



Groundwater Resource Quality Objectives for the Crocodile West Catchment

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Dissertation submitted in fulfilment of the requirements for the
degree *Master of Science in Environmental Sciences* at the
North-West University

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Graduation May 2018

22796177

ACKNOWLEDGEMENTS

During this study I have experienced good times and hardships. I have learned valuable skills in the fields of hydrology and geohydrology. I learned what it is to endure and never give up on something good that you have started. The truth is that none of this would have been possible if it weren't for the guidance and support of everyone involved in my life during the last 3 years. Because of this I would like to thank the following parties:

- **Dr. Rainier Dennis**

Thank you for your excellent scientific input and leadership during this project. You always showed patience and kindness when trying to help me understand key concepts and principles related to the field of geohydrology. Your input into this thesis was invaluable and I am truly grateful.

- **Family and Friends**

The nagging is finally over! I would like to thank all my friends who supported and encouraged me through the writing of this thesis. I want to give a special thanks to my parents who encouraged me to go further with my studies and provided for me still throughout this time.

- **NWU and GyroLAG**

I want to thank these parties for their much-appreciated financial support, for enabling me to study further and complete this Masters degree.

- **Heavenly Father**

Finally, I would like to give thanks to God, for the privilege and opportunity to study. Thank you for peace of mind and comfort during the last three years of my studies.

ABSTRACT

Setting groundwater Resource Quality Objectives (RQOs) are difficult as groundwater is not bound to surface water drainage regions. The primary purpose of this study was to determine generic groundwater RQOs for the Crocodile-West catchment on a regional scale. Secondly, a case study was done to test the methodologies as set out in this thesis and to set numerical RQO limits on a local scale, as this is required for RQOs to be gazetted. To achieve this purpose groundwater resource units (GRUs), units with similar geohydrological features, were delineated based on available geohydrological parameters and a prioritisation strategy was developed. A groundwater profile was delineated for use in the prioritisation tool.

The Reserve determination and management class classifications, projects preceded by the Department of Water Affairs (DWA), for Integrate Units of Analysis (IUAs) in the Crocodile-West catchment were consulted in conjunction with a prioritisation strategy as described in this thesis to determine groundwater RQOs for the study area. The groundwater RQOs must promote the Reserve determination and the management classes for each IUA as set out by the DWA.

Highly prioritised RUs were identified with use of the developed prioritisation tool. The reason behind prioritisation is to identify areas which need further, more in depth investigation on both groundwater quality and quantity. Adhering to all the RUs at once is impossible as it would be too expensive and time consuming.

Regional scale groundwater RQOs and groundwater RQOs for a local scale case study were successfully drafted based on available geohydrological data. GRUs were also successfully delineated and a prioritisation tool developed. The groundwater RQOs for the Crocodile-West catchment can easily be adjusted as more up-to-date data becomes available. The prioritisation tool proved useful in the setting of groundwater RQOs and identifying areas of concern. The quaternary drainage regions were chosen as the reporting RUs for RQOs to encourage Integrated Water Resource Management (IWRM). Also after frequency analysis of the geohydrological data it was found that groundwater in the catchment strongly correlates with the topography. There were no convincing reasons to report groundwater RQOs to any specific geological units.

Challenges included - setting RQOs without a public participation process; - Data which isn't up-to-date; - Groundwater characteristics varying a lot over the entire catchment. It is important that the methodologies for setting groundwater RQOs be updated regularly and with care as they are corner stone guidelines for preventing degradation of our precious resource- groundwater.

Key word: Resource Quality Objectives; Groundwater Resource Units; Prioritisation; Reserve; Quaternary drainage regions; Integrated Water Resource Management; Public participation

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LIST OF ABBREVIATIONS

GMA	Groundwater Management Area
DWA	Department of Water Affairs
DWS	Department of Water and Sanitation
RDM	Resource Directed Measures
RU	Resource Unit
GIS	Geographic Information System
GRA I	Groundwater Resources Assessment Phase 1
GRA II	Groundwater Resources Assessment Phase II
GDP	Gross Domestic Product
IUA	Integrated Unit of Analysis
mamsl	meters above mean sea level
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
NGA	National Groundwater Archive
GMA	Groundwater Management Areas
GRU	Groundwater Resource Units
EWR	Ecological Water Requirements
WMA	Water Management Area
WR	Water Resources
WRC	Water Research Commission
ESBC	Ecological Sustainable Base Configuration
IWRM	Integrated Water Resource Management
MC	Management Class
SI	Stress Index
NWA	National Water Act
BHN	Basic Human Need
EFR	Ecological Flow Requirements
SPATSIM	Spatial and Time Series Information Modelling
INR	Institute for Natural Resources
WARMS	Water Resource Management System
CGS	Council for Geoscience
TDS	Total Dissolved Solids

1 INTRODUCTION

The following chapter introduces the research problem, the aims and objectives of the study.

1.1 Background

Historically, the Resource Directed Measures (RDM) process for groundwater and surface water were done independently and each of the disciplines conducted their own studies and selected appropriate resource units.

Surface water boundaries, quaternary catchments in particular, are used as the template for RU boundaries in a RDM study. The use of quaternary catchment boundaries is popular for the following reasons:

- All regional reporting to the Department of Water and Sanitation (DWS) is done on quaternary catchment scale as the majority of DWS planning models use these boundaries.
- Country-wide Water Resources (WR) studies (WR90, WR2005, WR2012) are conducted on quaternary catchment scale and the associated datasets are updated after completion of the Water Resources studies.
- The Groundwater Resources Assessment Phase I was evaluated and Phase II (GRAII, 2006) was conducted on quaternary catchment scale for the whole of South Africa.

In general, shallow groundwater will follow surface water boundaries and this has been one of the justifications of reporting groundwater to surface water boundaries. When considering deeper groundwater systems, the assumption sometimes do not hold true as seen in Figure 1.

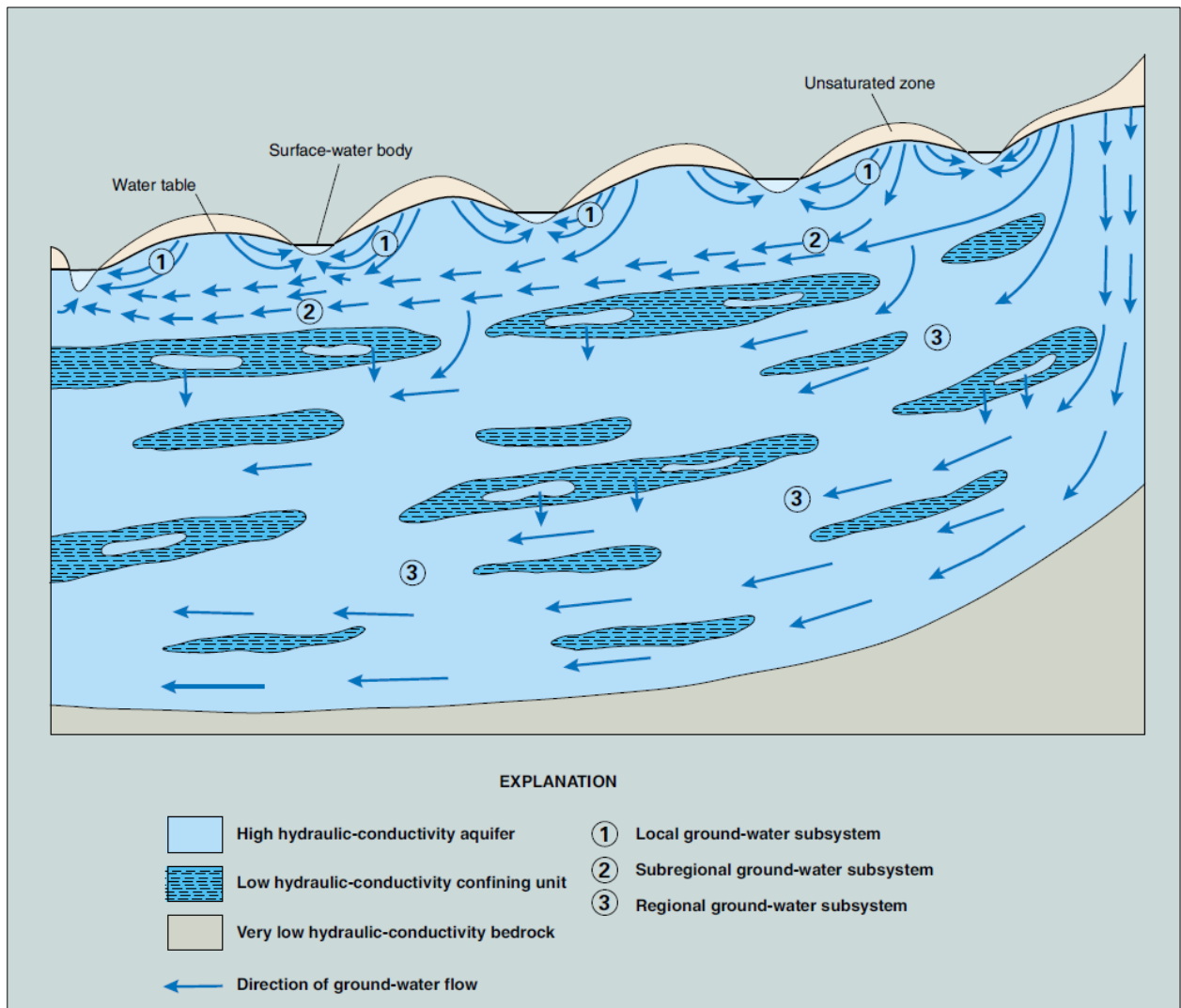


Figure 1 - Groundwater flow systems (USGS, 1999)

1.2 Research Problem

Specifying Resource Quality Objectives (RQOs) for groundwater is difficult because it's a highly distributed source. Groundwater is not bound to surface drainage regions, but groundwater movement is governed by aquifers which is related to the site geology (DWA, 2014a). Due to the complexity of determining representative groundwater RQOs for a whole Groundwater Management Area (GMA), a methodology is warranted that addresses the problem in a generic fashion on a regional scale, but requires implementation on a local scale.

Due to the cost implications associated with the implementation of RQOs it is imperative that prioritisation of groundwater management units take place based on analysis of existing geohydrological information of the study area and in consultation with stakeholders through a public participation process to address any data gaps that exist (DWA, 2014b).

1.3 Aims and Objectives of this Study

The aim of this study is to develop a set of generic RQOs that can be applied to groundwater within the Crocodile-West catchment. The application of the RQOs to a specific study area will be illustrated through the use of a case study.

The objectives of the study include the following:

- Delineation of groundwater Resource Units (RUs) based on available hydrogeological parameters even though final reporting will be done on surface water RUs.
- Formulation of a prioritisation strategy for the RDM resource units based on groundwater related criteria.
- Formulation of groundwater Resource Quality Objectives for the Crocodile West system.

Attention will be given to Step 1 to Step 5 in the RQO process as illustrated in Figure 2 as it relates to groundwater. Part of the RQO process requires stakeholder participation, which could not explicitly be addressed in this research study. The prioritisation presented in this study therefore relies solely on the available datasets. The prioritisation tool developed is provided to show how it can be used in the public participation process.

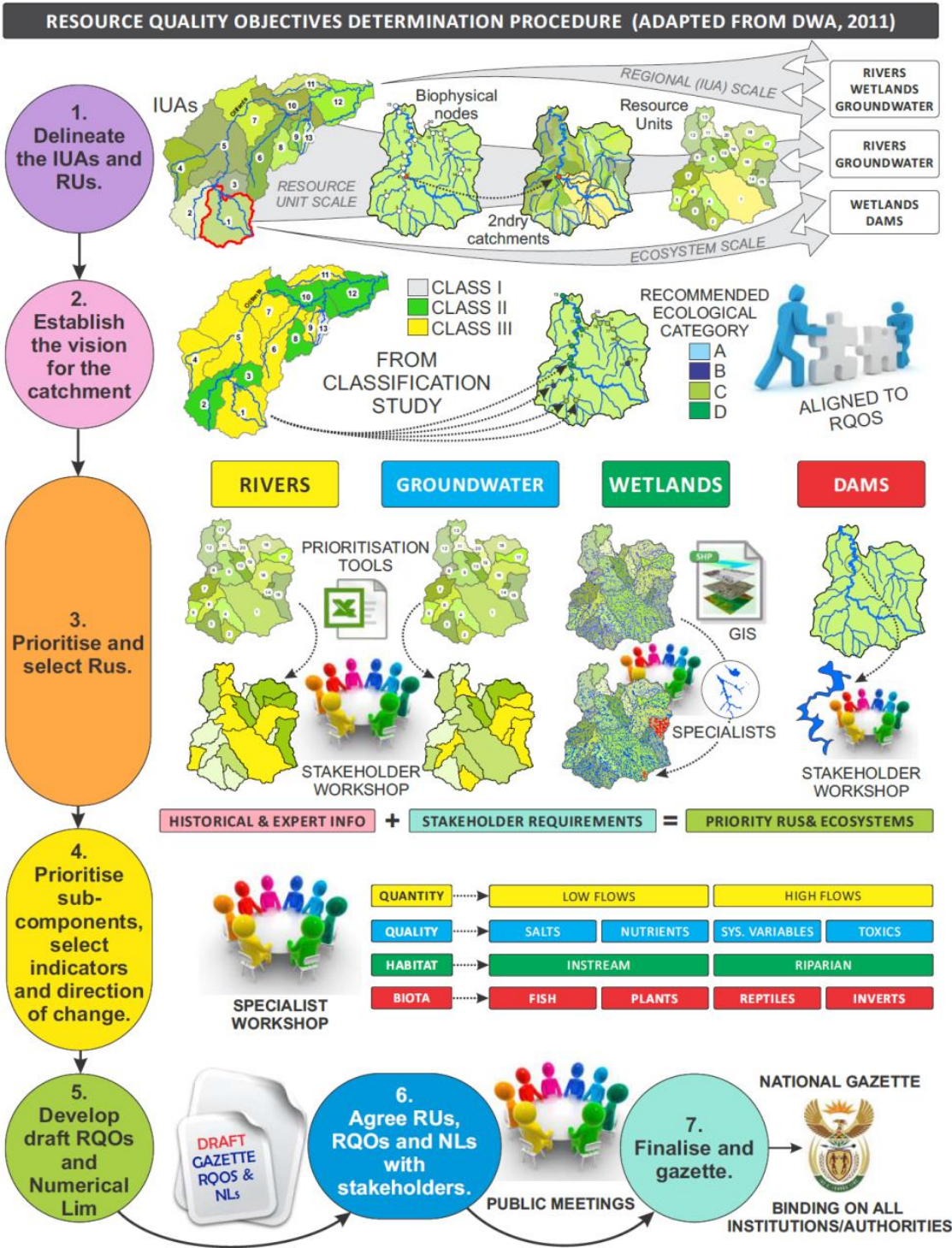


Figure 2 - RQO determination procedure (DWA, 2011)

2 LITERATURE REVIEW

The Constitution is the highest law in South Africa. Any acts or policies should be aligned with the Constitution. The Constitution offers everybody “the right to an environment not harmful to their health and well-being, to have an environment protected for the benefit of present and future generations, and to have access to sufficient food and water” (Constitution, Act no. 108 of 1996). To fulfil the basic water needs of the people of South Africa, the National Water Act (Act no. 36 of 1998), a build on of the Water Act of 1956 (Act no. 54 of 1956) and the Water Services Act (Act no. 108 of 1997) were established in alignment the Constitutional law. The National Water Act (NWA) is responsible for water resource management to ensure that there is enough water of an acceptable quality for basic human needs (BHNs) and ecological requirements while also providing space for economic growth. The Water Services Act (WSA) offers people of South Africa the right to access basic water supply and sanitation as well as a framework for delivery of these services.

The Water Act (Act no. 54 of 1956) considered groundwater mainly as a private use. For implementation purposes of the NWA, Resource Directed Measures (RDM) were established. The purpose of RDM is to enable practical and sustainable protection of the country’s water resources. Although the NWA (Act no. 36 of 1998) doesn’t directly refer to RDM, in Chapter 3 however, it does portray the fundamental tools from which RDM consists namely:

- Classifying a water resource
- Quantifying the Reserve
- Setting Resource Quality Objectives (RQOs)

It was recognised in the NWA (Act no. 36 of 1998) that there was a need for integrated management of all aspects of water resources, thus including groundwater. Methods for the groundwater component of RDM were first introduced in the 1999 version of RDM. This would come to be known as Groundwater Resource Directed Measures (GRDM).

Even though it was recognised that groundwater is essential to the RDM process, gaps still exist. Integrated Water Resource Management (IWRM) of RDM occur at quaternary catchments. There are some exceptions to the rule as will be explained in the literature to follow.

While the NWA requires integrated management of all water resources, groundwater and surface water are however still very different and need to be assessed separately before combining the results for integrated management to take place. The aim of this study is to focus on the setting of groundwater RQOs for the Crocodile-West Catchment. To be able to set groundwater RQOs for the Crocodile-West catchment, the preceding steps within the GRDM process need to be understood and assessed. The GRDM process and how it developed over the years will be

described shortly within the literature study. There are no significant differences between the 2005 and 2007 GRDM manuals, thus the later of the two will be referenced. The phases for GRDM assessments at the time were:

Preparatory phase
Description of the Study area
Delineation of Resource Units
Resource Classification
Quantifying the Reserve
Resource Quality Objectives

(Parson & Wentzel, 2007)

These steps were altered somewhat in the 2011 GRDM manual. The aim was intended to update the 2007 GRDM manual and fill in any existing gaps while still retaining the basic principles. Any GRDM process should adhere to the following procedure:

Data collection
GRDM initiation
Resource classification
Quantifying the Reserve
Resource Quality Objectives

(Dennis et al., 2011)

These phases, as set out by Dennis et al. (2011) will be described shortly in the literature study with the focus being on groundwater RQOs. Previous studies will be referenced, as the literature on the GRDM process is described.

2.1 Groundwater Resource Directed Measures

RDM is a strategy that The Department of Water Affairs and Forestry (DWAF), now known as the Department of Water and Sanitation (DWS), adopted with the purpose of implementing the NWA (Parson & Wentzel, 2007). Groundwater RDM is just one part of RDM which focuses solely on the groundwater aspect of RDM.

In 2005/2007 DWAF recognised the fact that GRDM needed to be updated. Guidelines for determining the class of a water resource, quantifying the Reserve and defining groundwater RQOs were lacking. The manual was set out to develop experts in the field who would be able to undertake GRDM studies with confidence and to promote information exchange, which could lead to the development of better methods for GRDM assessments (Parson & Wentzel, 2007). The GRDM manual has changed significantly since 2007. The 2011 GRDM manual describes detailed

steps which were Gazetted for Classification, Reserve determination and the setting of RQOs. These steps are described within the phases of GRDM to follow.

2.1.1 Data Collection

Before data collection can occur, the scale at which a GRDM assessment is to be conducted should be determined. Depending on the scale of an assessment different data sets may be better suited for the study to lessen uncertainty. The quantity and quality of data retrieved will dictate the confidence level of an assessment. Table 1 lists datasets that are required for a RDM study.

Table 1: Data to be acquired (Adapted from Dennis et al., 2011)

Data	Information
Study area	Quaternary catchment boundaries
Population	Population data per quaternary catchment
Conservation areas	Protected areas and world heritage sites
Water sources	Dams, rivers, wetlands, springs and groundwater occurrence
Digital Elevation Model (DEM)	Topography
Climate	Mean Annual Precipitation (MAP), Mean Annual Evaporation (MAE) and temperature
Geology	Lithology
Soils	
Drainage	Mean Annual Runoff (MAR) and flow data
Land use	Mines, irrigated cultivars, power generation, industrial use and borehole abstractions
Vegetation	
Geohydrology	Groundwater level, blow yield and Electric Conductivity (EC)

2.1.2 Uncertainty

Any limitations in measuring and interpreting geohydrological data sets are assessed in terms of a level of uncertainty. Groundwater recharge and storativity are two factors, which are difficult to calculate precisely and may vary, yielding a high uncertainty (Dennis et al., 2011).

Existing data should be updated regularly and as many analysis methods as possible should be used with the hope of defining the uncertainty to such an extent that decision making for management reasons is possible (Dennis et al., 2011).

2.1.3 Groundwater assumptions

As our understanding of groundwater's role in the environment is still developing, some assumptions need to be made to undertake a GRDM assessment. More specifically they are necessary for classification of a resource unit and to be able to quantify the Reserve so that water can be set aside for BHNs and ecological requirements. These assumptions were documented in the 2005/ 2007/ 2011 GRDM manuals:

- Groundwater has the ability to recover from negative impacts, although contamination can persist for years on end.
- Groundwater can be utilised for domestic and development purposes, to a certain extent, without diminishing its potential to sustain the Reserve and meet the RQOs set.
- If there isn't any significant decline in groundwater levels and water quality over a prolonged period, then an aquifer will still have the ability to satisfy the Reserve and to comply with generic RQOs.
- A sustainable groundwater abstraction rate is considered a function of the long-term mean annual recharge, while the volume of groundwater in storage acts as a buffer in dry phases.
- The distribution of recharge and abstraction from groundwater within a resource unit are considered relatively even.
- The suitability of every GRDM assessment will be evaluated every five years with monitoring data being considered.

Qualified personnel in the field of geohydrology will carry out the GRDM assessments in collaboration with other specialists such as ecologists and hydrologists with knowledge and an understanding of the study area.

2.2 GRDM initiation

2.2.1 Description of the study area

To obtain an accurate understanding of the geohydrological conditions of an area, for GRDM purposes, all intertwining factors of a selected area need to be reviewed, quantified and understood. Thus, an in-depth description of the study area is required. To describe an area the first step is to collect relevant and up to date data of that area (see Table 1).

In 2003, the Groundwater Resource Assessment Phase II project (GRA II) was initiated. The aim of this project was to quantify South Africa's groundwater resources on a national scale level. This project, which consisted of the development of algorithms to estimate recharge, storage, base flow and present groundwater use, several meaningful datasets and maps were generated. These maps and datasets are key for management of our water resources (Dennis & Dennis, 2009c).

2.2.2 Level of confidence

South Africa does not have the financial security or man power to carry out extensive GRDM assessments over the entire country. Thus, prioritisation is needed. An approach as described in the GRDM 2005/ 2007 manuals and also adopted by the 2011 manual is to prioritise GRDM assessments according to confidence levels. The four levels at which GRDM assessments are described in these manuals are illustrated in the following figure (figure 3):

1. Desktop GRDM study

- Data readily available
- Low intensity data requirements
- Quick assessment
- Low confidence results
- Useful planning tool

Low confidence

2. Rapid GRDM study

- Includes field trip for assessment of present state.
- Assess individual minimal impact licence applications
- Used in unstressed/ low ecological important catchments.
- Assessment duration less than 2 weeks.

3. Intermediate GRDM study

- Medium confidence results
- Field investigations required by specialists.
- Duration approximately 2 months, but less than 6.
- Assess individual licences with moderate impact in relatively stressed catchments.

