facie portray ancient water that is interacting with the salt ponds around Stella. Ca-Mg-HCO_3-Cl and Ca-Cl-HCO_3 interpret water undergoing a gradual hydrochemical transformation. In the two water types, Cl is slowly substituting HCO_3. In this regard, this shows that there is mixing of various water types. The high TDS values show high relations with the Ca, Mg, and HCO_3.

The groundwater quality was assessed based on the conformity with the SANS241, water quality guideline. The existing monitoring data was supplemented with the primary data. The integrated datasets were gridded using inverse distance weight (IDW) to produce physicochemical thematic maps. The pH and TDS showed that the groundwater quality in the area is of pristine quality. Based on these parameters, water is well suited for

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domestic consumption prior to any treatment. However, the following parameters F- NO_3, EC, Cl, SAR, Hardness, and TAL shows undesired concentrations of the parameters do exist. The EC, TDS, and Cl show a similar spatial relationship, the significant level occurs in Stella location hinting the occurrence of domestic effluents. The NO_3 is attributed to large commercial cattle farming and on-sight sanitation. Fluoride was largely due to natural sources. In short, the groundwater distribution is variable throughout the area.

The factor analysis indicated that the groundwater composition is influenced by both the natural and anthropogenic processes. Factor 1 is interpreted as the effects of the dissolution of the plagioclase minerals and the dissolution of the sodium salts into the groundwater. The similar loadings of NO_3 and K in factor 2 explain the effects of the agriculture in the water quality. The high Cl could be attributed to the effluence from the household. Factor 3 and factor 4 explains recent groundwater recharge due to the dominance of Ca and HCO_3. There could similarly be attributed do the dissolution of the dolomitic rocks. Lastly, factor 5 is dominated by NO_3 explains the effects of the human sanitation and the commercial cattle farming.

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4.8.1 Contribution of the Study

The present study was conducted in Naledi Local Municipality, an area that is underlain by the crystalline basement rocks. According to Holland and Withüser (2011), the borehole yields in these aquifers are highly variable over a short distance. Moreover, Clark (1985), defines the basement aquifers as a complex aquifer medium that is not easily apprehended. However, the study provided the basis for groundwater potential mapping particularly in crystalline basement rocks. This is substantial contribution to the body of knowledge since a significant portion of the country is water stressed and under laid by the crystalline basement rocks. Furthermore, the study provided an approach to overcome the biases that are associated with manual weighting of the thematic layers when using weighted multi-datasets overlay to assess the groundwater potential.

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4.8.2 Limitations of the Study

The main aim of the study was to evaluate the groundwater potential at Naledi Local Municipality and develop an illustrative map that signifies the spatial variation of water resource potential. Although this goal was successfully accomplished, the confidence level of the of the resultant groundwater potential map is not defined since the map was not authenticated by the pump tests data which was not available. Moreover, the nonexistence of the standardized practice that is associated with the reclassification of the thematic layers and respective scores subject the outcomes of the present study to slightly marginal discrepancies when the study is undertaken by a different author.

Although the primary hydrochemical data, specifically isotopic data provided significant insight on the relative groundwater age of the groundwater resources, the water samples were spatially insignificant and numerically inadequate to warrant a concrete conclusion with a significant confidence level. In order to ascertain this drawback, more water samples should have been collected at a specified sampling interval.

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CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

This chapter presents the concluding remarks and recommendations of the study regarding evaluation of groundwater potential within the crystalline basement settings on Naledi Local Municipality, North West Province of South Africa.

5.1 Conclusion

The main aim of this study was to investigate the groundwater potential of the study area using the compilation of geological, hydrogeological and borehole data. The following conclusions were drawn from the study;

- The study demonstrated that the use of principal components for the integration of the multi-thematic datasets is significant for the demarcation of the groundwater potential.
- The groundwater potential of the area coincides with the underlying lithological domains. The areas of high groundwater potential correspond with the Malmani dolomite and constitute 16.61% of the potential areas and, the poor groundwater potential conforms to the crystalline basement rocks.
- The significant parameters that control the groundwater potential are; lineaments density, drainage cover and lithological domains.
- The groundwater development within the crystalline basement rocks is controlled by the lineaments and lineaments density.