High confidence

4. Comprehensive GRDM study

- High confidence results
- Site specific data required.
- Used to assess all compulsory licenses.
- Duration less than 2 years.



Figure 3: GRDM levels of assessment illustration(Parson & Wentzel, 2007).

For areas with a low water usage, low groundwater stress and where water usage has a limited impact on the quantity and quality of groundwater, a low confidence GRDM study will suffice. In areas where specific groundwater problems occur or where groundwater is clearly under stress a more intensive GRDM assessment will be needed to obtain a high level of confidence (Parson & Wentzel, 2007).

By doing a quick desktop GRDM study for a catchment it will become clear if areas within will need a further intermediate or comprehensive GRDM study to obtain higher confidence in the results. The catchment is then by doing so prioritised according to its need. The 2007 GRDM manual tabulated the levels of GRDM assessment required under specific circumstances (see Table 2).

Table 2: Level of GRDM assessment required for specific indicators (Parson & Wentzel, 2007)

Indicator	Aquifer Type		
	Low Yielding	Moderate Yielding	High Yielding
Sole source dependency	Intermediate	Comprehensive	Comprehensive
Highly impacted	Intermediate	Comprehensive	Comprehensive
High risk of contamination / over-abstraction	Rapid	Intermediate	Comprehensive
Moderately impacted	Rapid	Intermediate	Intermediate
Moderate risk of contamination / over-abstraction	Rapid	Intermediate	Intermediate
No sole source dependency	Rapid	Rapid	Intermediate
Low level of impact	Rapid	Rapid	Intermediate
Low risk of contamination / over-abstraction	Rapid	Rapid	Intermediate

- Low yielding – harvest potential less than 10 000 m³/km²·a or average borehole yield less than 1 l/s
- Moderately yielding – harvest potential between 10 000 and 50 000 m³/km²/a or average borehole yield between 1 and 2 l/s
- High yielding – harvest potential greater than 50 000 m³/km²·a or average borehole yield greater than 2 l/s

Desktop assessments are not mentioned in Table 2. This is because a desktop assessment should be done preliminary before any other assessment is to be considered (Parson & Wentzel, 2007).

2.3 Resource Classification

After the GRDM initiation process, which includes the description and delineation of a study area, a class can be assigned to a water resource. Classes to assign for a specified resource unit, are the present state in which the resource is as well as the state to which stakeholders decide to manage the resource in a sustainable manner (Dennis et al., 2011).

As the 2005 and 2007 GRDM manuals described it, the purpose of classification of groundwater resources at that time was to determine (Parson & Wentzel, 2007):

- Present status category
- Water resource category in terms of natural, good, fair and poor.
- Record each groundwater unit in the GRDM assessment data sheet.

This class warrants long-term protection of groundwater resource units while also promoting the development and effective use of these units. The management class is used to define the level

at which the Reserve is quantified and to which RQOs are required to be developed (Parson & Wentzel, 2007).

In 2005/ 2007 no definite steps for classifying a water resource were set. This was changed in the 2011 GRDM manual, which defines a fixed frame with definite steps to be followed in the classification process. They are described as follows:

Step 1: Delineate the units of analysis (UA) and describe the status quo of the water resource(s)

The delineation entails demarcating areas that have similar characteristics and take into account surface water and groundwater. These units are referred to as integrated units of analysis (IUA). Maps are delineated with use of data as described in the description of study area phase. Each IUA is to be classified, its Reserve calculated and RQOs defined for it.

An IUA can be defined as areas within a study range which were grouped together because they portray similar physical, chemical or ecological characteristics. Grouping is necessary to simplify classification and Reserve quantification over a study area and it will also allow for more confidence in the resulting RQOs (Parson & Wentzel, 2007). The Department of Water and Sanitation requires that quaternary catchments form the basic unit for IUAs as integrated management of all water resources is essential for any RDM study. However, there are exceptions:

DWAF (1999) described a situation where the dolomitic aquifers contributed to 60% of the baseflow. This lead to the exception that the dolomitic aquifers within the Crocodile-West catchment were delineated as a unique water resource unit.

In the resource unit delineation report for the Olifants catchment, delineation was based on surface drainage regions with the exceptions of certain hot spots (Department of Water Affairs (DWA), 2014a). These hot spots were defined as areas within IUAs that are subject to severe stress in terms of quantity, quality or both. The problem stated again, is that groundwater doesn't report to the quaternary boundaries. This is illustrated in Figure 4. The surface geology varies widely within each respective IUA of the Olifants Water Management Area.

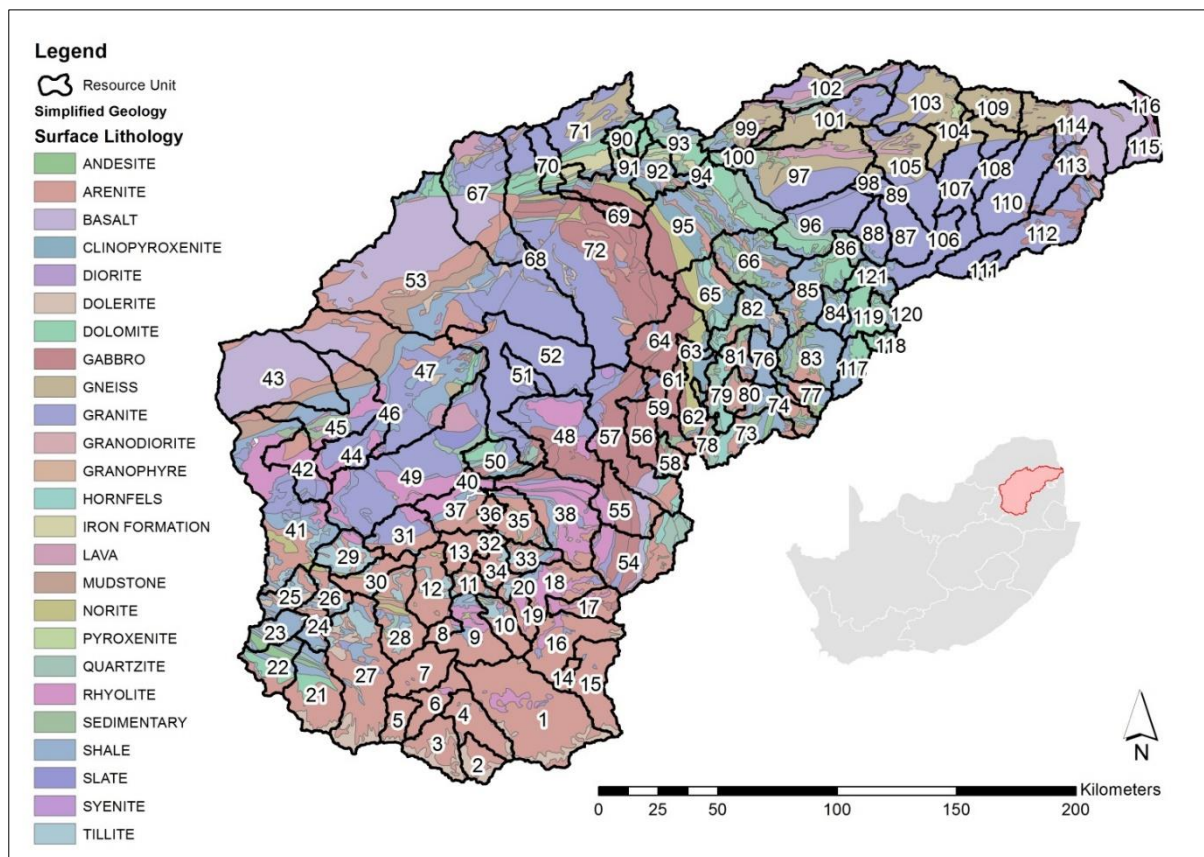


Figure 4: Surface geology vs. resource unit boundaries (DWA, 2014a)

The criteria chosen for the delineation process should be extensively and properly motivated as to authenticate the confidence level of the assessment. Geographical Information Systems (GIS) is an important tool for conveying the data collected and for delineating IUAs so that other specialists can conform to a clear understanding of the study area's condition (Parson & Wentzel, 2007; Dennis et al., 2011).

Step 2: Link socio-economic and ecological value and condition of the water resource(s)

After IUAs have been identified, selected areas of importance are then subject to more detailed studies. The aim is to locate areas with probable groundwater- surface water interactions, referred to by Dennis et al. (2011) as nodes. These nodes can be defined by:

- Lithological boundaries at aquifers and aquitards.
- Groundwater contribution to base flow.
- Groundwater contribution to wetlands
- Geological faults.
- Groundwater levels.

- Springs.

Socio-economic matters such as land-use, population size and Gross Geographical Product (GGP) should also be assessed in conjunction with the above mentioned as to meet the requirements of stakeholders, whom should be included in every step of the GRDM assessment (Dennis et al., 2011).

Step 3: Quantify the ecological water requirements (EWRs) and changes in non-water quality ecosystems goods, services and attributes

In this step, BHNs and ecological requirements are calculated. The following needs to be taken into account (Dennis et al., 2011):

- Recharge estimation
- Groundwater surface water interaction
- Groundwater use
- Groundwater quality estimations
- Aquifer vulnerability

Step 4: Assess system and set baseline class (or configuration)

In step 4 the water quantity and quality base configuration should be determined for long-term sustainability. It isn't a straightforward process to quantify a baseline configuration for groundwater. Therefore, certain indices were created to describe the baseline class. The purpose of these indices/indicators is to cover the physical and chemical characteristics of a water resource (Dennis et al., 2011).

Visual impact indicators of unsustainable use of groundwater resources include:

- Land subsidence or sinkhole formation.
- Long-term declining water levels on a regional level.
- Long-term declining water quality levels.

A guide is given in Table 3, for setting the present class of a IUA which is based on observable groundwater impacts.

Table 3: Guide for setting the present class of a groundwater unit based on observed environmental impact indicators (Dennis et al., 2011)

Present category	Generic description	Affected environment
Minimally used (I)	The water resource is minimally altered from its pre-development condition	No sign of significant impacts observed
Moderately used (II)	Localised low-level impacts, but no negative effects apparent	Temporal, but not long-term significant impact to: - spring flow - river flow - vegetation - land subsidence - sinkhole formation - groundwater quality
Heavily used (III)	The water resource is significantly altered from its pre-development condition	Moderate to significant impacts to: - spring flow - river flow - vegetation - land subsidence - sinkhole formation - groundwater quality

Stress

The objective of classification of resources is to ensure that the resource can be used in a sustainable manner over an extended period of time. The stress index (SI) (Table 4) as an indicator can help to achieve this objective and assist in defining the class to which an IUA should be managed (Dennis et al., 2011). According to DWA (2013a) the NWA does not define stressed aquifers, but it does hint on what causes groundwater stress. Stress occurs whenever the demand for water exceeds the possible supply and/or when water quality problems become a threat to the resource where the groundwater use should include current water use, the required water to sustain the Reserve and BHNs. SI categories are assigned as indicated in Table 4.

Table 4: SI for groundwater resources (DWA, 2013a)

Present category	Description	Compliance (Spatial/Temporal)
I	Minimally used	≤ 20%
II	Moderately used	20% - 65%
III	Heavily used	> 65%

The SI quantifies water stress by dividing groundwater abstraction in an IUA with the projected recharge for that unit, see below equation (Parson & Wentzel, 2007). A guide for quantifying groundwater use is documented in Table 5.

$$SI (\%) = \frac{gwUSE}{Recharge(Volume)} \times 100$$

Table 5: Guide for quantifying groundwater use (Dennis et al., 2011)

Activity	Percentage of recharge
Stock watering, farm domestic water supply, rural water supply	Use ranges between 5% and 20% of recharge
Small-scale irrigation, rural water supply, water supply for villages and small towns	Use ranges between 20% and 40% of recharge
Water supply for large rural communities, medium to large towns, large scale irrigation	Use ranges between 40% and 65% of recharge

Present status category

The present status category is another indicator to be used in the classification procedure which is based on the DWS water quality guidelines for use in households as documented in Table 6.

Table 6: Present status category based on DWA water quality guidelines for domestic use (Dennis et al., 2011)

Present class	Description	Compliance (Spatial/Temporal)
I	DWA class 0 or 1 natural background	95%
II	DWA Class 2 (95% compliance) or natural background (75% compliance)	75%
III	DWA class 3 or 4 or natural background (< 75% compliance)	<75%

With this indicator, it should be remembered that the natural state of some groundwater resources, due to geology, may not be suitable for the proposed use. The highest beneficial use which should earn the strictest quality requirements is that of domestic use. It is accepted that if a water resource is deemed fit for domestic use, it will be acceptable for ecological requirements.

Step 5: Scenario development within the IWRM process

The aim of this step is to create catchment configuration scenarios to be evaluated within the IWRM process by the stakeholders. Scenarios may include climate change impact and land-use changes (Dennis et al., 2011).

Step 6 (evaluate scenarios with stakeholders) and 7 (gazette class configuration) are not included in the scope of this study as they are both part of the further assessment of IWRM. The GRDM 2011 manual refers to Dollar et al. (2006) for the procedures of steps 6 and 7.

2.4 Quantifying the Reserve

The Reserve is clearly described in the NWA (Act no. 36 of 1998) as the quantity and quality of water needed:

- (a) to satisfy BHNs by securing a basic water supply, as prescribed under the Water Services Act (Act no. 108 of 1997) for people to be supplied with water from that resource, and
- (b) to protect aquatic ecosystems in order to secure ecologically sustainable development and use of water resources.

The Reserve in terms of groundwater is the portion of groundwater required for sustaining BHNS and aquatic ecosystems to which a groundwater resource is connected (Parson & Wentzel, 2007). It is the DWS's responsibility to quantify, manage and monitor the Reserve.

The 8 steps of the Reserve determination process as described by Dennis et al. (2011) are all interlinked with the steps as set out in the classification phase:

Step 1: Initiate the basic human needs and EWRs assessment

To quantify the Reserve for groundwater the volume of water needed to sustain BHNS and which contributes to the EWRs needs to be calculated. To calculate the Reserve in terms of groundwater the equation below is used:

$$Reserve(\%) = \frac{\{(EWR_{gw} + BHN_{gw})\}}{Re} \times 100$$

Re = recharge

BHN_{gw} = basic human needs derived from groundwater

EWR_{gw} = groundwater contribution to EWR

Groundwater contribution to EWRs should consist of:

- The contribution of groundwater to the baseflow of rivers.
- The contribution of groundwater to wetlands.
- The contribution of groundwater to springs and other groundwater dependant ecosystems (GDEs).

All people have a right to water for BHNS, which is currently set at 25l/p/d.

To quantify recharge is a complicated process due to the differences in aquifer characteristics and inconsistent rainfall. Recharge is defined as water addition to the zone of saturation. It should be kept in mind that recharge doesn't only occur because of rainfall but because of sub-surface-seepage from rivers, dams or lakes and inflows from other aquifers as well. The above mentioned should all be included in recharge calculations depending on the specific IUA conditions (Dennis et al., 2011).

As described in the Upper Vaal WMA further measures need to be taken to protect the Reserve due to a lack of groundwater sub-components for prioritisation (DWA, 2014c). Protection zones are presented as an extra means of protecting the Reserve.

Parson & Wentzel (2007) describes the concept of infringements as well as four types of protection zones. These protection zones will be discussed here but the calculations are given in Chapter 8.4.

A. River protection zone

If a river system is fed through groundwater, the groundwater gradient must be maintained to protect the ecological system. This can be done by specifying a protection zone around rivers.

B. Wetland protection zone

If a wetland is fed through groundwater, the groundwater gradient must be maintained to protect the ecological system. This can be done by specifying a protection zone around wetlands.

C. Microbial protection zone

To sustain groundwater quality, it needs to be protected against microbial pollution.

D. Radius of influence

For multiple boreholes in a wellfield, a wellfield model is needed to see if the protection zone of a borehole is violated.

Infringements occur when abstraction from a groundwater resource overlaps a proposed protection zone. RQOs should be set so that infringements of protection zones do not occur; however, this is only possible on a local scale as each protection zone will have its own parameters. If an infringement was present before the protection zone was set, the RQOs should allow it, but the protection zone must be monitored with the purpose of preventing any further infringements (DWA, 2014c).

Once the Reserve has been determined and RQOs for a groundwater resource met, then allocation of groundwater to potential users may occur.

*Step 2: Determine eco-regions, delineate resource units and select study sites
(aligns with step 1 in the classification phase)*

Step 3: Determine the reference conditions, present ecological status and the ecological importance and sensitivity of each of the selected study sites (aligns with step 2 of the classification phase)

Step 4: Determine the basic human needs and EWRs for each of the selected study sites (aligns with step 3 and 4 of classification phase)

Step 5: Determine operational scenarios and its socio-economic and ecological consequences (aligns with step 5 of classification phase)

Step 6: Evaluate the scenarios with stakeholders (aligns with step 6 classification phase)

Step 7: Design an appropriate monitoring programme

Monitoring might not directly be a part of the GRDM process, but it's essential for determining whether the Reserve and RQOs as set out in the GRDM process are realistic and met. The aim of monitoring groundwater resources, is to simply quantify groundwater's response to certain stressors such as abstraction or recharge. In other words, groundwater resources could be susceptible to change in water level, quality or both (Dennis et al., 2011). Monitoring of data from groundwater resources enables us to understand groundwater environments and changes within it, and therefore effectively apply groundwater management.

Because of the labour and costs involved in monitoring groundwater resources, a monitoring class system was developed (Figure 5). This class will combine both the potential importance of a groundwater resource as well as its quality. Only significant groundwater dependant ecosystems (GDEs) and highly vulnerable aquifers should be considered in such an assessment.

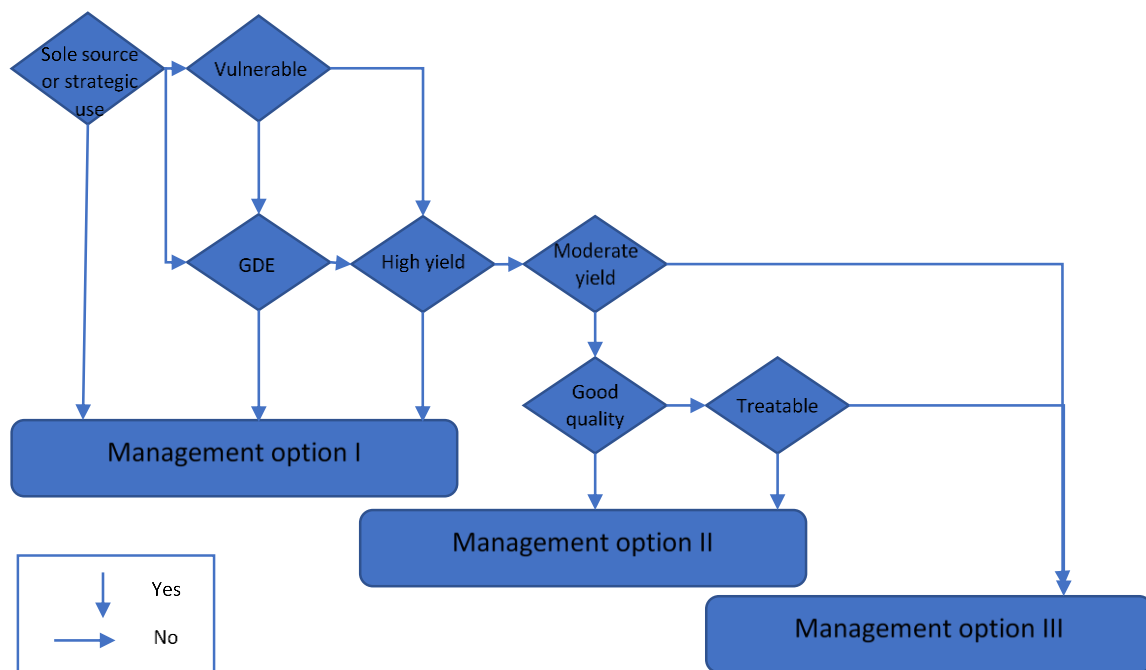


Figure 5: Flow chart to determine the recommended aquifer management class (Dennis et al., 2011). The options for managing each class is given in Table 7.

Table 7: Definition of each management option (Dennis et al, 2011)

Management option	Recommended monitoring
I	Monthly monitoring of groundwater levels and chemistry
II	Monitoring of groundwater levels and chemistry every 3 months
III	Monitoring of groundwater levels and chemistry every 6 months

Water quality analysis should include the following parameters: pH, EC, Ca, Mg, Na, K, Palk, Malk, F, Cl, NO₂(N), Br, NO₃(N), PO₄, SO₄.

Step 8: Gazette and implement the Reserve

2.5 Resource Quality Objectives

RQOs are numerical or descriptive limits which should be set to reflect a balance between the need to develop and use a water resource while also protecting the water resource in a sustainable matter. They are measurable goals for a resource that define its utility (Colvin & Cave,

2004). For groundwater, these descriptions are made based on quality and quantity measurements and need to be met (DWAF, 2007).

RQOs may include any conditions that have to be met to ensure that the water is maintained in a sustainable and desired state, as long as it's in agreement with the National Water Resource Strategy (Colvin & Cave, 2004) and takes into account the Reserve. RQOs should always portray the management class and should never be set more stringent than reference conditions. They can be based on both the Reserve and the classification of an IUA with the purpose of putting the Reserve and classification system into practice. The Minister is responsible for determining RQOs for significant water resources (Parson & Wentzel, 2007). They must be based on DWS's policy statements and methodologies and be aligned with the National Water Resource Strategy (NWRS).

Considerations are to be made before RQOs can be set. The purpose of sustaining balance between use and protection should always be kept in mind during these considerations. As set out in Section 13.3 of the NWA (Act No. 36 of 1998) they are:

(a) the Reserve;

(b) the instream flow;

(c) the water level;

(d) the presence and concentration of particular substances in the water;

(e) the characteristics and quality of the water resource and the instream and riparian habitat;

(f) the characteristics and distribution of aquatic biota;

(g) the regulation or prohibition of instream or land-based activities which may affect the quantity of water in or quality of the water resource; and

(h) any other characteristic of the water resource in question.

(The highlighted text can be directly linked to groundwater resources).

2.5.1 Setting RQOs

Setting of groundwater RQOs needs to be based on the management class and the Reserve as determined for each resource unit in a GRDM assessment. The procedure for setting groundwater RQOs as described in the 2005/ 2007 GRDM manuals are:

- To define the specific characteristics of each groundwater resource unit that need to be sustained with the purpose of maintaining the aquifer functionality.
- Select and monitor measurable indicators from a resource unit's characteristics which may be impacted by immediate anthropogenic surroundings or other posed risks.

- Monitoring protocols should be defined to assess whether or not the RQOs are being met and to be utilized in GRDM assessment reviews in the future.

The following 6 steps were described for setting RQOs in the 2011 GRDM manual:

Step 1: Identify water users within each water resource management unit, and where appropriate, align with Step 1 of the water resource classification procedure set out in Regulation 2(4) of gazetted Classification.

Step 2: Determine the present state per water user and, where appropriate, align with Step 5 of the water resource classification procedure set out in Regulation 2(4).

Step 3: Determine the desired water quality per user and, where appropriate, align with Step 6 of the water resource classification procedure set out in Regulation 2(4).

Step 4: Determine water user specifications and, where appropriate, align with Step 6 of the water resource classification procedure set out in Regulation 2(4).

Step 5: Determine water quality requirements of water uses and, where appropriate, align with Step 6 of the water resource classification procedure set out in Regulation 2(4).

Step 6: Gazette and implement the resource quality objectives.

Another requirement from the NWA is that water use licences be reviewed. Thus, to be efficient it is needed to monitor data for a significant resource on a regular basis. Data to be monitored include but is not limited to:

- Level of groundwater
- Groundwater gradient
- Quality of groundwater
- Abstraction volumes from a groundwater resource
- Any activities that may influence groundwater quality and quantity
- Aquifer integrity

Monitoring groundwater RQOs for an entire resource unit is impossible, it's simply too large. Resource units can be broken into smaller monitoring areas, as done in the groundwater Reserve determination of the Thukela and the Mhlathuze regions. These monitoring regions should be representative of each resource and the underlying aquifers. Time series data should be compared within a monitoring area to see whether the RQOs are realistic and being met (Dennis & Dennis, 2009a; Dennis&Dennis, 2009b). Due to costs and time implications it is necessary to choose representative boreholes for a specific aquifer or area. These monitoring boreholes should adhere to the following criteria:

- In dry periods the water level may drop, but should not be allowed to drop beyond the main water strike.
- Abstraction rates should be lowered if the water level doesn't reach its original position after a wet period (Dennis et al., 2011).

2.5.2 Types of groundwater RQOs

The types of RQOs are more extensively covered in the 2007 and 2011 GRDM manuals than in the 2005 manual. The National Water Resources Classification System (NWRCS) expresses certain constraints with regards to BHNs, surface water, international responsibilities and the strategic use of water.

Rivers

Rivers can be groundwater fed and/or have riparian vegetation. If the river in question is assessed and complies with one of the above-mentioned criteria, then RQOs need to be set as a water level or water level gradient which should be maintained for a specified distance from the river. Figure 6 can be consulted to decide whether RQOs need to be set or not.

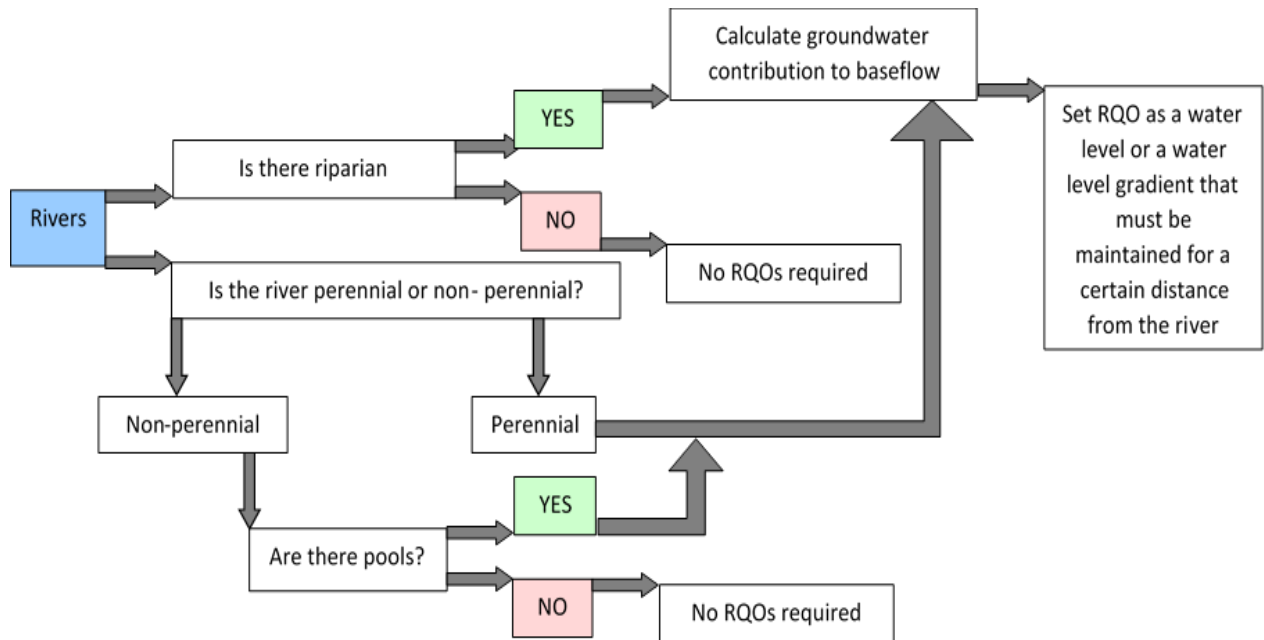


Figure 6: Mapping of classification to RQOs for rivers (Parson & Wentzel, 2007)

Wetlands/ estuaries

The volume of water flowing into groundwater driven wetlands must be determined for setting RQOs. As with rivers, the groundwater level/ gradient can be set for a certain distance from the wetlands in the RQOs in order to maintain the wetland. See Figure 7.

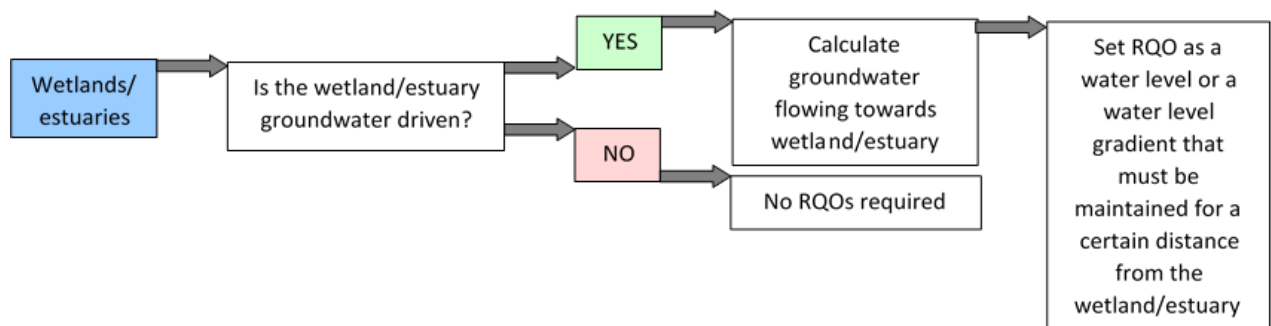


Figure 7: Mapping of classification to RQOs for wetlands/estuaries (Parson & Wentzel, 2007)

Springs

Groundwater is the driving factor for all springs and therefore it is necessary for them all to be protected. Hot springs are usually deeper than cold springs, therefore Figure 8 distinguishes between them. It is important that no potentially harmful activities take place within the vicinity of a spring or the source of a spring.

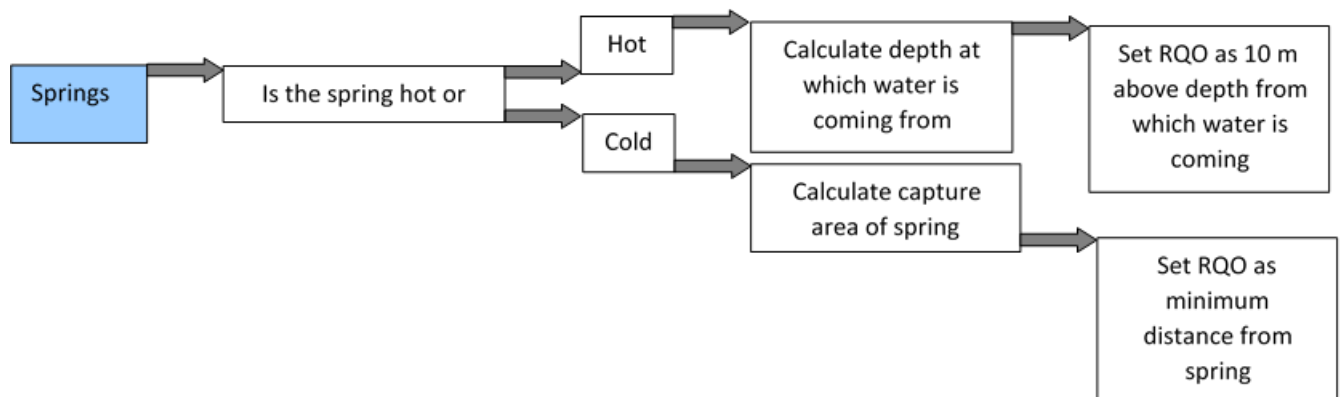


Figure 8: Mapping of classification to RQOs for springs (Parson & Wentzel, 2007)

Groundwater use

It is important to protect groundwater for BHNs. International obligations and strategic use of our groundwater resources are also driving factors for setting RQOs for groundwater. Flow rates in boreholes and across international borders must be quantified for delineation of protection zones. The RQOs can then be set as a groundwater level or gradient. This RQO must be maintained at a specified distance from the protection zone. See Figure 9.

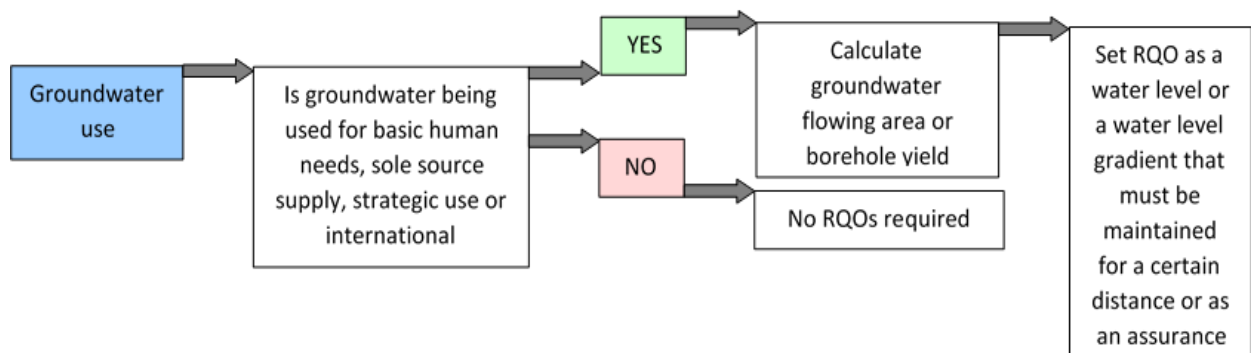


Figure 9: Mapping of classification to RQOs for groundwater use (Parson & Wentzel, 2007)

Protected areas

RQOs need to be set for protected areas such as national parks and world heritage sites. RQOs can then be set after calculating the volume of flow into these regions as water level or gradient at a certain distance from the protection zones. Figure 10 can be consulted.

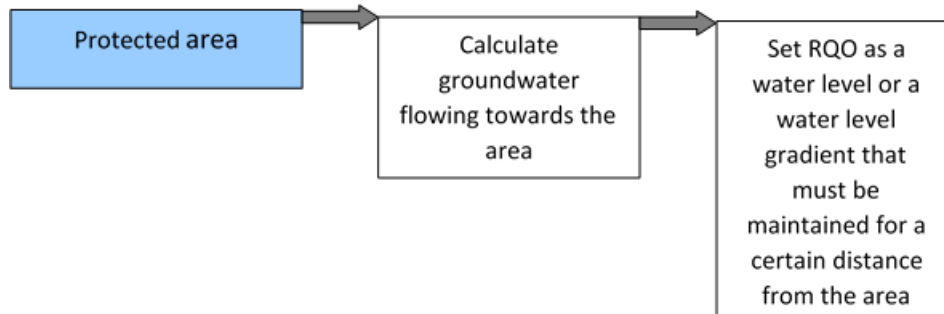


Figure 10: Mapping of classification to RQOs for protected areas (Parson & Wentzel, 2007)

Karst aquifers

For Karst aquifers specified RQOs are already defined. They are that groundwater level within a Karst region may not vary more than 2m with time. The reason for this is because South Africa experiences a lot of sinkholes due to too much abstraction from Karst aquifers (Parson & Wentzel, 2007).

2.6 Post GRDM

After the GRDM process has been evaluated and groundwater RQOs set the following should take place:

Implementing RQOs
Allocation and licensing

The methods used should be scientifically and legally defensible before they are published. Allocation of groundwater can only be done after the groundwater volume contributing to the Reserve has been established and only if the RQOs are met.

Parson & Wentzel (2007) stated that all water resources should be assessed to the same degree and the results should be of high confidence. With the idea of integrated water resource management and the fact that according to the NWA, water management strategies should be addressed at National and catchment level, it is difficult to see a way of building higher confidence in GRDM assessment. As previously mentioned, groundwater is not bound to quaternary catchments as surface water is, but still they need to be assessed at quaternary levels.

3 DESCRIPTION OF STUDY AREA

3.1 Locality

The Crocodile-West catchment is only one part of the Crocodile-West and Marico WMA (Figure 11) but is focused on separately because of the difference in catchment dynamics and characteristics as well as social and economic structure (DWAF, 2004b).

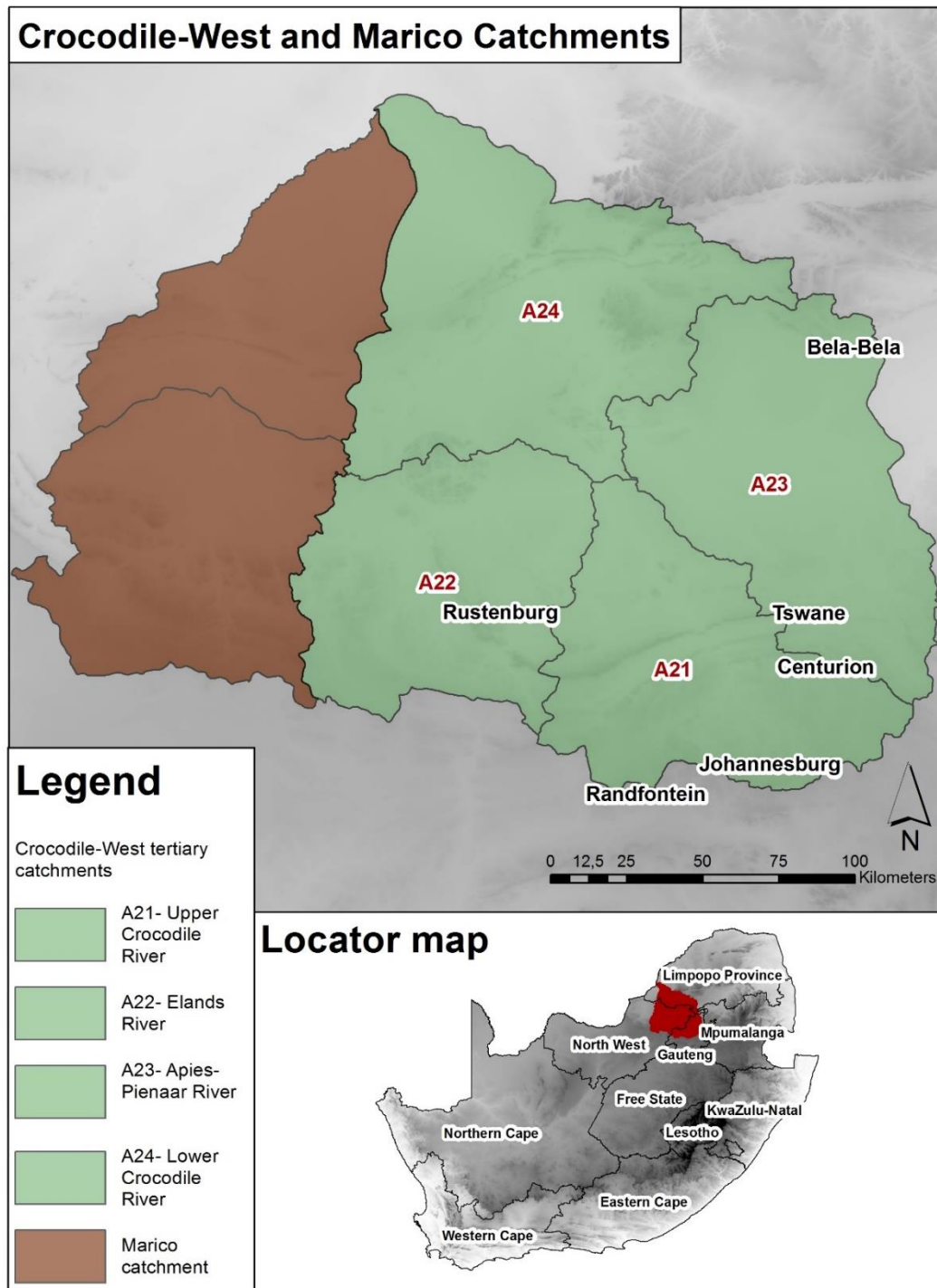


Figure 11 – Crocodile-West catchment (Bailey & Middleton, 2005)

The Crocodile-West and Marico WMA is the second most populated in the country. This area generates almost a third of the country's GDP. About 5,5 million people inhabit this area according to 2005 data (Basson & Rossouw, 2008). The Crocodile-West catchment spans over parts of the North West, Limpopo and Gauteng provinces (DWAF, 2004b) and was further divided into four tertiary-catchment areas the Upper Crocodile River (A21), Elands River (A22), Apies-Pienaars River (A23) and Lower Crocodile River (A24). Together they consist of 39 quaternary catchments with a combined area of 29 400 km².

Water transfer to this catchment, plays a key role in water demand. In 2000 about 520 Mm³ was transferred to this system while only about 3 Mm³/a is transferred out of the catchment (Basson & Rossouw, 2003; DWAF, 2004b; Bailey & Middleton, 2005). Potable water supply from the Rand Water bulk distribution system is transferred from the Upper Vaal to urban areas such as Johannesburg, Rustenburg and Tswane and is also considered the most significant transfer into the study area. Smaller transfers into the study area include water from the Olifants catchment to the Cullinan mine. Transfers out of the catchment is mostly from the Pienaars River to the Limpopo WMA (more specifically to Modimolle and Bella Bella) and from Vaalkop Dam to the Deelkraal cement factory in the Marico catchment. Inter-basin transfers occur from the Roodekopjes Dam to Vaalkop Dam via the Magalies bulk water distribution system (Basson and Rossouw 2008).

3.2 Climate

Climate has a significant impact on evaporation and transpiration rates, these values will differ at different climatic regions, and need to be measured at each subsequent region (Winter, et al., 1998).

In the higher areas of the catchment cold winters of about 1°C to 15°C can be expected at night and day respectively and hot summers at about 10°C to 30°C. North of Magaliesberg Mountain range winters are more moderate and summer reach temperatures of up to 35°C to 40°C in midday. Figure 12 shows the monthly average temperatures of major cities within the Crocodile-West catchment recorded over a 112-year period.

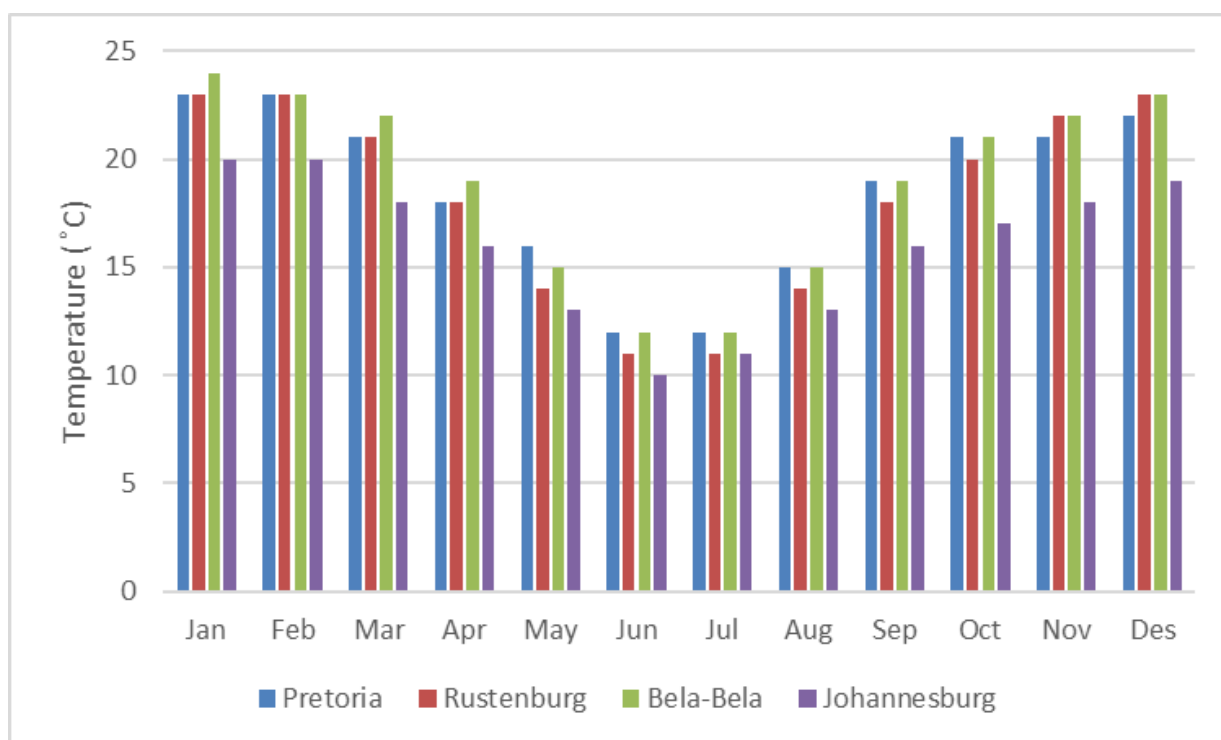


Figure 12 - Monthly average temperatures of major cities (Weatherbase, 2016)

Rainfall with thundershowers are normal in the summer months from October to April, peaking between December and January. MAP is generally higher in the southern and eastern parts of the catchment where this value is at average 800 mm/a as shown in Figure 13.

The northern and western lower lying areas tend to have a MAP of between 500 mm/a and 600 mm/a. Annual precipitation fluctuate in dry/wet cycles between 7 and 10 years (variations from 300 mm in dry years to 1000 mm in good rainfall years). In the past, a lot of damage has been caused to irrigation farms on the broad floodplains in the middle and lower Crocodile River systems due to floods (DWAF, 2004b). Figure 14 shows the mean annual precipitation of major cities within the Crocodile-West catchment recorded over 81 years. MAE fluctuates from 2000mm in the south to 2600 mm at the confluence of the Crocodile River.