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- The groundwater quality of the study is ideal for human consumption with the exception of the boreholes in Stella and Vryburg that shows significant nitrates concentrations.
- The groundwater quality of the area is controlled by the by the anthropogenic activities, such as agricultural activities, household waste disposal, and on-sight sanitation.
- The water resource within the crystalline basement rocks was derived from sub-modern recharge and recent groundwater occurs in Malmani aquifer.
- The high TH values within the Malmani dolomite are attributed to the dissolution of the dolomites.
- The water resource in the area can be effectively used for irrigation without tempering with the structure of the soil. More particularly in the Malmani aquifer.

5.2 Recommendations

In the light of the findings obtained and conclusions reached the following recommendations are presented;

- The present study was conducted based on the integration of the thematic layers to demarcate the groundwater potential of the area, the same approach may be employed to address the same issue in similar hydrogeological settings.
- The boreholes within Stella should be avoided, specifically for domestic consumption.
- The groundwater potential of the area, should to be updated as new data is made available.
- There is a need to conduct a comprehensive groundwater quality assessment, which includes trace elements and the microbial contaminant analysis.
- Borehole pump tests should be conducted in order to establish the hydraulic parameters of the aquifer.

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- There is a need for continuous borehole monitoring, particularly for boreholes that are used for household purposes.
- The study indicated excessive reliant on groundwater resource, therefore, groundwater-modelling study is recommended to establish the sustainable exploitations of this precious resource.

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REFERENCES

Adams S., Tredoux, G., Harris, C., Titus, R., and Pietersen, K., (2001). Hydrochemical characteristics of aquifers near Sutherland in the Western Karoo, South Africa. Journal. Hydrology: 24, pp 91–103.

Adams, S., (2009). Overview and research Needs, Basements Aquifers of Southern Africa: Water research Commission, Report: TT 428. pp 1-4.

Adial, K.A.N., Nanawi, M.N.M., and Abdullah, K., (2012). Integration of geographical information system and 2D imaging to investigate the effects of subsurface conditions on flood occurrence. Modern applied science Vol 6, no 3, march 2012, pp 11-21.

Andarge, Y., Moumtaz, R., Tenalem, A., Engida, Z., Tilahun, A., (2012). Hydrogeological and hydrochemical framework of Upper Awash River basin, Ethiopia, With special emphasis on inter-basins groundwater transfer between Blue Nile and Awash Rivers, Journal of African Earth Sciences: 65 (2012), pp 46–60

Back, W., (1960). Origin of hydrochemical facies of groundwater in the Atlantic Coastal Plain, Proc. 21st Int. Geol. Cong., Copenhagen, Part 1, pp. 87-95.

Back, W., (1966). Hydrochemical facies and groundwater flow pattern in northern part of Atlantic Coastal Plain, U. S. Geol. Prof. Paper, No. 498-A, pp. 1-42.

Baran, E., (2003). An Explanation for the 1,500 000 General Hydrogeological Map Kroonstad 2725. Pretoria, Department of Water Affairs and Forestry, pp 1-17

Barnard, H.C., (2000). An Explanation of the 1,500 000 General Hydrogeological Map. Pretoria, Department of Water Affairs and Forestry.

Barrett, M.H., Hiscock, K.M., Pedley, S., Lerner, D.N., Tellam, J.H. and French, M.J. (1999). Marker species for identifying urban groundwater recharge sources. A review and case study in Nottingham, UK.- Water Research (in press), pp 3083–3097.

© University of Venda

Bartolino, J.R., and Cole, J.C., (2002). Ground-water resources of the Middle Rio Grande Basin, New Mexico: U.S. Geological Survey Circular 1222, pp 132.