Crocodile-West Mean Annual Precipitation

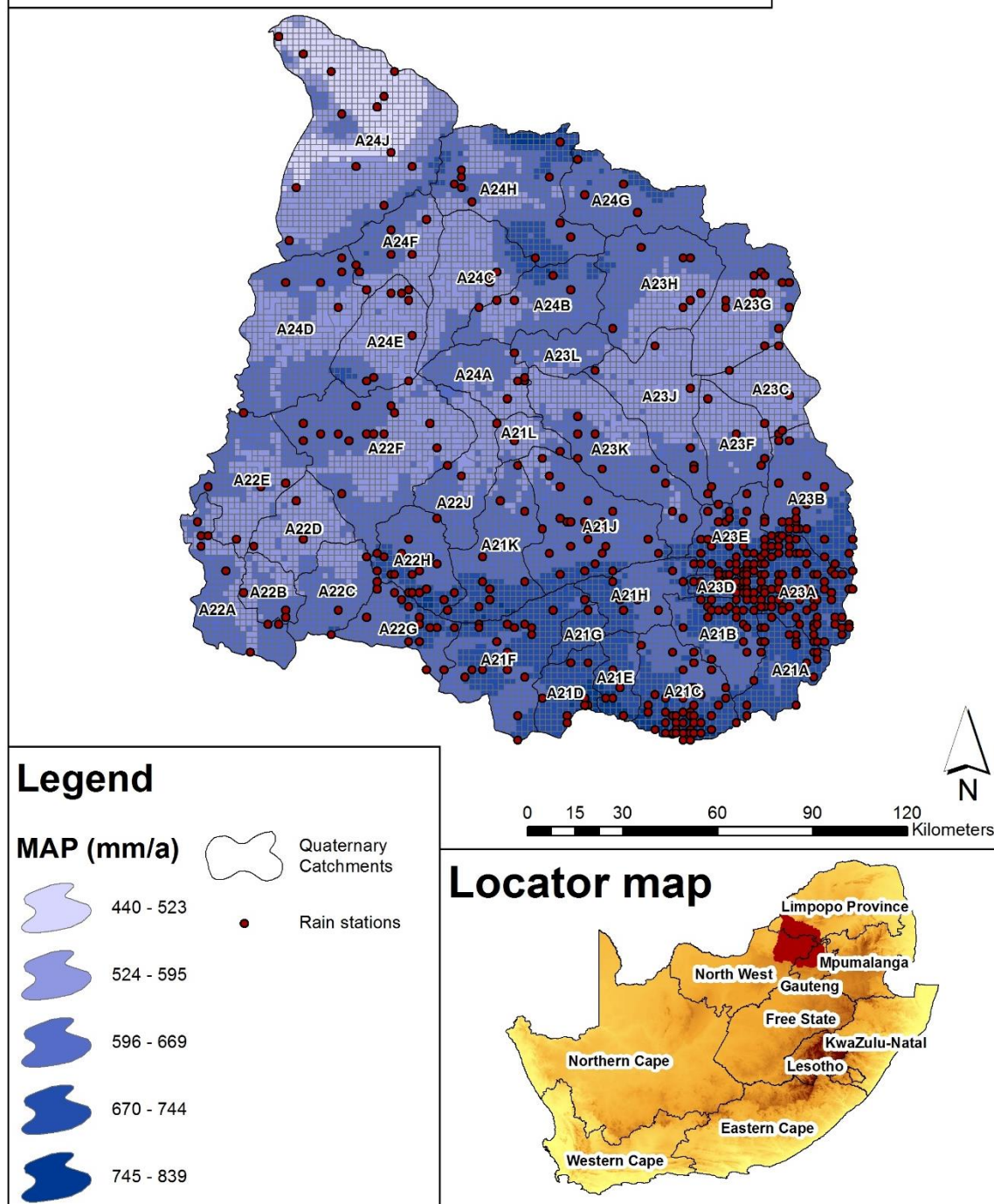


Figure 13 - Precipitation map of the study area (Bailey & Middleton, 2005)

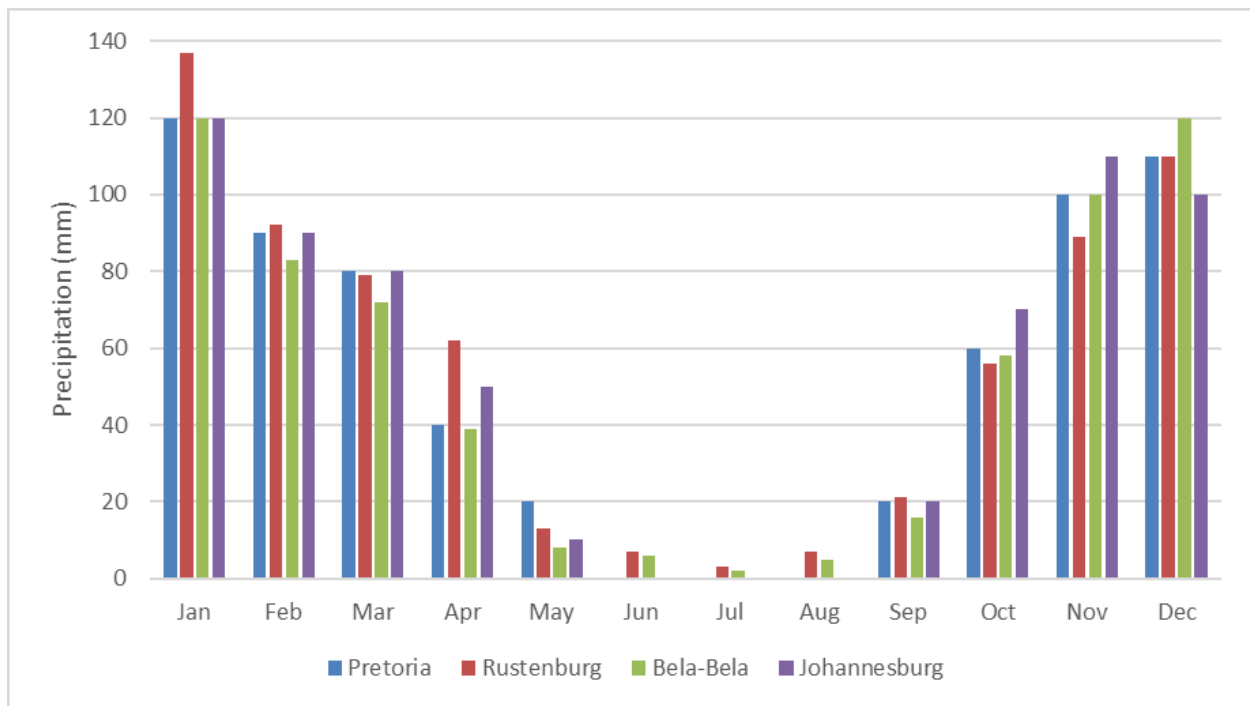
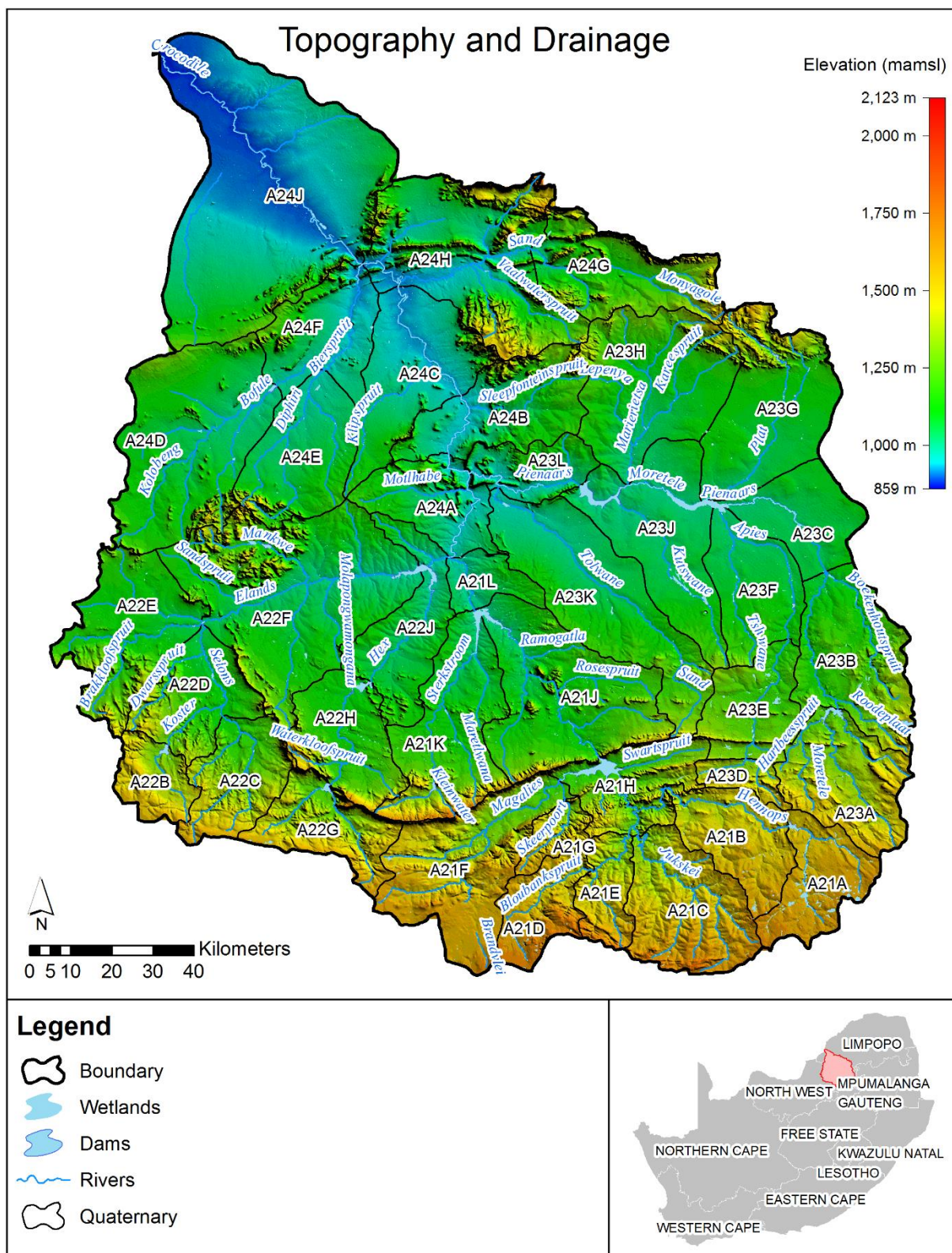


Figure 14 - Long-term average rainfall of major cities in study area (Weatherbase, 2016)

3.3 Topography and Drainage

The topography and drainage can be consulted in figure 15. The Crocodile River and some of its main tributaries are situated at an altitude close to 2000 mamsl. The area in the south of the catchment consists of gently rolling hills on the plateau of the Highveld. From the south of the study area the Crocodile River runs through the Magaliesburg mountain range towards Hartebeespoort dam which is at an altitude close to 1200 mamsl. The river then follows a path past the Pilansberg volcano, now extinct, to its west through the flat volcanic landscape and through the Thabazimbi mountain range. Thereafter it converges with Groot Marico and forms the Limpopo River at 900 mamsl (DWAF, 2004b). There are 9 major dams and a few smaller ones within the catchment as shown in Figure 16.

Wetlands are present at areas where climate allows it and groundwater discharges to the land surface in surplus or where rapid drainage of water is prevented. Wetlands may receive groundwater, recharge aquifers or both. If wetlands are groundwater driven, they need a stable influx of groundwater throughout the year even with seasonal and weather changes. Too much abstraction of water could deplete the water source to wetlands and even destroy it (Winter et al., 1998).



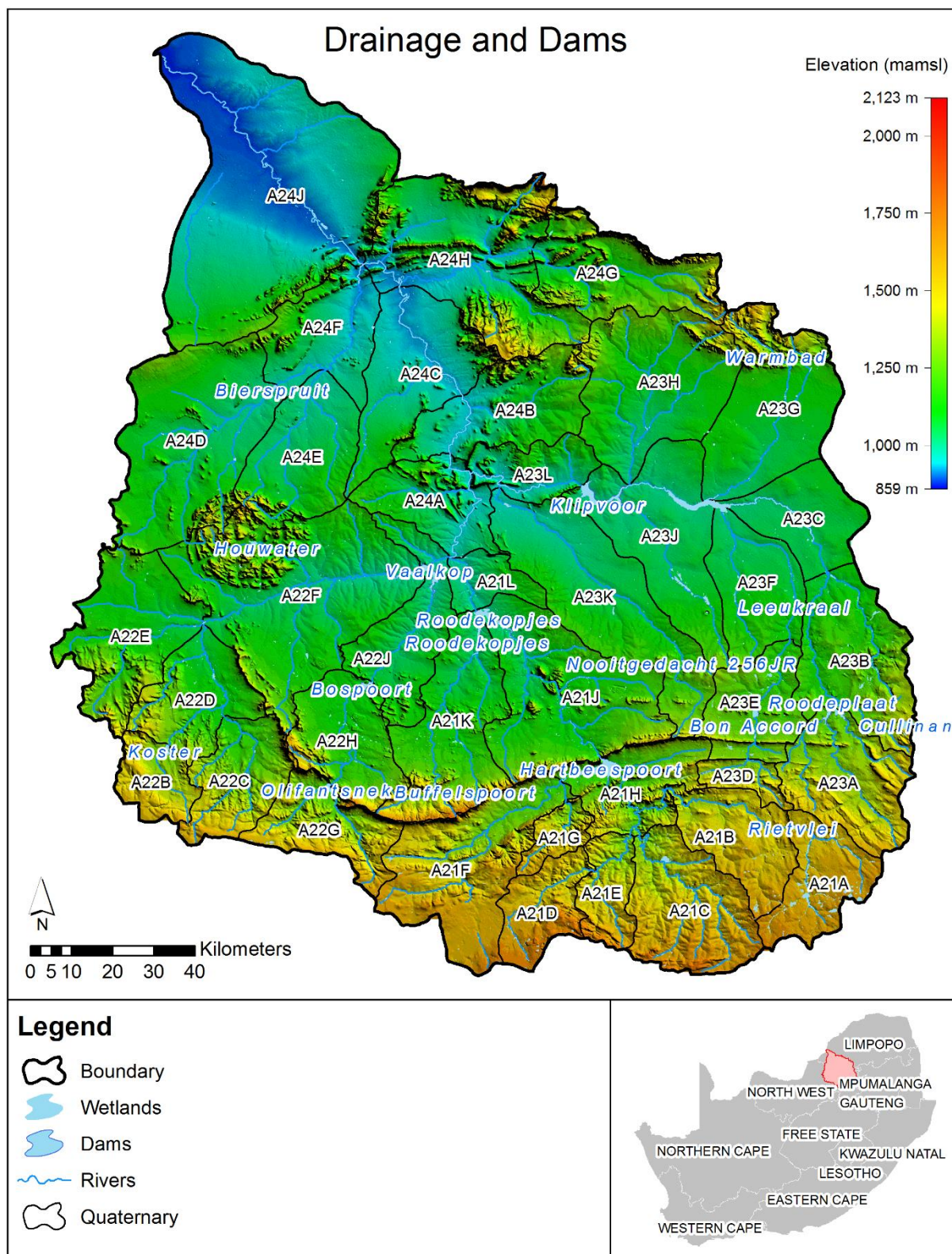


Figure 16 - Drainage and dams within study area

3.4 Geology

Many of the geological features within the study area is of volcanic intrusive rock, the Bushveld Igneous Complex. Dolomitic rock complexes are found running east to west at the south of the catchment. These dolomites have high storage capacities, but can lead to sinkhole formations if dewatered (HWE, 2016). Within the upper catchment area some of the seams bear gold, with a few mines operating there. The study area lithology is indicated in Figure 17.

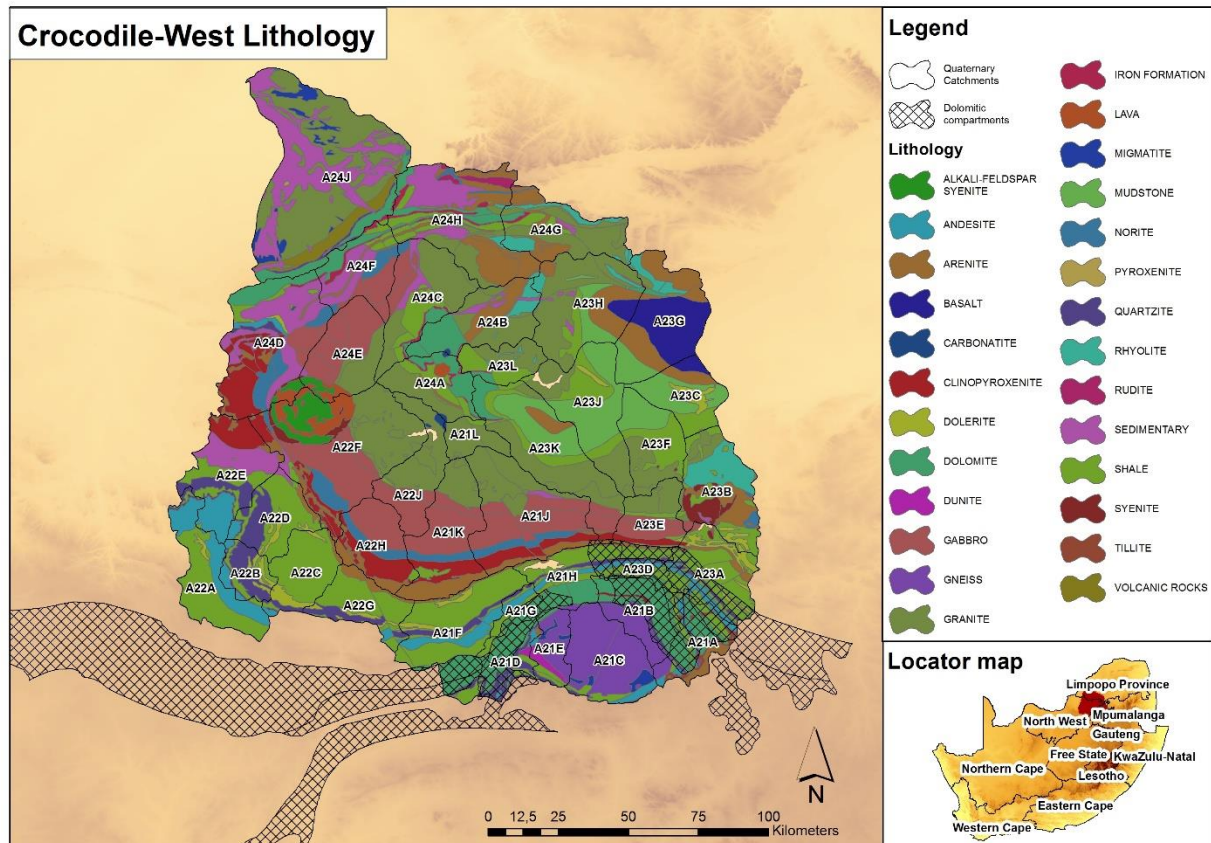


Figure 17 - Lithological map of the study area

Figure 18 illustrates a simplified geological map of the study area. The prevailing lithology of any area controls the groundwater occurrence (HWE, 2016). It is expected that the dolomitic areas would be representative of high yielding aquifers.

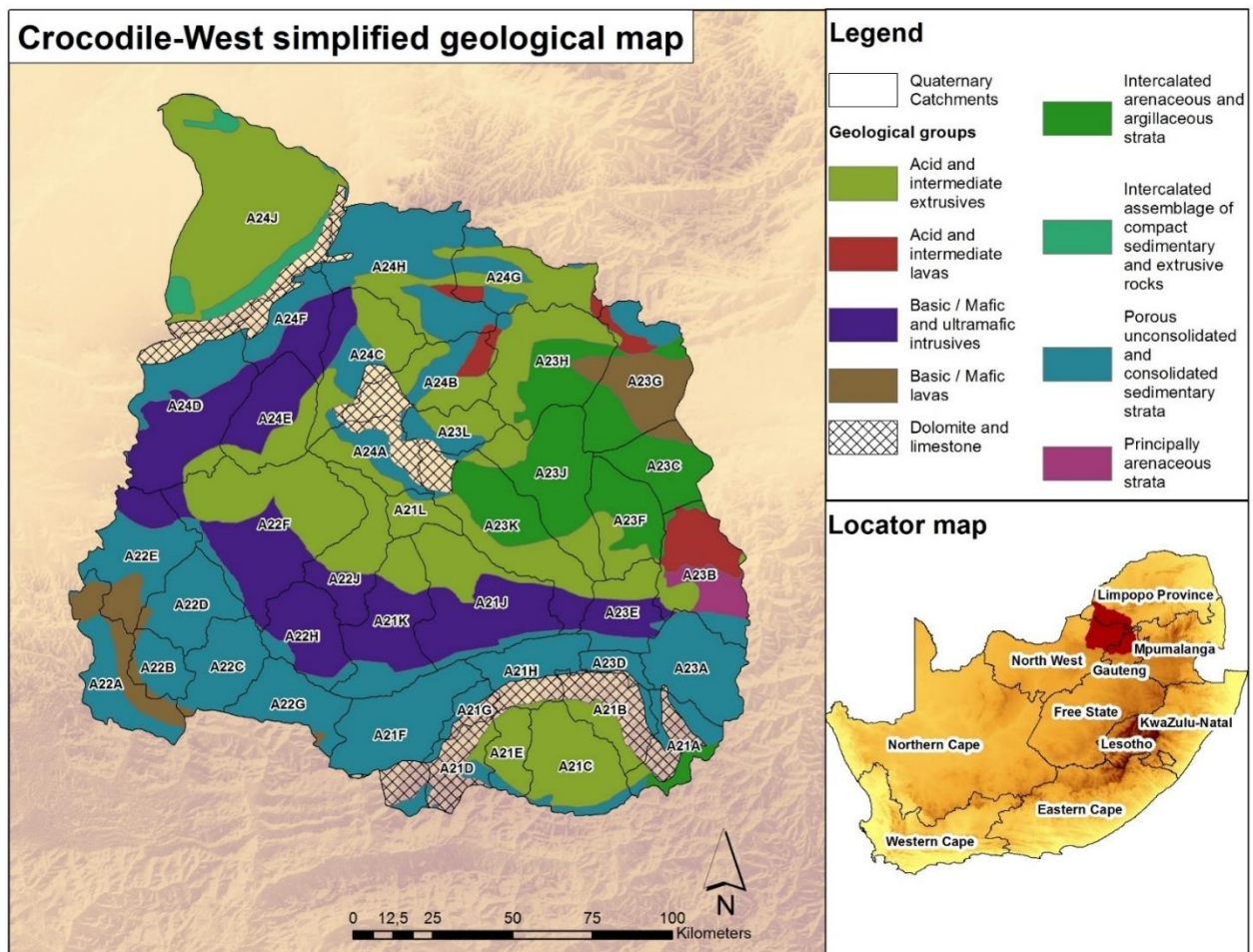


Figure 18 - Simplified geological map of study area

3.5 Geohydrology

3.5.1 Recharge

Recharge is the addition of water to the saturated zone through rainfall, from surface water or the movement of water from one aquifer to another. Recharge is vital to replenish aquifers. (DWS, 2015). Aquifers are mostly replenished through indirect flow paths in semi-arid areas, such as South Africa, as there are a lot of factors obscuring rainfall water from directly recharging an aquifer such as soil type or landcover.