Boocock, C., van Straten, O.J., (1962). Notes on the geology and hydrology of the Central Kalahari region. Bechuanaland Protect. Trans. Geol. Soc. S. Afr. 65, pp 125–171.

Braune, E., and Mutheiwana, S., (2009). Towards sustainable utilization of basement aquifers in southern. Water. Pretoria, Water Research Commission, pp 104-113.

Bredenkamp, D.B., (1995). Dolomitic groundwater resources of the Republic of South Africa. Report No. GH 3857, Pretoria, Department of Water Affairs and Forestry.

Census, (2011). http,//www.statsa.gov.za/census01/census96/wards/catb/FS171.htm

CFCFF-Committee on Fracture Characterization and Fluid Flow (1996). Rock fractures and fluid flow, contemporary understanding and applications. National Academy Press, Washington

Charon, J.B., (1974). Hydrogeological applications of ERTS satellite imagery. In, Proc UN/FAO regional seminar on remote sensing of earth resources and environment, Cairo. Commonwealth Science Council, pp 439-456.

Chilton, P.J., and Foster, S.S.D., (1995). Hydrological characterization and water supply potential of crystalline aquifers in tropical Africa. Hydrogeology Journal 3, pp 36-49.

Clark, I. D., and Fritz, P., (1997), Environmental isotopes in hydrogeology. CRC Press/Lewis Publishers, Boca Raton, FL, pp 328 pp.

Clark, I.D., (1985). Groundwater abstraction from Basement Complex areas of Africa. Q J Engineering Geology 18, pp 25-34.

Coplen, T. B., (1993). Uses of environmental isotopes, in Alley, W. M., ed., Regional Ground-Water Quality: New York, Van Nostrand Reinhold, pp 227-254. ISBN: 978-0-471-28453-6.

Craig, H., (1961). Isotopic variations in meteoric waters. Science, 133: pp 1702-1703.

© University of Venda

De Villers, and Mangold, (2002). The Biophysical Environment State of the Environment Report, North West Province South Africa, North West Province Department of Agriculture Conservation and Environment, Mmabatho,

De Villiers, S. B., (1961). Boorplekaanwysing vir water in Suidwes-Transvaal. Bulletin 34, Pretoria, Department of Mines.

Department of Water Affairs and Forestry, (1996a). South African Water Quality Guidelines (2nd Edition) Volume 1, Domestic Use

Directorate National Water Resource Planning. Department of Water Affairs and Forestry, South Africa, September 2009. Integrated water quality management plan for the vaal river system: Task 2: Water Quality Status Assessment of the Vaal River System. Report No. P RSA C000/00/2305/1

DoH, Department of Health. (2011). National Environmental Health Policy. Notice 517, 2011. Government Gazette No. 34499

Du Toit and Van Dyk, (1993). Geohydrological Investigation For SADF Pomfret,District Vryburg, Drainage Region D410, Kuruman, DWAF.

Du Toit, W.H., and Lelyveld, M., (2006). An explanation for the 1,500 000 general hydrogeological map, Phalaborwa 2330. Pretoria, Department of Water Affairs and Forestry.

Du Toit, W.H., and Sonnekus, C., (2010). Explanation of the 1,500 000 Hydrogeological Map 2326 Polokwane. Pretoria, Department of Water Affairs.

Du Toit, W.H., and Sonnekus, C.J., (2011). Explanation of the 1,500 000 Hydrogeological map 2127 Messina. Pretoria, Department of Water Affairs.

DWA, (2009). Reconciliation Strategy for the Vryburg Town Area in Naledi Local Municipality in the Lower Vaal WMA. Prepared by WRP Consulting Engineers (Pty) Ltd.

DWA, (2011). South African National Standard (SANS South African National Standard (SANS241) for Drinking Water.