Vegter (1995) stated that recharge is rainfall dependent and Figure 19 shows the recharge map as described by Vegter. On average Vegter's map estimate recharge as 6.04% of MAP.

The GRA II (DWAf, 2006) recharge map for the study area is shown in Figure 20, this recharge estimate averages at 3.71% of MAP.

The map displays the Tlokweng Catchment area, divided into 48 sub-catchments labeled A21A through A24J. The sub-catchments are color-coded according to their recharge potential in millimeters (mm). The map also shows the locations of major towns: Johannesburg, Tswane, Rustenburg, Bela-Bela, and Randfontein. A legend indicates the recharge ranges: 3-8 mm (lightest blue), 8-20 mm (light blue), 20-45 mm (medium blue), 45-65 mm (dark blue), and 65-95 mm (darkest blue). A scale bar shows distances from 0 to 100 kilometers. A locator map of South Africa is included, showing the catchment area's location within the country and its proximity to neighboring provinces and countries.

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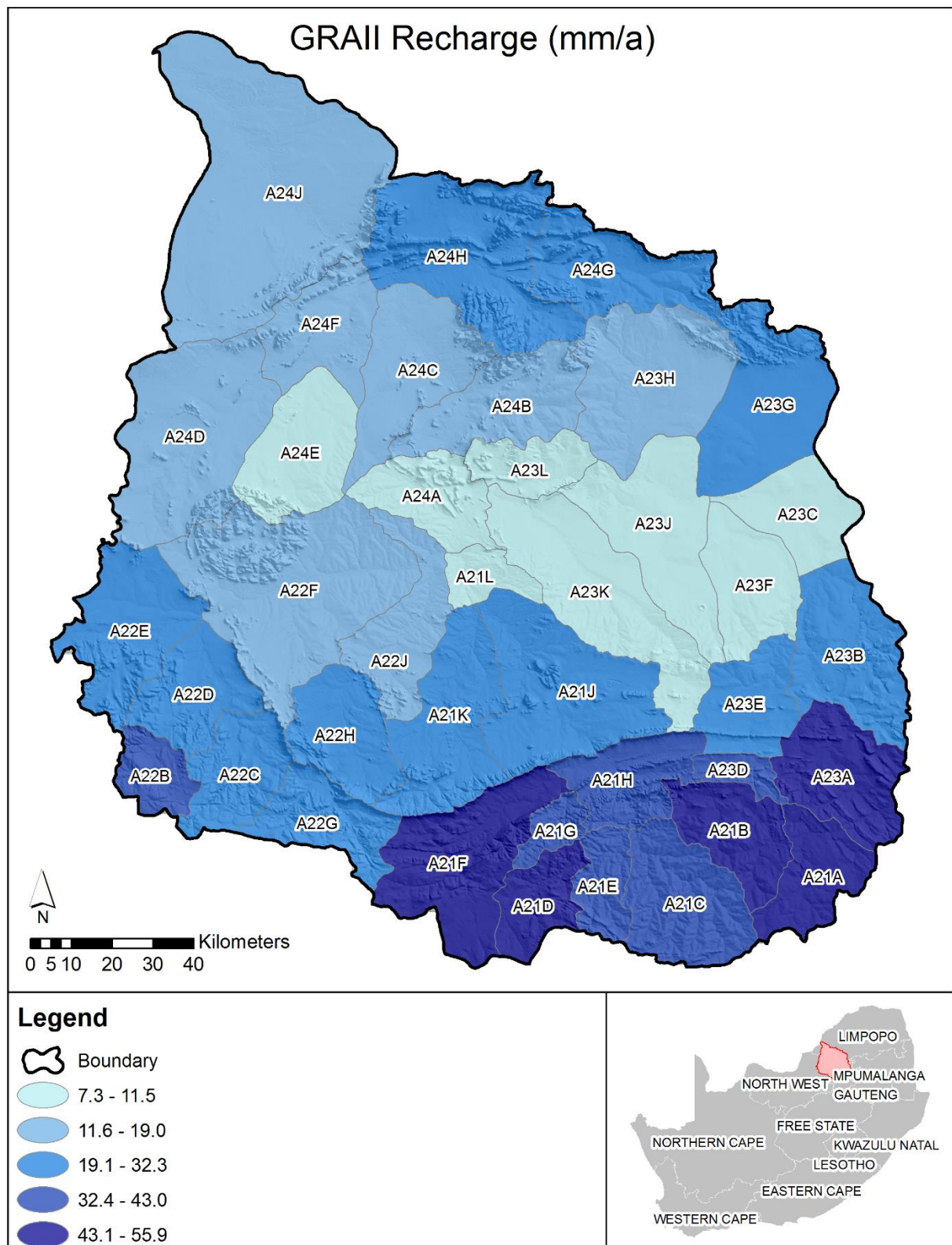


Figure 20 - GRAII recharge Figures for the study area

The 4.86% groundwater recharge (average between Vegter and GRAII) relates to an estimated 862.31 Mm³/annum recharge of the MAP of 619.81mm/a in the Crocodile-West catchment.

3.5.2 Groundwater Occurrence

There is extensive pumping of groundwater from the dolomitic aquifer northeast of Johannesburg and south of Pretoria and northwest of Krugersdorp for irrigation, domestic, industrial and municipal supply. The Lower Crocodile River contains sandy aquifers which are mainly used for irrigation purposes. These aquifers are fed through rainfall and river flow. The rest of the study area comprises mostly of fractured rock aquifers (DWAF, 2004b). Ground water occurrence in the Crocodile-West catchment is indicated in Figure 21.

3.5.3 Aquifer Vulnerability

The DRASTIC aquifer vulnerability method makes use of seven (7) factors to calculate the vulnerability index value (Aller et al., 1987):

- Depth to groundwater (D) – determines the maximum distance contaminants travel before reaching the aquifer;
- Net recharge (R) – the amount of water that can travel from ground surface to the water Table;
- Aquifer (A) – the composition of the aquifer material;
- Soil media (S) – the uppermost portion of the unsaturated zone;
- Topography (T) – the slope of the ground surface;
- Impact of vadose zone (I) – the type of material present between the bottom of the soil zone and water Table; and
- Hydraulic conductivity of the aquifer (C) – indicates the aquifer's ability to allow for the flow of water to occur.

This vulnerability index is used to determine the aquifer's vulnerability to pollution and the index ranges from 1 to 200, where 200 represents the theoretical maximum aquifer vulnerability. The DRASTIC map for the study area is shown in Figure 22.

When compared to the simplified geology map (Figure 18), the dolomitic areas are rated as having a high vulnerability as compared to the surrounding geologies. It is further noted that the dolomitic areas are also associated with high yielding aquifers (Figure 21).

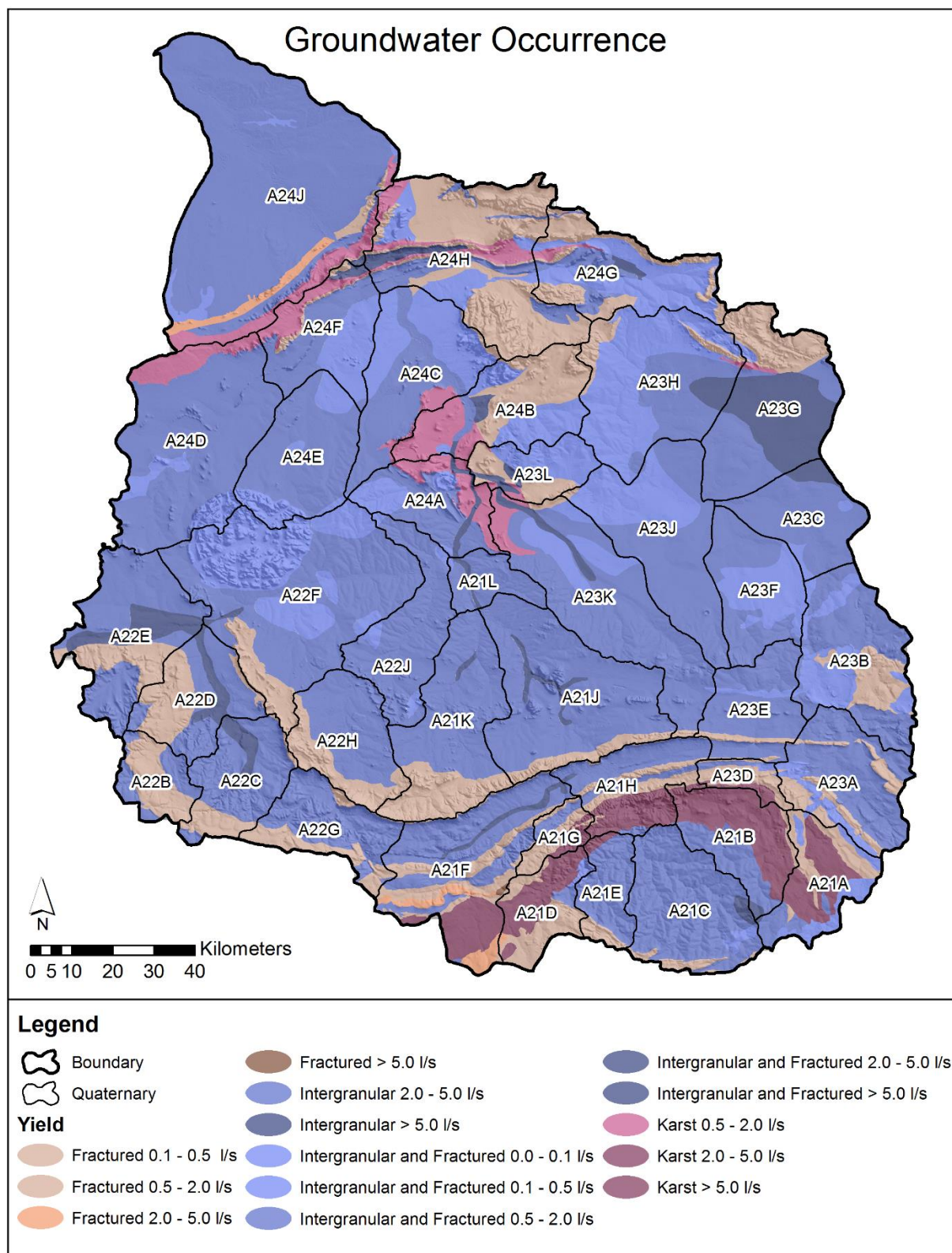


Figure 21 - Groundwater occurrence within the study area

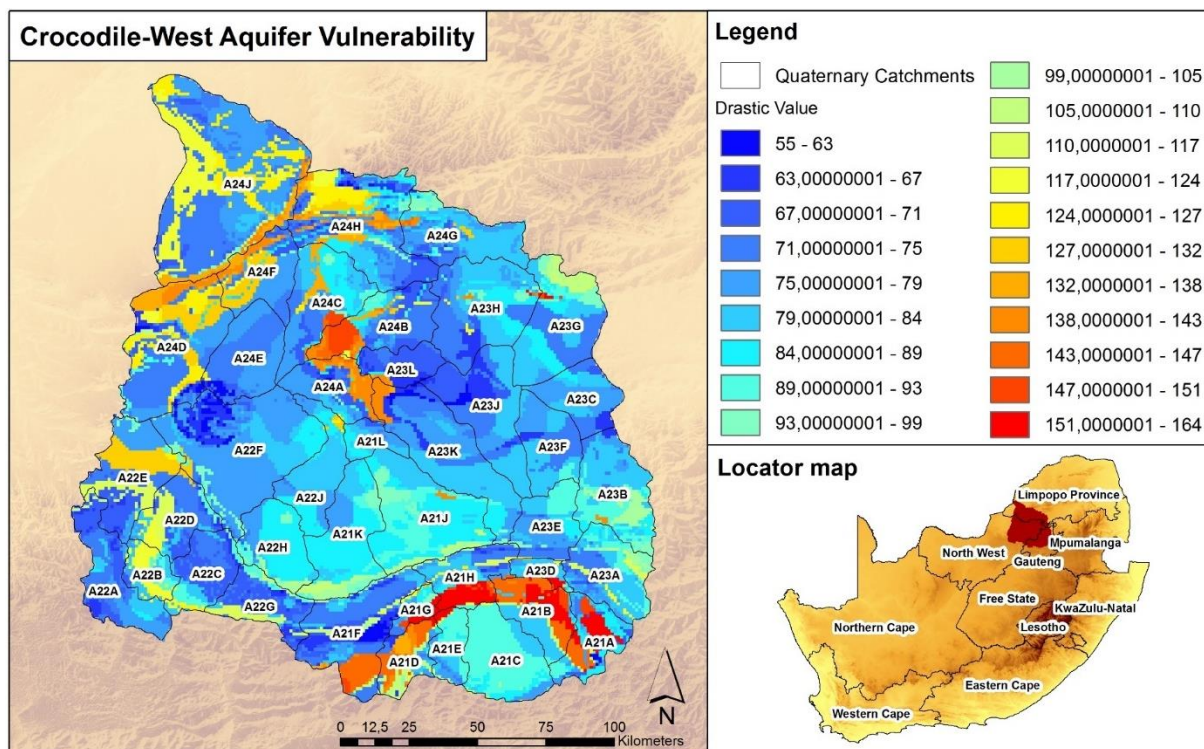


Figure 22 - Aquifer vulnerability map of the study area

3.5.4 Groundwater Contribution to Baseflow

The assumption is usually made that groundwater is safe to drink without treatment, this is not always the case. It is important to keep groundwater clear of pollution because of its hydraulic connection to surface water and vice versa; they could easily contaminate each other (Winter et al, 1998). Much of groundwater contamination occurs in low lying aquifers which are directly connected to surface water (Winter et al, 1998). These low-lying aquifers are more susceptible to contamination than deeper aquifers due to faster travel times which can be between a few days to a few years (Winter et al, 1998).

Groundwater contributes to base flow via sub surface seepage and springs in the study area. The contribution of groundwater to base flow in the entire Crocodile River catchment is estimated to be 95.77 Mm³/a. The larger portion is due to spring flow from dolomites in the quaternary regions A21A, A21B, A21D, A21F, A21G and A21H (DWAF, 2004b). These spring flows have mostly been secured for bulk municipality supply.

Since groundwater contribution to baseflow is a difficult parameter to measure, this study relies on modelled values as presented in Table 8 (Dennis et al., 2011). For the purpose of this study the modelled values are considered to represent the groundwater contribution to baseflow.

Table 8 - Modelled baseflow values for study area

Quaternary	Area km²	MAR mm/a	Hughes mm/a	Pitman mm/a	Schultz mm/a	Van Tonder mm/a
A24J	2515.9	5.5	0.1	0.0	0.0	0.0
A24H	1338.2	34.0	13.7	1.4	6.8	5.3
A24G	735.3	28.0	9.0	3.2	6.6	5.3
A24F	590.7	12.5	0.0	0.0	0.0	0.0
A24C	801.4	9.6	0.0	0.0	0.0	0.0
A23G	951.4	39.6	11.2	2.2	11.4	6.8
A23H	1058.1	11.2	4.8	1.6	3.2	2.7
A24D	1326.5	11.7	0.2	0.0	0.0	0.0
A24B	709.1	16.5	4.0	0.8	2.2	1.8
A24E	687.7	11.5	0.0	0.0	0.0	0.0
A23L	328.8	12.9	1.6	0.5	1.0	0.8
A23J	930.3	9.8	3.8	1.4	2.7	2.2
A24A	493.1	14.5	2.4	0.5	1.5	1.2
A23C	491.0	8.8	1.9	0.7	1.4	1.1
A23K	1130.8	13.1	5.5	1.5	3.4	2.8
A22F	1688.3	16.3	9.2	1.8	5.1	4.1
A23F	564.6	10.0	2.4	0.8	1.7	1.4
A22J	591.5	17.1	3.3	0.6	1.8	1.4
A22E	811.8	16.3	4.5	0.8	2.4	2.0
A21L	212.8	12.5	1.0	0.2	0.6	0.5
A23B	814.1	19.4	7.6	3.3	6.3	5.0
A21J	1150.2	18.6	7.1	1.8	3.7	3.3
A21K	864.1	100.0	28.6	8.6	28.5	18.6
A22D	541.3	14.6	2.7	0.5	1.6	1.2
A23E	490.4	29.3	5.7	1.8	4.3	3.3
A22H	578.7	23.7	4.4	0.8	1.9	1.8
A23A	682.4	42.2	17.1	10.4	16.7	13.6
A22C	514.9	16.2	3.2	1.0	3.1	2.1
A22B	283.8	20.1	2.0	0.5	1.5	1.1
A21H	513.7	36.3	6.8	2.2	4.1	3.6
A23D	144.8	114.9	13.5	10.6	12.8	11.8
A22G	498.6	23.4	4.2	1.1	3.3	2.3
A21F	1000.2	25.0	12.1	7.3	10.2	9.1
A21B	526.5	19.1	6.0	4.4	5.3	5.0
A21G	160.5	82.4	10.1	9.1	11.4	10.0
A21A	482.8	33.6	9.7	7.0	9.6	8.3
A21C	761.0	49.0	22.9	15.4	21.3	18.6
A21E	289.8	54.6	9.4	6.1	8.6	7.5
A21D	371.5	56.3	14.8	12.1	16.5	14.0

It is clear that the modelled values presented by Hughes are generally higher than the rest and this is due to the fact that the modelled value also includes the interflow component. The Pitman values on the other hand seem to represent the lower end of the scale.

3.6 Land Cover

The area's vegetation consists of false grassland south of the Magaliesberg and tropical bushveld and savannah north of the Magaliesberg. Much of the vegetation have been modified due to urban development and agricultural activities to the southern, central and eastern parts of the study area (RHP, 2005; DWAF, 2004b). Mines and water bodies are spread throughout the study area. See Figure 23.

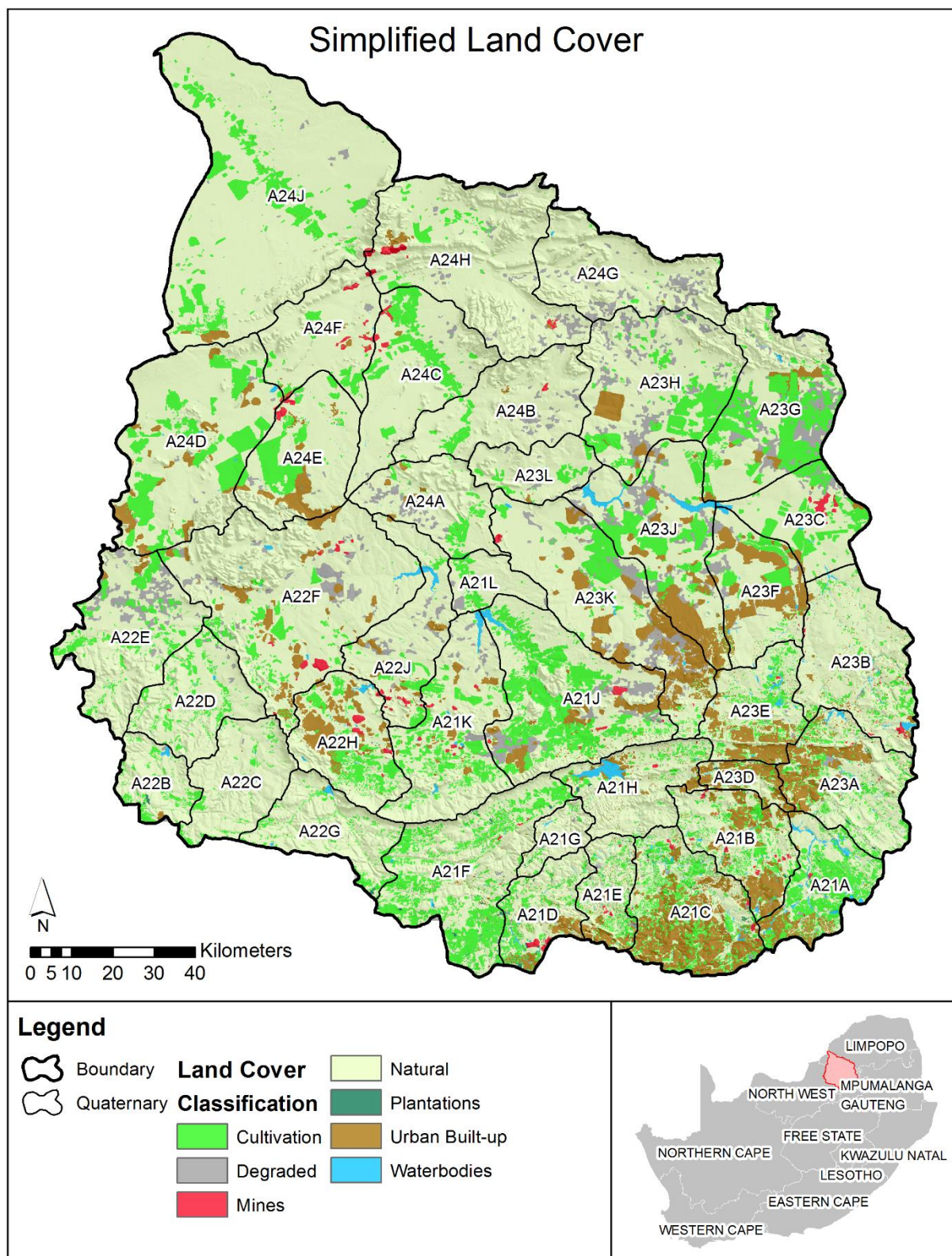


Figure 23 - Simplified land cover of the study area

3.7 Tertiary-Catchments

The most prominent urban areas within the Crocodile-West catchment cover a total of 655 km² in quaternary regions A21 and A23. Mining together with urban activities in the catchment are responsible for the generation of about a quarter of South Africa's GDP. Mines in the catchment

are mostly found around the Bushveld Igneous Complex. Irrigation consists over an area of 650 km² in this catchment (DWAF, 2004b). The area left over is utilised by game farms and for grazing cattle. There are three small power stations within the catchment which are dependent on local water resources.

The main concern with mines are acid mine drainage which effects both the surface- and groundwater. The impact of potential decant from abandoned mines must also be considered, its impact on groundwater identified and remediated (DWAF, 2004a). Other concerns which are more site specific are dewatering of aquifers to create a dry and safe workspace which can lead to sinkhole formation or cause ground settlements which can in turn cause damage to any structures in the drawdown zone (GWE, 2013). Mining in the Crocodile River catchment is mainly for platinum and associated group metals such as gold, chrome, palladium, iron ore, manganese and vanadium and also for granite, diamonds, limestone, mineral sands and andalusite.