© University of Venda

DWA. (2010). Northwest Groundwater Master Plan. PRINTED BY, ROODTL.

Dziembowski, Z. M., and Appelcryn, D. T., (1987). Kalahari-Oos (Soutblok-oos-area) Grondwaterbronne Distrik Kuruman. Report No. GH3531, Pretoria, Department of Water Affairs.

El-Baz, F., Himida, I., Kusky, T., and Fielding, L., (1995). Groundwater potential of the Sinai Peninsula, Egypt. United States Agency for International Development, Cairo, Egypt, pp 1-10.

Environmental Protection Agency (1993). Paper Report No. EPA 910-R-99-013.

Ferguson, A.S., Layton, A.C., Mailloux, B.J., Culligan, P.J., Williams, D.E., Smartt, A.E., Sayler, G.S., Feighery, J., McKay, L.D., Knappett, P.S.K., Alexandrova, E., Arbit, T., Emch, M., Escamilla, V., Ahmed, K.M., Alam, J., Streatfield, K., Yunus, M., and van Geen, A., (2012). Comparison of faecal indicators with pathogenic bacteria and rotavirus in groundwater. Science of the Total Environment, 431, pp 314-322.

Gupta, A.K., Gupta, S.K., and Patil, R.S., (2005). Statistical analyses of coastal water quality for a port and harbour region in India. Environ. Monit. Asses. 102, pp 179-200.

Han, L., Groning, M., Aggarwal, P., and Helliker, B., (2006.). Reliable determination of oxygen and hydrogen isotope ratios in atmospheric water vapour adsorbed on 3A molecular sieve, Rapid Commun. Mass Sp., 20, pp 3612–3618.

Holland, M., and Withüser, K. T., (2011). Evaluation of geologic and geomorphologic influences of borehole productivity in crystalline bedrock aquifers of Limpopo Province, South Africa. Hydrogeology J., Issue 19, pp 1065-1083.

Hülya. B., (2006). Surface water quality assessment using factor analysis Water SA Vol. 32 No. 3. ISSN 0378-4738. PP 389-393.

Ingel, J. D., and Crouch, S. R., (1998). Spectrochemical Analysis; Prentice Hall: New Jersey, pp 560-563.

© University of Venda

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Creating Future Leaders

Ishaku, J.M., Ahmed A.S., and Abubakar, M.A., (2011). Assessment of groundwater quality using chemical indices and GIS mapping in Jada area, Northeastern Nigeria. Journal of Earth Sciences and Geotechnical Engineering, vol. 1, no. 1, 2011, pp 35-60.

Jaiswal, R.K., Mukherjee, S., Krishnamurthy, J., and Saxena, R., (2003). The role of remote sensing and GIS techniques for generation of groundwater prospect zones towards rural development. International Journal of Remote Sensing 24(5), pp 993-1008.

Jha, M., Chowdhury, A., Chowdary, V., and Peiffer, S., (2007). Groundwater management and development by integrated remote sensing and geographic information systems, prospects and constraints. Water Resources Management 21(2), pp 427-467.

Kafri, U., Foster, M., Detremmerie, F., Simonis, J., Weigmans, F.E., (1986). The hydrogeology of the dolomite aquifer in the Klipriver-Natalspruit Basin. Report No. GH3408, Pretoria,

Karim. S., (2009). Groundwater exploration and development, Basement Aquifers of Southern Africa, Water Research Commission Report TT428, pp. 428, pp 1-5.

Kazi, T., Arain, M., Jamali, M., Jalbani, N., Afridi, H., Sarfraz, R., Baig J., and Shah A., (2009). Assessment of water quality of polluted lake using multivariate statistical techniques, A case study. Ecotoxicology and Environmental Safety 72, pp 301– 309.