Extensive mining for Platinum and its associated group metals of both open cast and underground mines on the northern side of the Magaliesberg mountain range has caused a lot of destruction to the surrounding habitats and could be responsible for dewatering of aquifers in the surrounding area. Dewatering could possibly affect the farming practices and natural vegetation growth in the area.

3.7.1 Upper Crocodile River tertiary-catchment area (A21)

A lot of economic activity takes place here that generates a substantial portion of South Africa's GDP. Due to these activities, large volumes of water are transferred from the Vaal River system because the local surface water resources are insufficient to supply for the demand alone. Significant amounts of water are used for irrigation north of the Hartbeespoort dam which take place over approximately 270 km² of the area. The most irrigation taking place for citrus and high valued crops (DWAF, 2004b). Gold mines in the Upper Crocodile River tertiary-catchment are mostly mined out and closed. This leaves a risk of dangerous chemicals leaching into the groundwater and acidic water decanting into nearby surface water systems (DWAF, 2004b). The Kelvin Power Station which receives 12.8 Mm³/a purified raw water is situated in this catchment (Figure 24).

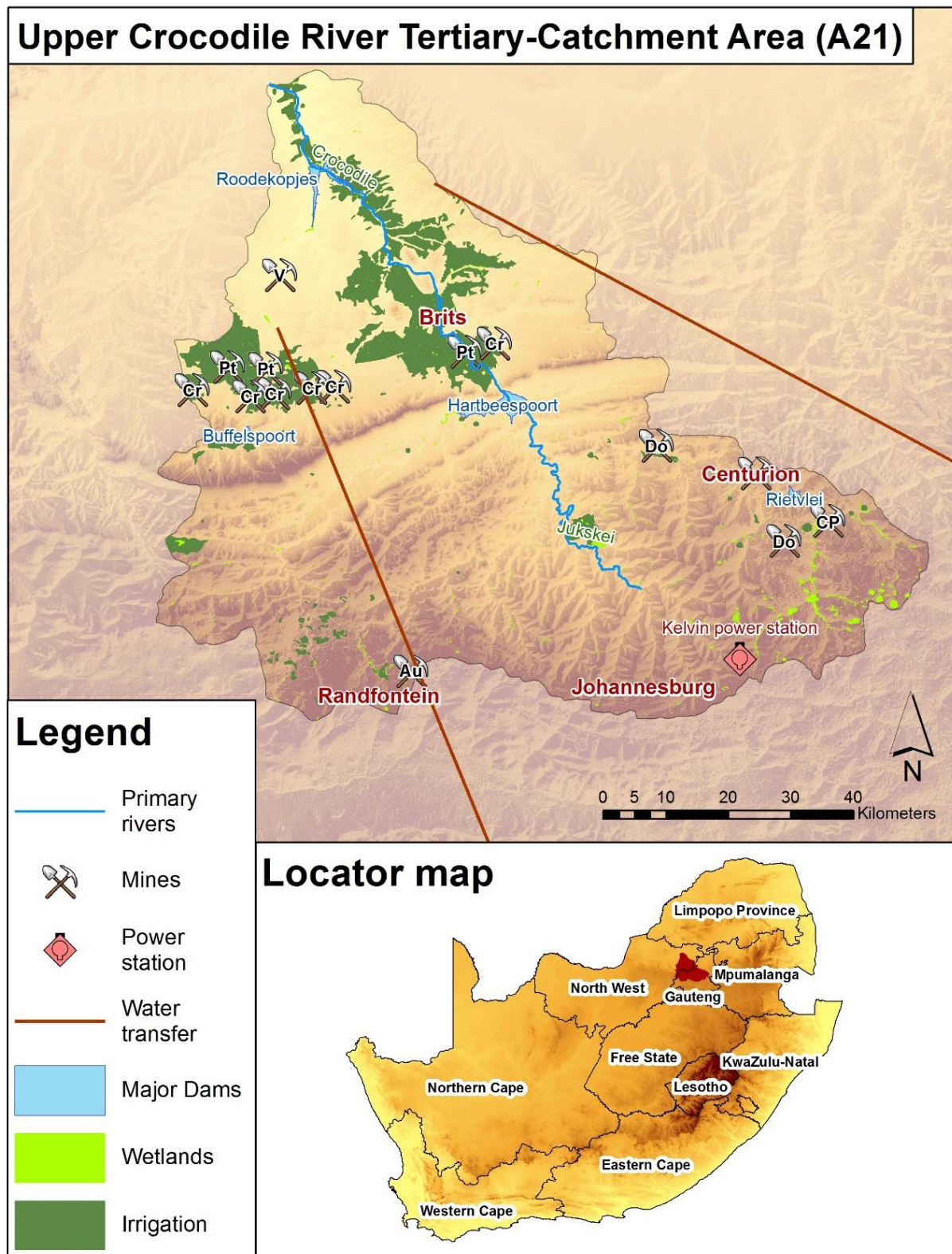


Figure 24 - Upper Crocodile River tertiary catchment A21

3.7.2 Elands River tertiary-catchment area (A22)

This area is in the western parts of the catchment and is much drier. Platinum mining is expanding around the area of Rustenburg and there is potential for new mines to develop (Figure 25). Citrus

farmers between Rustenburg and Brits (A21) are especially concerned that their main water supply, groundwater, is being depleted by mining activities in the area (DWAF, 2004b). Irrigation in this area consists of about 50km². Economy is rapidly growing in this area which will in turn lead to more water requirements. These requirements should be met by using local water sources to their full potential and to improve the use of an increasing return flow in the Crocodile River (DWAF, 2004b).

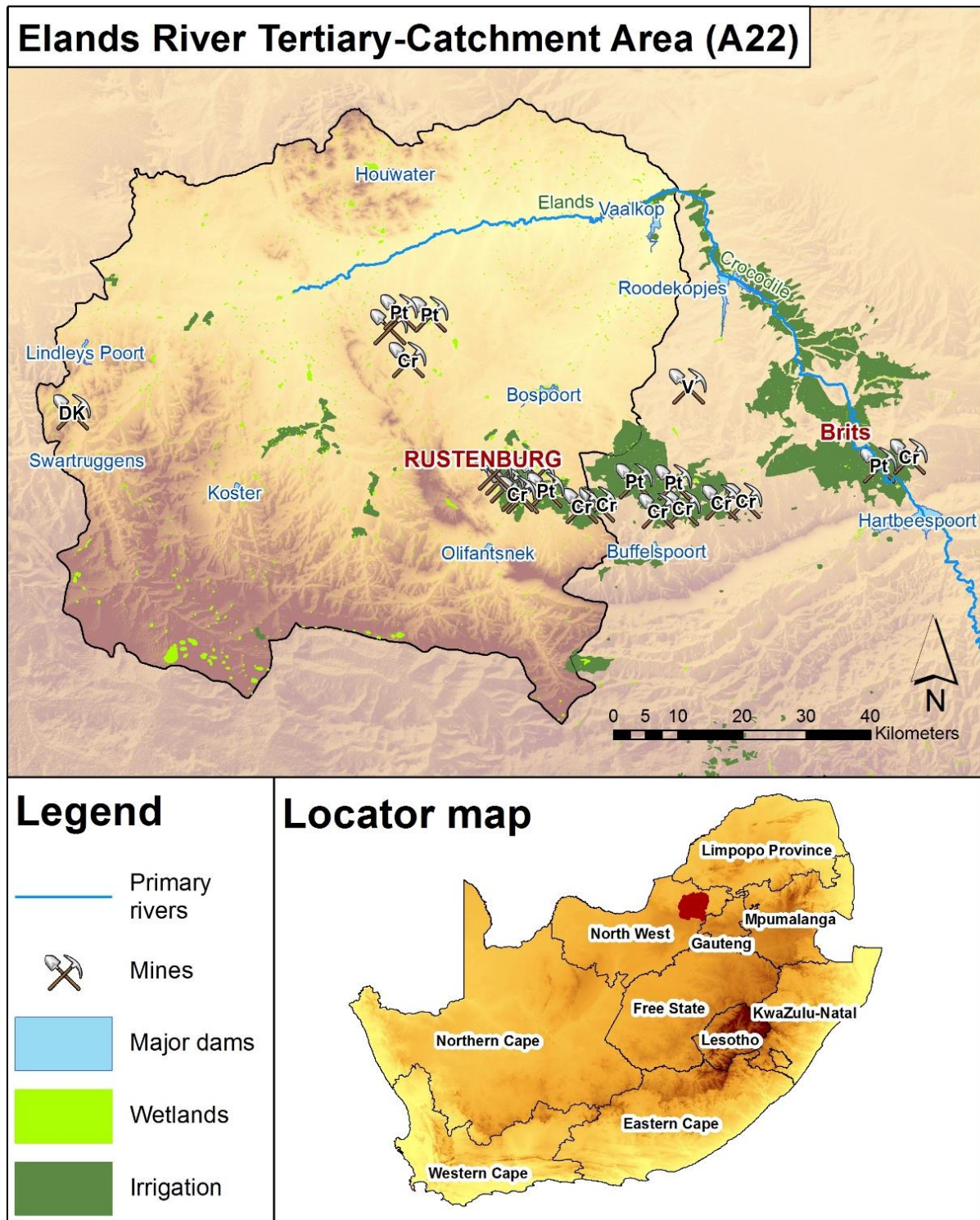


Figure 25 – Elands River tertiary catchment A22

3.7.3 Apies-Pienaars River tertiary-catchment area (A23)

This area is densely populated by the city of Tshwane (Figure 26). Most of the water requirements are supplied by Rand Water from the Vaal River system, although the local sources and groundwater in the area are also used. Irrigation in this sub-catchment consists of 67km² (DWAF, 2004b). The Tshwane Power Station receives 6 Mm³/a purified raw water. The Rooiwal Power Station receives 7.7 Mm³/a purified raw water (DWAF, 2004b).

3.7.4 Lower Crocodile River tertiary-catchment area (A24)

Large-scale irrigation takes place in this area, over about 134km². Other major activities include game and cattle farming along with a few mining activities. A water volume of 45 Mm³/a was reserved for development of a new power station in Limpopo WMA (DWAF, 2004b). The most irrigation taking place around the Amandelbult (Figure 27) area for lower value crops (DWAF, 2004b).

3.7.5 Other

The industrial section of the Crocodile West Catchment is situated mostly in and around the urban areas of Tshwane and Johannesburg. These industries receive and purchase their water supply from local authorities (DWAF, 2004b). Forest plantations are mostly present within the south-eastern parts of the catchment.

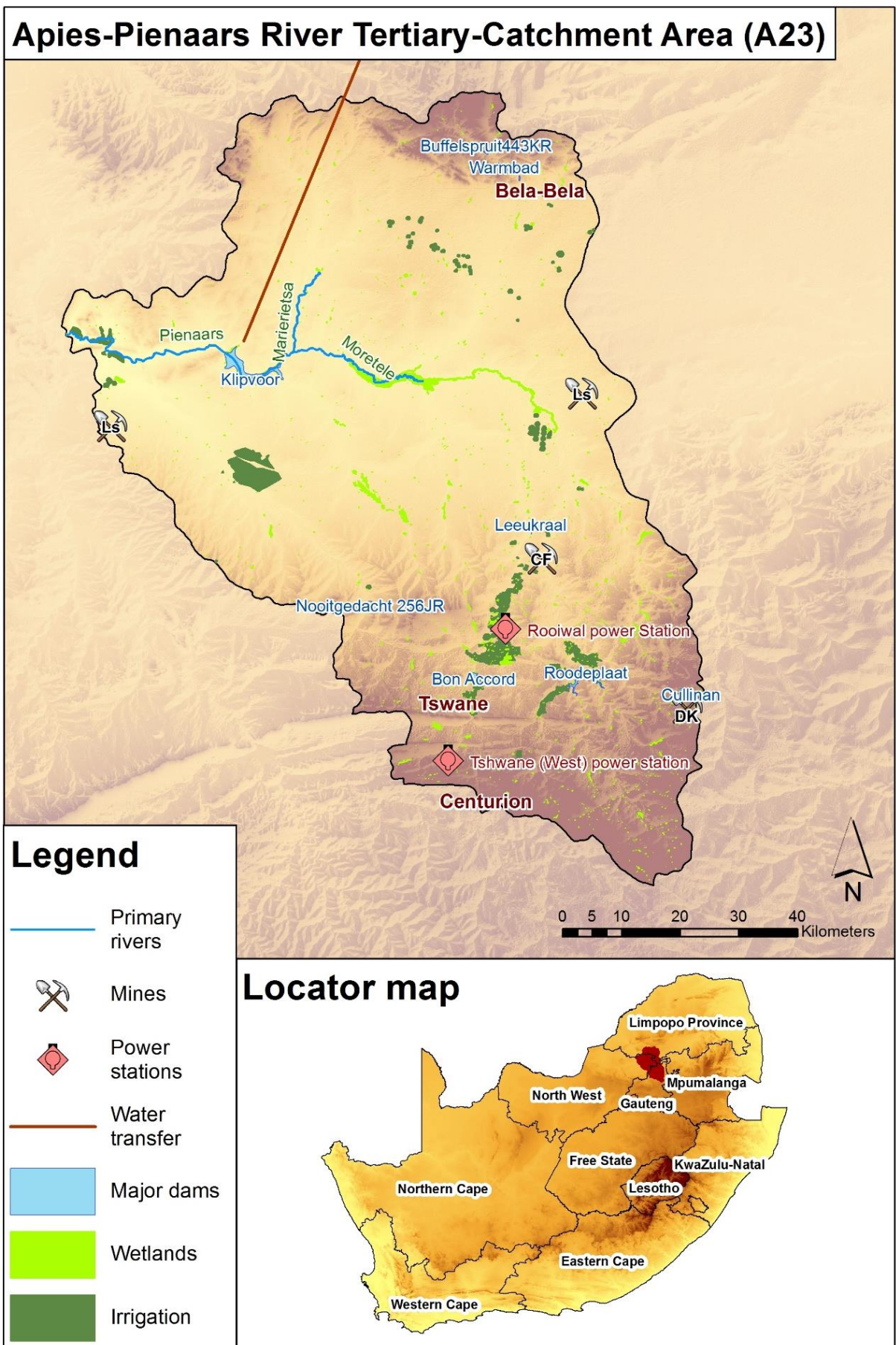


Figure 26 - Apies-Pienaars River tertiary catchment A23

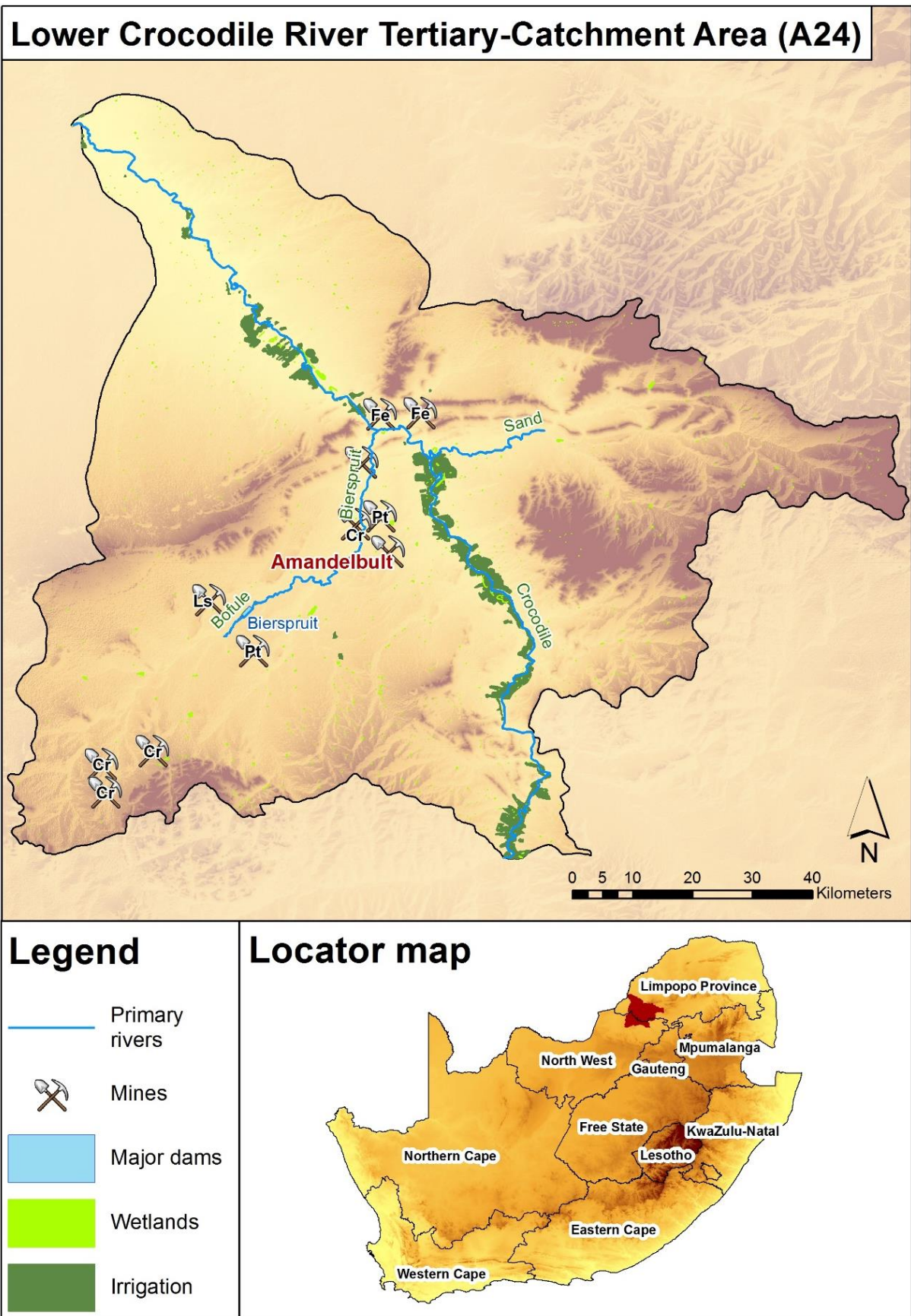


Figure 27 - Lower Crocodile River tertiary catchment A24

4 DATA ANALYSIS

The first step in the RQO process (Figure 2) is delineation of Integrated Units of Analysis (IUA) and Resource Units (RUs). As part of the RDM process the IUAs and RUs are generally determined by the surface water boundaries as discussed in Chapter 1. For the purpose of groundwater RQOs, groundwater delineation is required, even though the final reporting will be on the official IUA and RU boundaries.

4.1 National Groundwater Archive (NGA)

The only national borehole data set available for the area is the NGA and is used for analysis purposes. The study area does have mining and various industries within the it, each with their own monitoring data. If this additionally becomes available in the public domain, it can be incorporated into the methodology to refine the analysis.

The data used from the NGA for analysis purposes include:

- Average borehole water levels
- Water strike positions
- Borehole depths
- Average water quality

The NGA borehole distribution for the study area is presented in Figure 28. The highest borehole densities occur along the alluvial aquifer in the north and within the dolomitic aquifer in the south of the study area. On a regional scale there are some evidence of boreholes occurring next to magnetic structures.

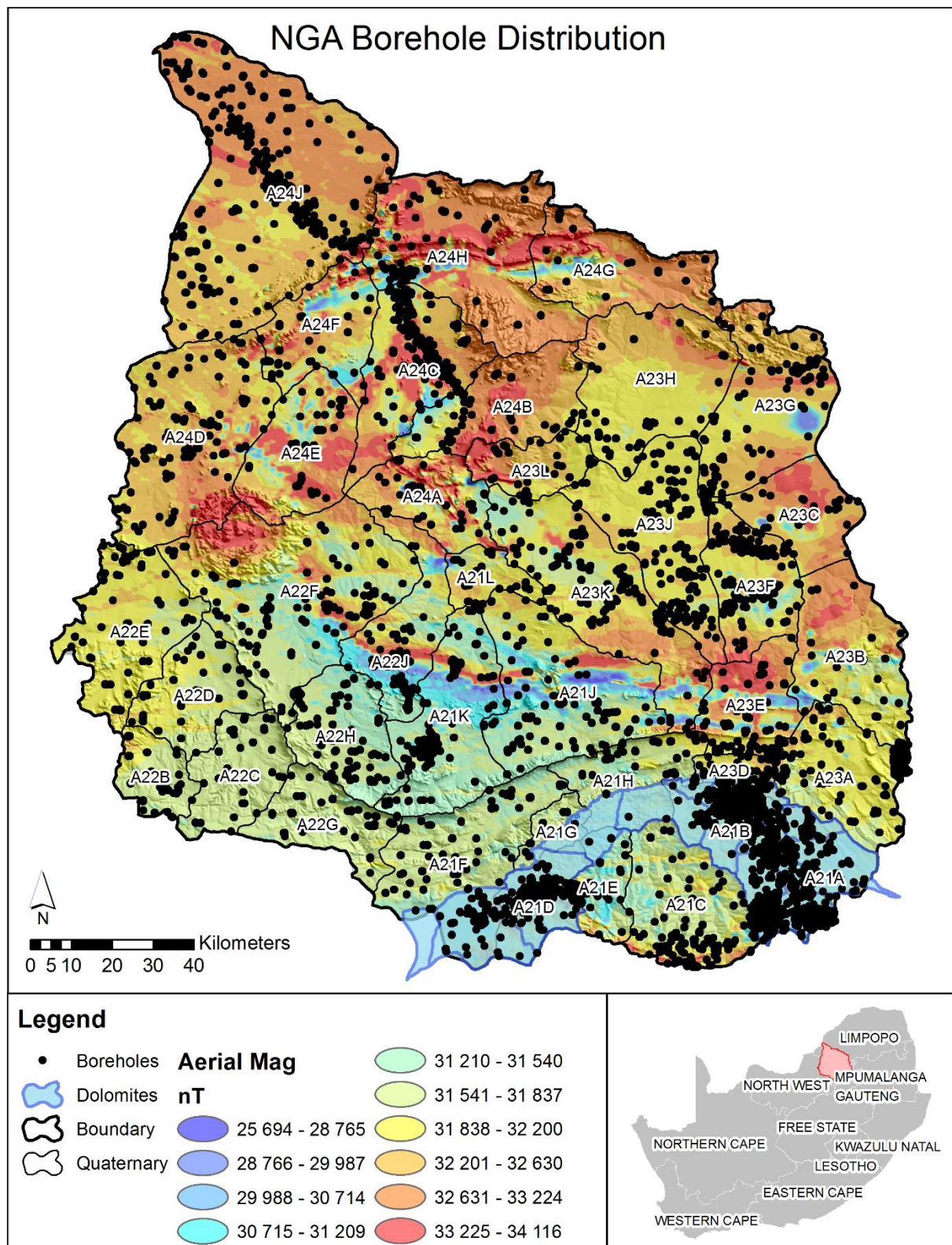


Figure 28 - NGA borehole distribution

4.2 Geostatistical Analysis

A geostatistical analysis was conducted on the NGA boreholes and the same methodology was followed as set out by the delineation of Vegter regions (Vegter, 2001). The analysis was conducted with respect to the geological units as shown in Figure 29.

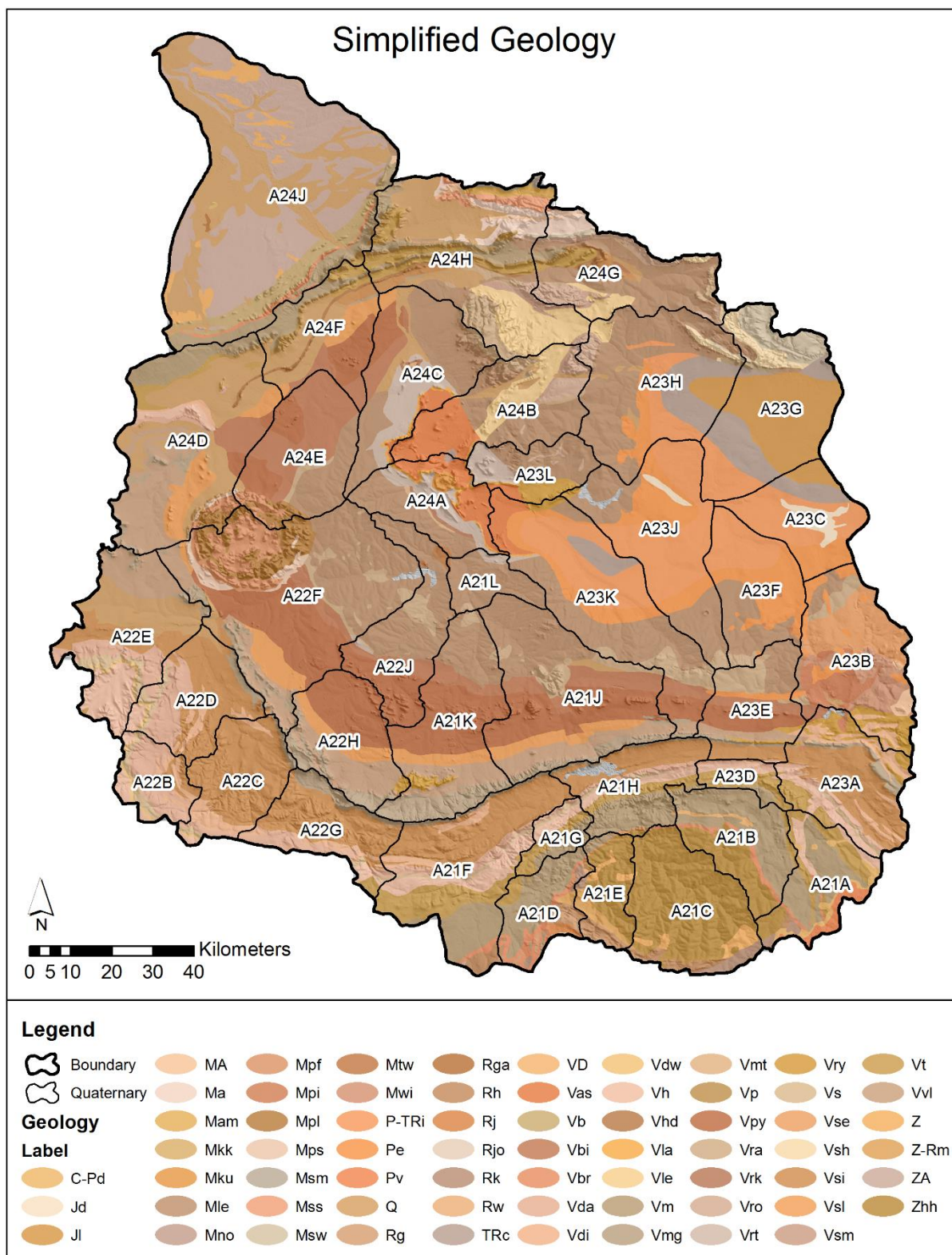


Figure 29 - Geological map of study area

The lithologies associated with the geology presented in Figure 29 is shown in Table 9.

Table 9 - Geological lithologies

Label	Stratigraphy	Lithology 1	Lithology 2	Lithology 3	Lithology 4	Lithology 5
C-Pd	DWYKA	TILLITE	ARENITE	MUDSTONE	SHALE	
Jd	KAROO DOLERITE	DOLERITE				
Jl	LETABA	BASALT				
Ma	ALMA	ARENITE	RUDITE	CONGLOMERATE	MUDSTONE	SILTSTONE
MA	*	NORITE	EPIDIORITE			
Mam	MATLABAS	ARENITE	MUDSTONE			
Mle	LEBOWA GRANITE	GRANITE				
Mno	NOOITGEDACHT CARBONATITE	CARBONATITE	SYENITE			
Mpf	PILANESBERG	ALKALI-FELDSPAR SYENITE				
Mpi	PIENAARS RIVER	SYENITE	ALKALI-FELDSPAR SYENITE	ANDESITE	TUFF	CARBONATITE
Mpl	PILANESBERG	LAVA	TUFF			
Mps	PILANESBERG	SYENITE				
Mss	MATLABAS	RUDITE	CONGLOMERATE	ARENITE		
Msw	SWAERSHOEK	ARENITE	TRACHYTOID			
Mwi	WILGE RIVER	ARENITE	CONGLOMERATE			
Pe	ECCA	SHALE				
P-TRi	IRRIGASIE	MUDSTONE	ARENITE			
Pv	VRYHEID	ARENITE	SHALE	COAL		
Q	*	SEDIMENTARY	SAND	CALCRETE		
Rg	GOVERNMENT	QUARTZITE	SHALE			
Rh	HOSPITAL HILL	SHALE	QUARTZITE			
Rk	KLIPRIVERSBERG	ANDESITE	TUFF			
TRc	CLARENS	ARENITE	SILTSTONE			
Vas	CHUNIESPOORT	DOLOMITE	QUARTZITE			
Vb	BUFFELSFONTEIN	VOLCANIC ROCKS	ARENITE			
Vbi	BIERKRAAL MAGNETITE GABBRO	GABBRO				
Vbr	BLACK REEF	QUARTZITE	CONGLOMERATE	SHALE	BASALT	
VD	*	SYENITE				
Vda	DASPOORT	QUARTZITE				

<i>Label</i>	<i>Stratigraphy</i>	<i>Lithology 1</i>	<i>Lithology 2</i>	<i>Lithology 3</i>	<i>Lithology 4</i>	<i>Lithology 5</i>
Vdi	POST-TRANSVAAL DIABASES	DOLERITE				
Vdw	DWAALHEUWEL	QUARTZITE	SILTSTONE	CONGLOMERATE		
Vh	HEKPOORT	ANDESITE				
Vhd	PRETORIA	ARENITE	SILTSTONE	CONGLOMERATE	SHALE	ANDESITE
Vla	PENGE	IRON FORMATION				
Vle	LEEUEWPOORT	ARENITE	SHALE			
Vm	MALMANI	DOLOMITE	CHERT			
Vmg	MAGALIESBERG	ARENITE				
Vmt	SILVERTON	SHALE				
Vp	PENGE	IRON FORMATION	SHALE			
Vpy	PYRAMID GABBRO-NORITE	GABBRO	NORITE			
Vra	RASHOOP GRANOPHYRE	GRANITE				
Vrk	DASPOORT	ARENITE				
Vro	ROOIBERG	RHYOLITE				
Vrt	PRETORIA	SHALE	ARENITE			
Vry	RAYTON	SHALE	ARENITE			
Vs	STRUBENKOP	SHALE				
Vse	SELONS RIVER	RHYOLITE				
Vsh	SCHRIKKLOOF	RHYOLITE				
Vsi	SILVERTON	SHALE				
Vsl	SCHILPADNEST	NORITE	PYROXENITE	ANORTHOSITE		
Vt	TIMEBALL HILL	SHALE	ARENITE			
Vvl	VLAKFONTEIN	CLINOPYROXENITE	HARZBURGITE	NORITE ULTRAMAFIC ROCKS		
Z	*	MIGMATITE	GNEISS		AMPHIBOLITE	LAVA
ZA	*	GRANITE	GNEISS			
Zhh	HALFWAY HOUSE GRANITE	GNEISS	MIGMATITE	GRANODIORITE		
Z-Rm	MULDERSDRIF	DUNITE	HARZBURGITE	PYROXENITE	GABBRO	

Due to the substantial number of geological units present, a detailed analysis was only done on the geological units covering 81% of all borehole locations and covering 72% of the total area. The selected geological units that represent the aforementioned distribution is presented in Table 10.

Table 10 - Geological units selected for analysis

Label	Stratigraphy	Aquifer Index	% Boreholes	% Area
Vsi	SILVERTON	1	14.3%	8.1%
Vm	MALMANI	9	11.8%	4.2%
Zhh	HALFWAY HOUSE GRANITE	4	9.4%	3.9%
Mle	LEBOWA GRANITE	4	7.8%	16.8%
Vvl	VLAKFONTEIN	3	6.6%	2.7%
Vpy	PYRAMID GABBRO-NORITE	3	5.0%	7.1%
Q	*	7	4.7%	7.9%
Vt	TIMEBALL HILL	2	3.8%	3.0%
Vda	DASPOORT	7	3.2%	2.5%
Vbi	BIERKRAAL MAGNETITE GABBRO	3	2.9%	3.4%
Vmg	MAGALIESBERG	4	2.6%	2.7%
P-TRI	IRRIGASIE	2	2.6%	5.2%
ZA	*	4	2.1%	2.4%
Vry	RAYTON	2	1.9%	1.0%
Pe	ECCA	1	1.8%	1.5%

The aquifer index presented in Table 10 represent the aquifer potential, where 10 represents highest potential and 1 represents the lowest potential. It is expected that the Malmani dolomites (Vm) have a high borehole density as also seen in Figure 28 and is rated as a high potential aquifer. What is noteworthy is the high percentage boreholes located in the Silvertown (Vsi) which is rated as a low potential aquifer. Unfortunately, there isn't enough information to explain this anomaly, but possibilities include that some of the boreholes might be prospecting boreholes. Another possibility is that lithology types with more aquifer potential might be present underneath or between the shale of the Silvertown as the average water strike in this stratigraphic group is 30m. Figure 30 is a good example of the aforementioned possibility as the sandstone and dolerite are encapsulated between the shale. This anomaly is a good motivation for public participation as the local people should be able to give clarity on why there is such a large number of boreholes present within this Silvertown stratigraphy.

The frequency diagrams of the analysis of each of the geological units considered is presented in Table 11.

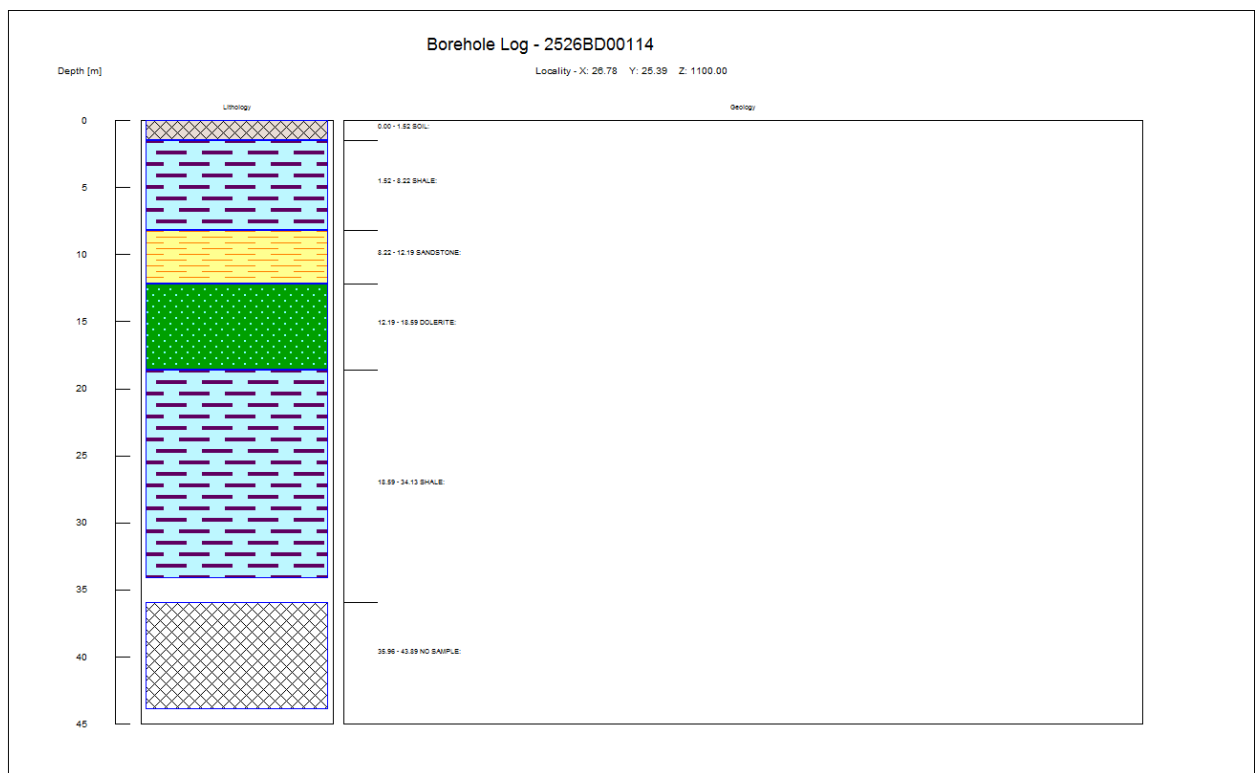
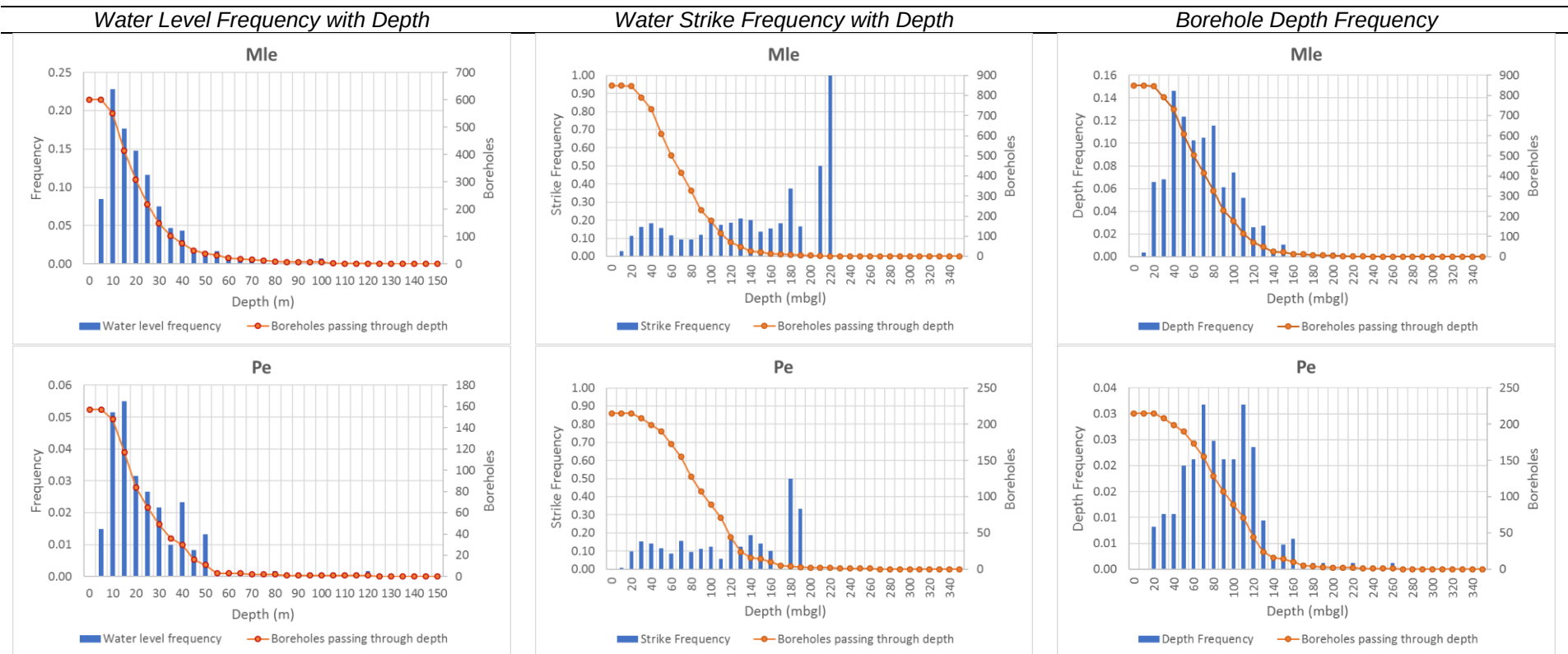
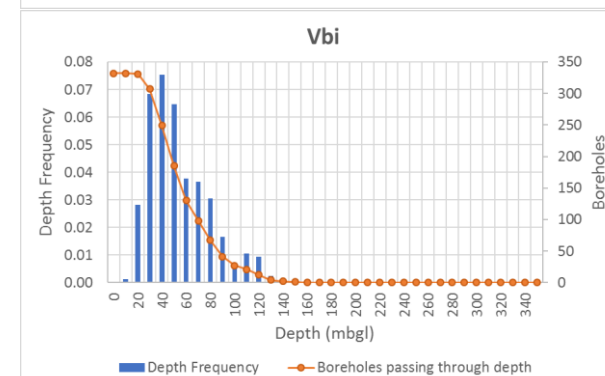
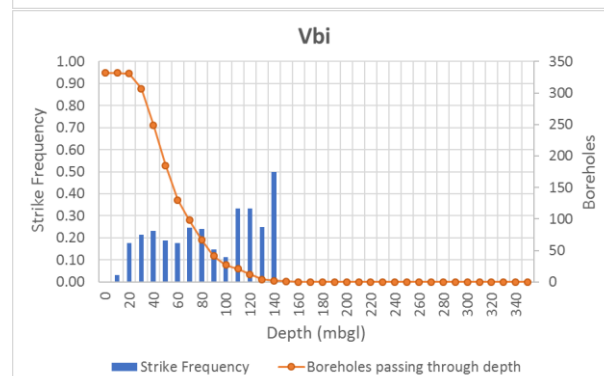
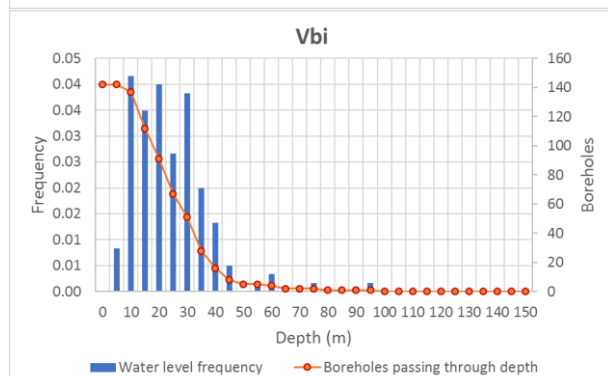
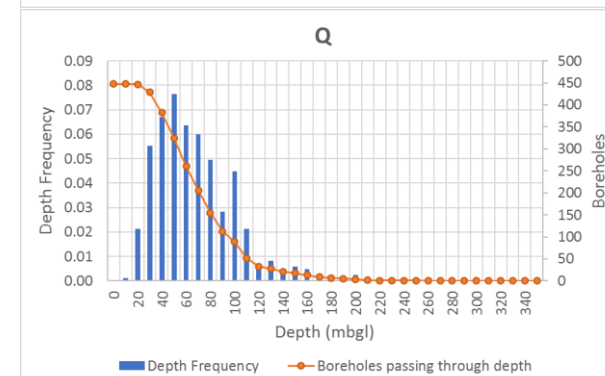
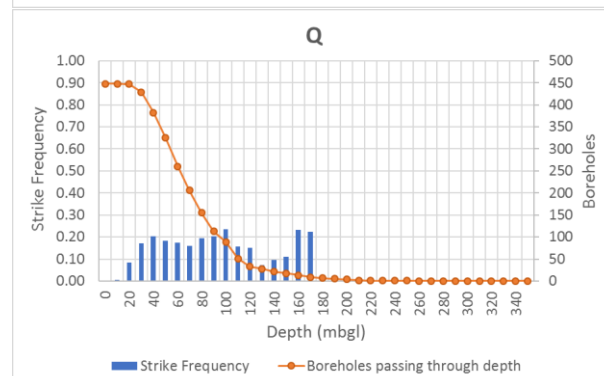
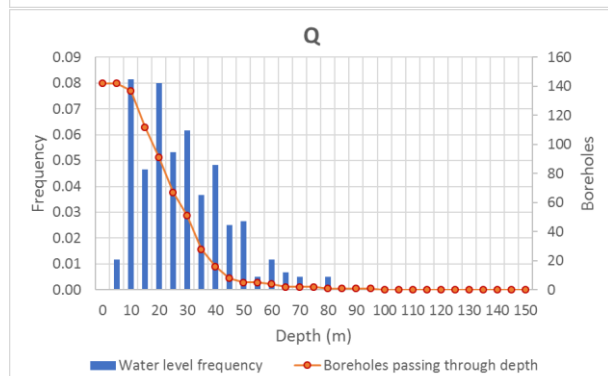
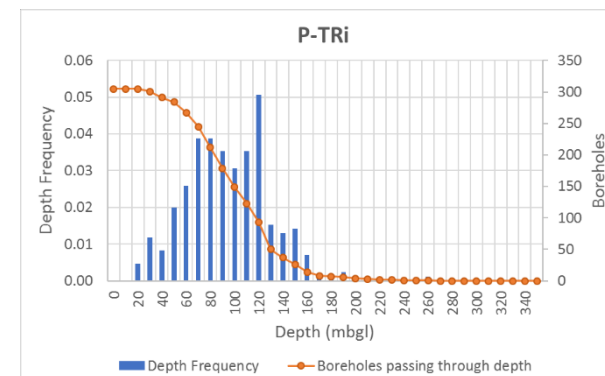
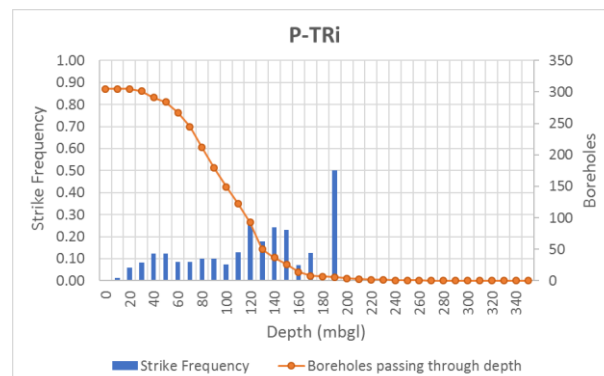
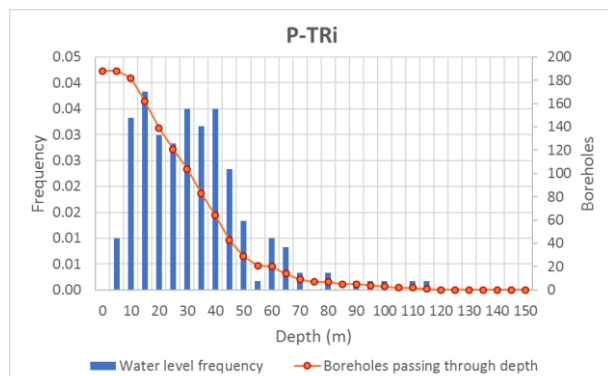
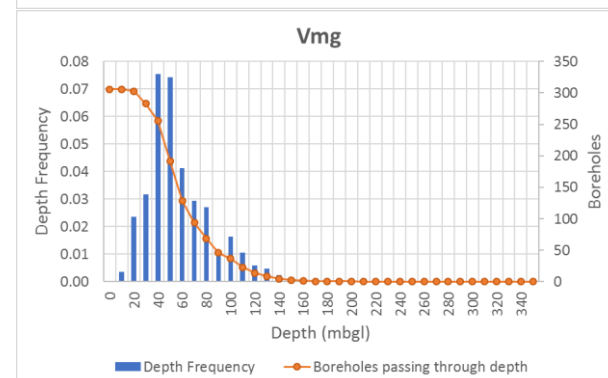
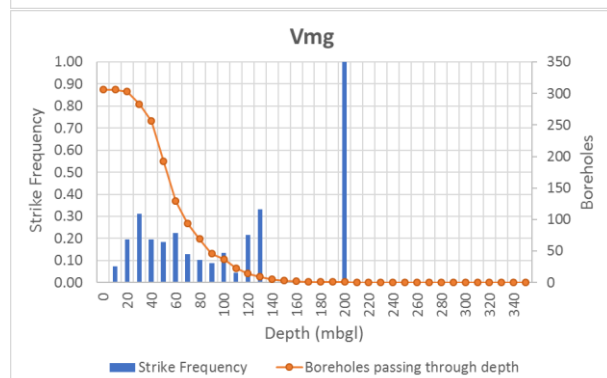
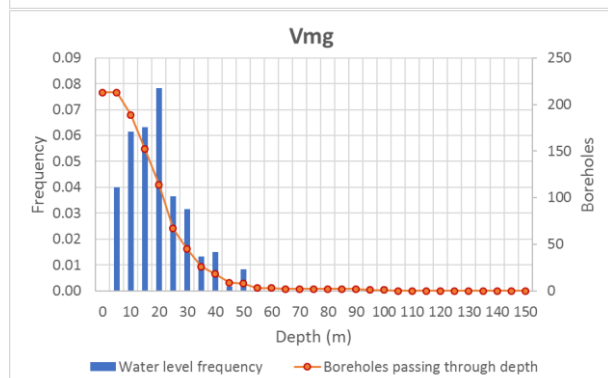
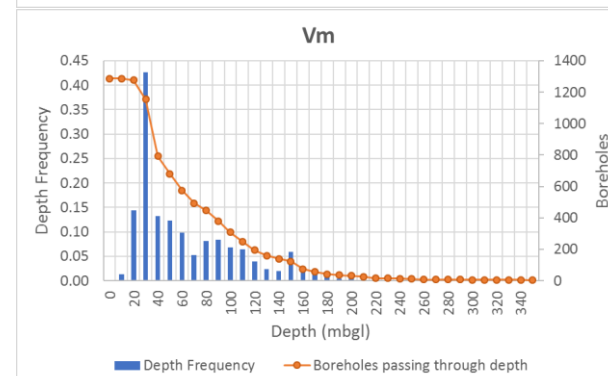
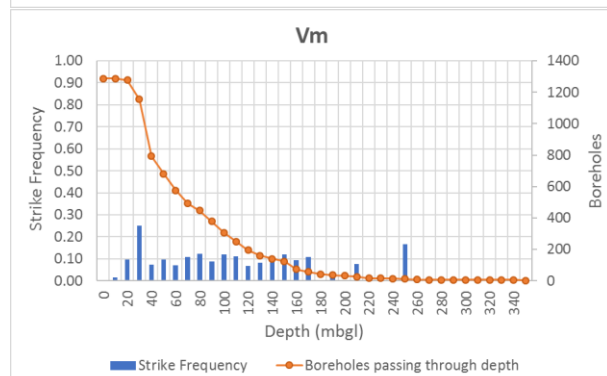
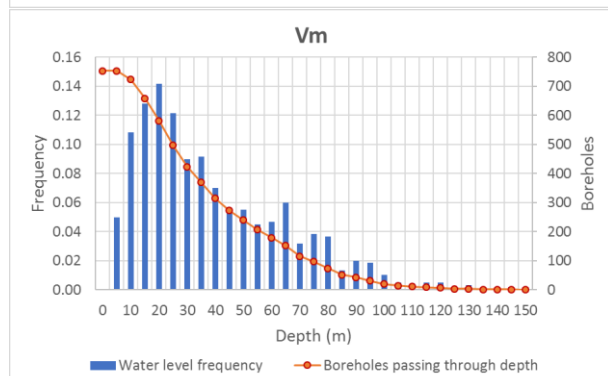
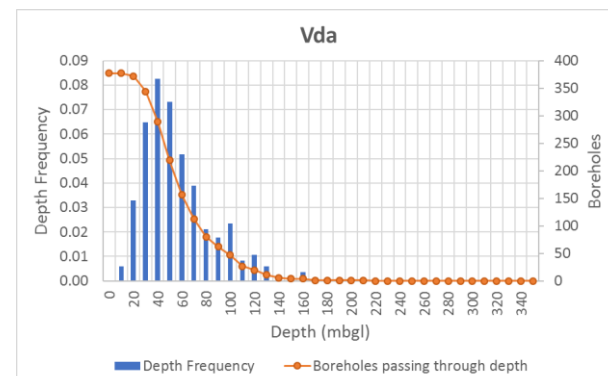
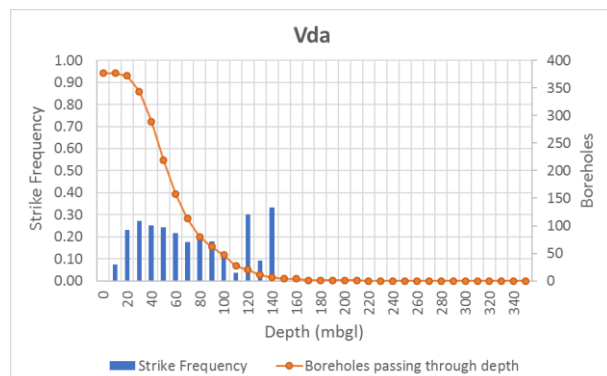
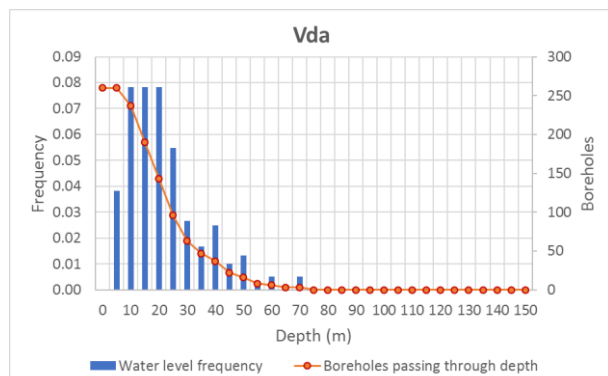