Kellet, R., (2004). Mapping groundwater in the regolith and fractured bedrock using ground geophysics, A case study from Malawi, SE Africa. CSEG RECORDER, February edition, pp 2433

Keyser, and Du Plessis. (1993). The geology of Vryburg Area. 2624 (Vryburg) (1, 250 000 Geological map). (one Sheet). Pretoria, South Africa, Government Printer.

Krishnamurthy, J., Venkataesa Kumar, N., Jayraman, V., and Manivel, M., (1996). An approach to demarcate groundwater potential zones through Remote Sensing and GIS. International Journal of Remote Sensing, 17, pp 1867-1884.

Lattman, L.H., and Parizek, R.R., (1964). Relationship between fracture traces and the occurrence of groundwater in carbonate rocks. J Hydrol 2, pp 73–91

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University of Venda
Creating Future Leaders

Liu, C.W., Lin, K.H., and Kuo Y.M., (2003). Application of factor analysis in the assessment of groundwater quality in a blackfoot disease area in Taiwan. Sci Total Environ. 2003 Sep 1;313 (1-3), pp 77-89.

Machiwal, D., Jha, M.K., and Mal, B.C., (2011). Assessment of groundwater potential in a semi-arid region of India using remote sensing, GIS and MCDM techniques. Water Resour Manage 25, pp 1359–1386.

Mackintosh, G., and Colvin, C., (2003). Failure of rural schemes in South Africa to provide potable water. Environmental Geology, 44, pp 101-105.

Magowe, M., and Carr, J.R., (1999). Relationship between lineaments and groundwater occurrence in Western Botswana. Ground Water 37(2), pp 282–286.

Meyers, R.A., (Ed.) (2000). Encyclopedia of Analytical Chemistry Ó John Wiley and Sons Ltd Publishers, Chichester, pp. 9468–9485.

Momba, M.N.B., Malakate, V.K., and Theron, J., (2006). Abundance of phathogenic Escherichia coli, Salmonella typhimurium, and Vibrio cholerae in Nkonkobe drinking water sources. J. Wat. Health, 4, pp 289-296.

Motebe, N.S., (2004). Hydrogeological chapter of the 1,250,000 Vryburg (2624) Geological Map. Unpublished CGS Technical report, pp 33.

Mpenyana-Monyatsi, L., and Momba M. N. B., (2012). Assessment of groundwater quality in the rural areas of the North West Province, South Africa Department of Environmental, Water and Earth Science, Tshwane University of Technology, Arcadia Campus, Scientific Research and Essays Vol. 7(8). pp. 903-914, 29 February 2012 Available online at http,//www.academicjournals.org/SRE DOI, 10.5897/SRE11.906 ISSN 1992-2248 ©2012 Academic Journals Full Length Research Paper, Private Bag X680, Pretoria 0001, South Africa

Mukherjee, P., Singh, C.K., and Mukherjee, S., (2012). Delineation of groundwater potential zones in arid region of India, A remote sensing and GIS Approach. Water Resour Manage 26(9), pp 2643–2672

© University of Venda

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Ncube EJ, Schutte CF (2005). The Distribution of fluoride in South African groundwater, A water quality and health problem. Wat. SA, 31(1), pp 365-372.

Nel, J.M., (2001). Assessment of the groundwater potential of the Middle Kop/Appleby aquifer, Stella District, North West Province. Unpublished M.Sc thesis, University of Free State, pp 78

Nel, J.M., and van Wyk, E., (1999). Preliminary assessment of the groundwater potential of the Middlekop/Appleby Aquifer, Stella District, North Western Region. Unpublished, DWA technical report, pp 43.

NWDACE-SoER, North West Department of Agriculture, Conservations and Environment. (2008). State of the Environment Report, North West Province, South-Africa.

NWPG (North West Provincial Government) (2002). State of the Environment Report, South Africa. Web: http://www.nwpg.gov.za/soer/fullreport/html [Date accessed: 12 June 2010].

NWP-SoER, North West Department of Agriculture, Conservations and Environment. (2002). State of the Environment Report, North West Province, South-Africa. The Web, http,//www.nwpg.gov.za/soer/FullReport/toc.html [Date accessed 3 March 2015].

NWPSoER. (2002). North West Department of Agriculture, Conservation and Environment Report on the State of the Environment in the North West Province - Preliminary Survey. Mmabatho, Department of Agriculture, Conservation and Environment (Unpublished).

Piper, A.M., (1944). A graphic procedure in geochemical interpretation of water analyses. Trans Am Geophys Union 1944; 25, pp 914–923.

SACS, 1980. (1980). Stratigraphy Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia, and the Republic of Botswana, Transkei and Venda, Handbook of the Geology.

© University of Venda

Sami, K., (2013). Vryburg scheme operating rule. Establishment of draught operating rules for standalone dams and schemes typically for small and rural municipal water supply schemes. WRP consulting engineers, report no. P RSA 000/00/14311/central/vryburg

Sami. K., (2009). Groundwater exploration and development. The Basement Aquifers of Southern Africa. Report. Water Research Commission. WRC Report No. TT 428-09. pp 19-30.

Sander, P., (2007). Lineaments in groundwater exploration, a review of applications and limitations, Hydrogeology Journal, 15(1), pp 71-74.

Sander, P., Minor, T.B., Chesley, M.M., (1997). Ground-water exploration based on lineament analysis and reproducibility tests. Ground Water 35(5), pp 888–894

Sati, M., Al-Rawi, A., Shihab, S., (2005). Application of Factor Analysis as a Tool for Water Quality Management of Tigris River within Mosul City Raf. Jour. Sci., Vol. 16, No. 1 Geology, Special Issue, pp 56-64.

SAWS. (2010). South African Weather Services. Retrieved from www.saws/vryburg.weal78.gov.za

Schutte, (1994). De geologie van die Gebied. Christina, unpublished Report, Council for Geosciences

Sener, E., Davraz, A., and Ozcelik, M., (2005). An integration of GIS and remote sensing in groundwater investigations, a case study in Burdur, Turkey. Hydrogeol. J, 13, pp 826-834.

Shaban, A., Khawlie, M., and Abdallah, C., (2006). Use of remote sensing and GIS to determine recharge potential zones, the case of Occidental Lebanon. Hydrogeology Journal 14(4), pp 433-443

Shafick, A., (2009). Basement aquifers of southern Africa, Overview and research needs. Water Research Commission, TT 428, pp 1-4

© University of Venda

Singh, K., Panda and Kumar, (2013). Artificial groundwater recharge zones Mapping using Remote Sensing and GIS, A case study in India Punjab. Environ Earth Sci, 4(62). pp 871–881.

Solomon, (2003). Groundwater study using remote sensing and geographic information systems (GIS) in the central highlands of Eritrea, Doctoral Dissertation, Environmental and Natural Resources Information Systems, Royal Institute of Technology, SE-100 44 Stockholm, Sweden.

Statsoft Incorporated, Electronic Statistics Textbook, Principal Components and Factor Analysis, http://www.statsoftinc.com/textbook/stfacan.html, 2002.

Sturm, P., and. Knohl, A., (2010). Hand ^{18}O measurements using off-axis integrated cavity output spectroscopy. Atmospheric Measurement Techniques Water vapor.

Tabachnik, B.S., and. Fidell, L.S., (2001). Using Multivariate Statistics, 4th Edition. Allyn and Bacon, Needham Heights, Massachusetts.

Teixera, J., Chamine, H.I., Maeque, E., Gomes, Carvalho, J. M., Alberti, A.P., and Rocha, F.T., (2008). Integrated approach of hydrogeomorphology and geographic information system mapping to the evaluation of groundwater resources. An example from the hydromineral system of Caldas Da Cava Northwest Portugal. Global Groundwater Resources. Eds B. S Paliwal. Selected papers from the 33 rd International geological Congress general symposium. Hydrogeology Scientific publishers India; pp 227-232.

Terblanche. M., and Stroebel. L., (2012). Case Study, groundwater exploration in the basement granites of the Kraaipan Group using aeromagnetic survey, pp 1-10.

Tredoux, G., (2004). Nitrate and associated hazard quantification and strategies for protecting rural water supplies. Water Research Commission Report. WRC Report No. 1058/1/04, CSIR Project No JW546 ISBN No.1-77005-173-2, CSIR Report No ENV-S-C 2004-021.

© University of Venda

Tredoux, G., Talma, A.S., and Engelbrecht, J.F.P., (2000). The increasing nitrates hazard in groundwater in the rural areas. Presented at the WISA 2000 Biennial Conference, Sun City, South Africa, 28 May -1 June 2000.

Van der Weisthuizen, C., and Hodgson, F.D.I., (1981). Development and evaluation of groundwater techniques for the determination of the groundwater potential in the southern Orange Free State and Northern Cape Province. Institute for groundwater studies (South Africa). WRC Report No. KV 273/11 ISBN 978-1-4312-0122-8.

Van der Westhuizen, W., de Bruiyin., H. and Meintjies, P., (1991). The Ventersdorp Supergroup, An overview. Journal of African Earth Sciences, Volume 33, pp. 83-105.

Van Dyk, G., (2011). Geohydrology of the Namaqua complex, Transvaal dolomites, Ventersdorp Supergroup and Kalahari Group.

Van Dyk, G., and du Toit, S., (1993). DWAF report, GH3813. Geohydrological investigation for SADF Pomfret. District Vryburg, Drainage Region D410.

Van Dyk, G., and Kisten, S., (2006). An explanation of the 1,500 000 general hydrogeological map. Pretoria, Department of Water Affairs

Van Dyk, G., and Sagadevagan, (2006). An Explanation of the 1, 500,000 General Hydrogeological Map Vryburg 2522

Van Dyk, T., (1993). Geohydrological investigation of SADF, Vryburg. Unpublished DWAF Report, 53P, GH3813.

Van Wyk, E., (1987). The Geohydrology of the Kalahari Gemsbok National Park. Report No. GH3499, Pretoria, Department of Water and Forestry

Van Wyk, E., (2011). Geology and geohydrology of the Northern Cape Province, South Africa.

Vegter, J.R., 1995. An explanation of a set of National Groundwater Maps. Water Research Commission. Report No TT 74/95.

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Vegter. J.R., (1990). Groundwater Regions and Sub-regions of South Africa. Unpublished Report Gh3697.

Winter, H., (1976). A Lithostratigraphic classification of the Ventersdorp Succession

Woodford, A., Rosewarne, P., and Girman, J., (2006). How much groundwater does South Africa have? www.srk.co.uk/groundwater/PDFs/1_A_Woodford.pdf.

Wright, E.P., and Burgess W.G., (1992). The hydrogeology of crystalline basement aquifers in Africa. Geological Society Special Publication, London

Yang, Y., Lerner, D.N., Barrett, M.H., and Tellam, J.H., (1999). Quantification of groundwater recharge in the city of Nottingham, UK.- Environmental Geology (in press).

Yeh, H.F., Lee, C.H., Hsu, K.C., and Chang, P.H., (2008). GIS for the assessment of the groundwater recharge potential zone. Environmental Geology. Doi, 10.1007/s00254-008-1504-9.

Yu, S., Shang, J., Zhao, J., and Guo, H., (2003) Factor analysis and dynamics of water quality of the Songhua River Northeast China. Water, Air Soil Pollut. 144 159-169.

Zingoni, E., Love, D., Magadza, C., Moyce, W., and Musiwa, K., (2005). Effects of a semi-formal urban settlement on groundwater quality Epworth, Zimbabwe: a case study and groundwater quality zoning. Physics and Chemistry of the Earth. 30, pp.680-688.

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