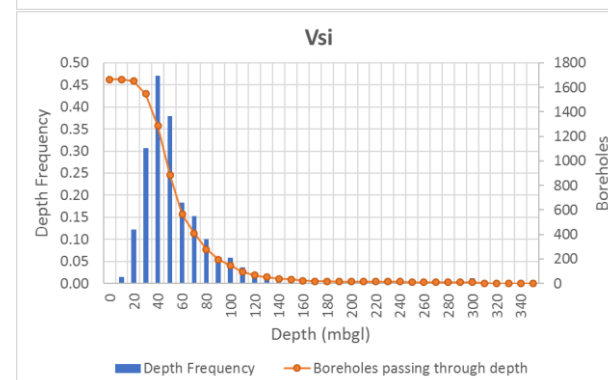
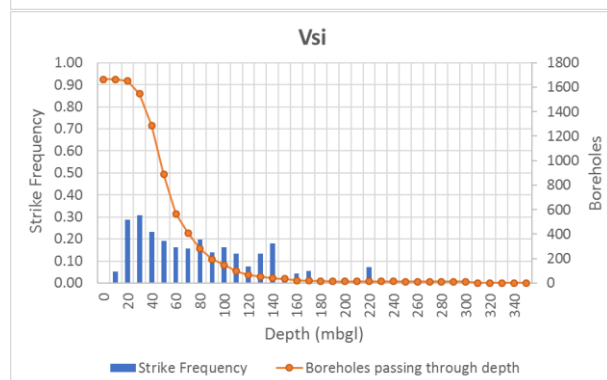
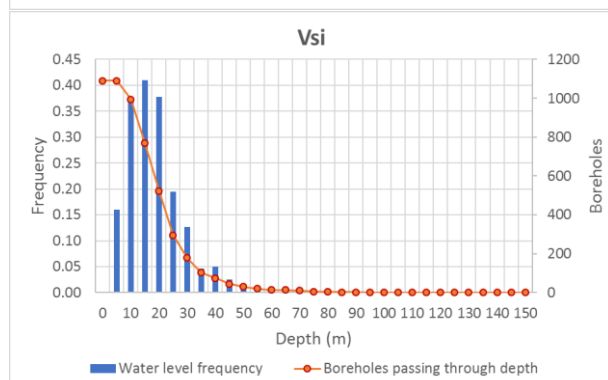
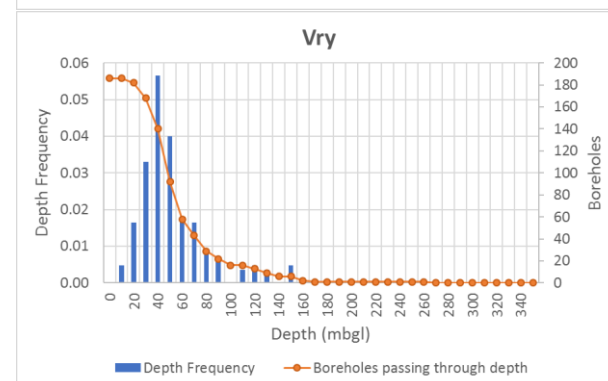
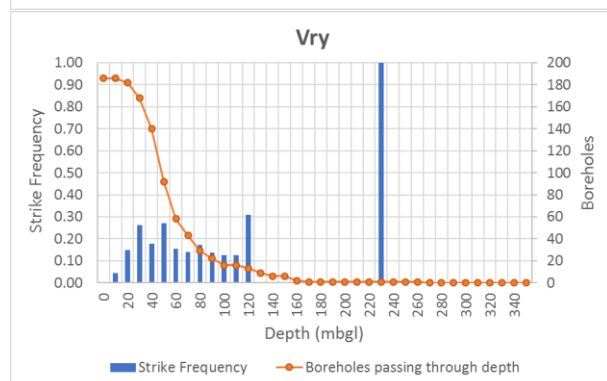
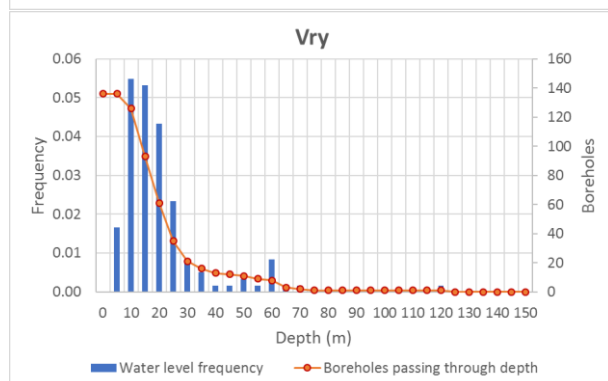
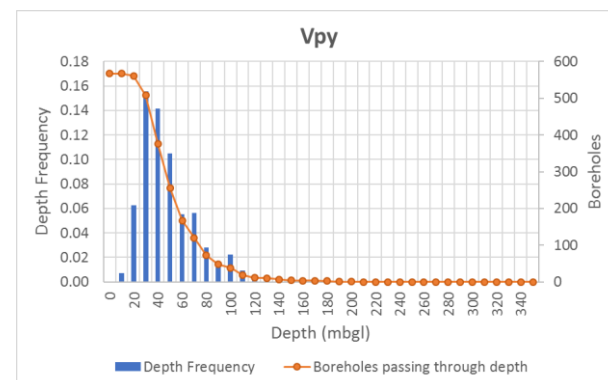
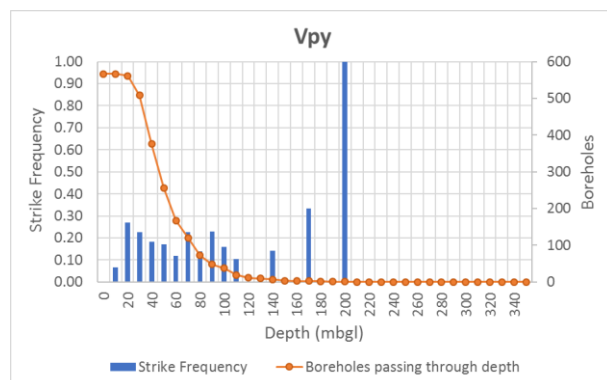
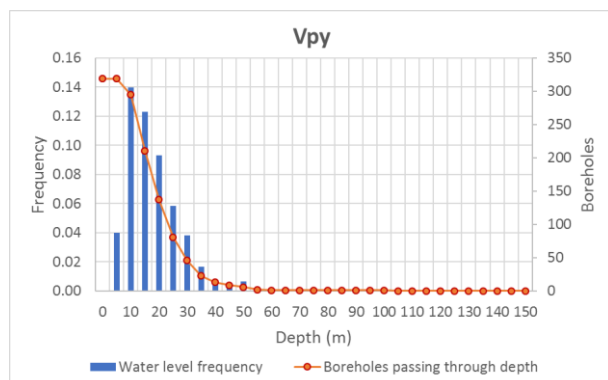
Figure 30: Stratigraphy example

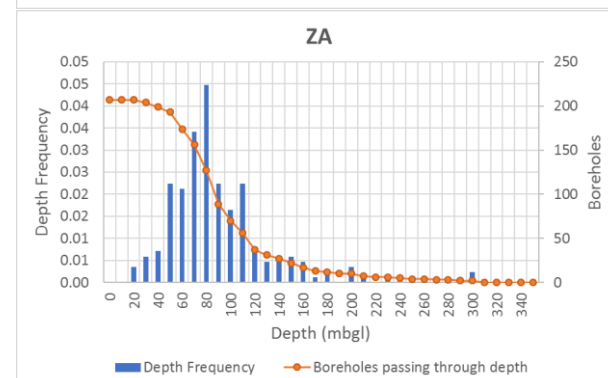
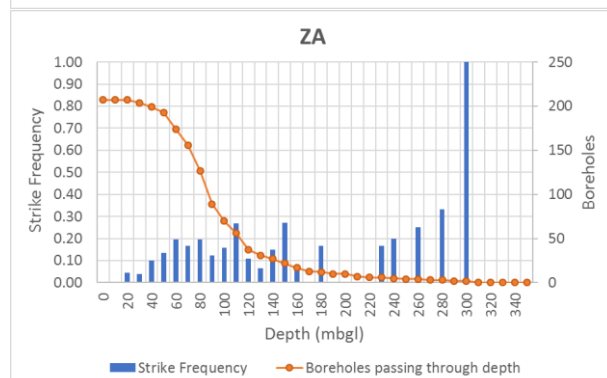
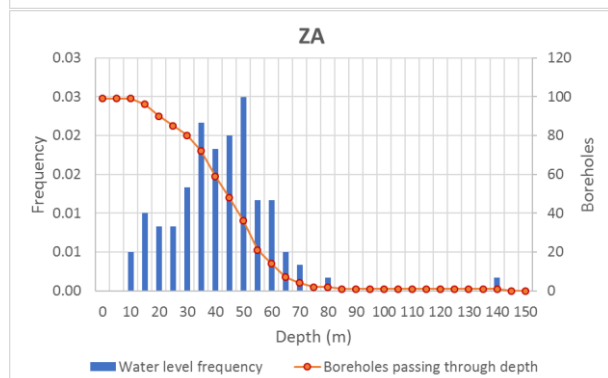
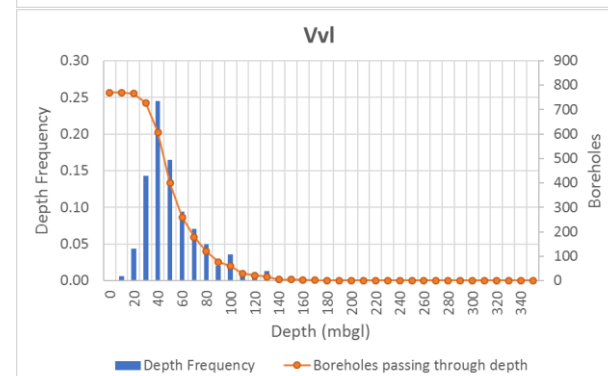
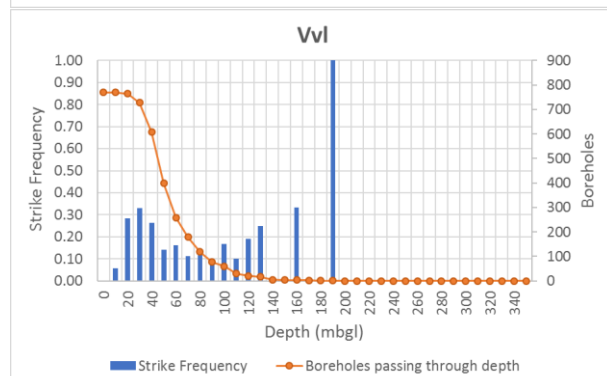
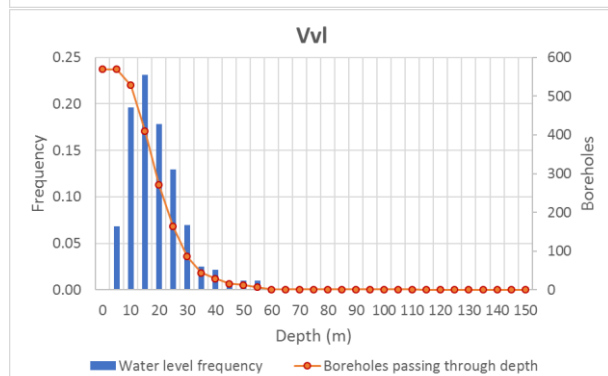
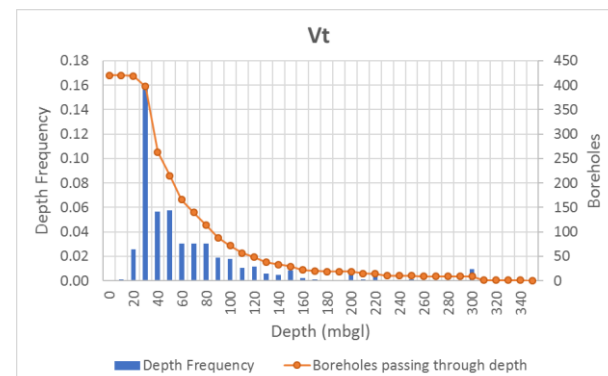
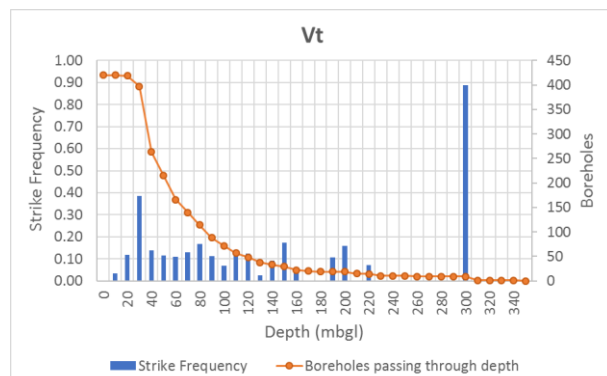
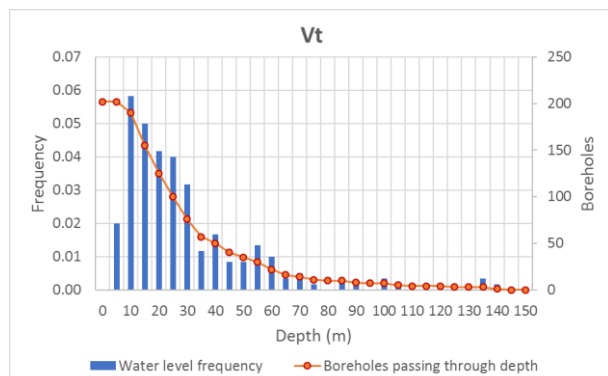
Table 11 – Analysis results of borehole water level, strike and depth

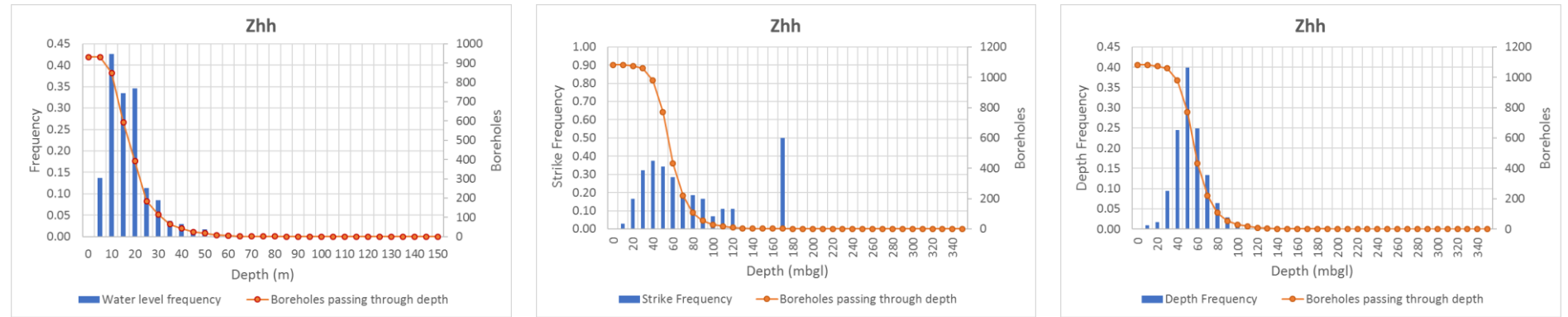












The associated water level analysis for each of the above mentioned geological units are presented in Appendix A. When looking at the results of the geological unit analysis it becomes clear that none of the geological units with regards to water movement stand out. In general a high correlation exist between surface topography and groundwater level with the exception of magnetite (VBI) at deeper water levels- this isn't significant as the deviation is based on only 6 boreholes spread over the catchment. It is also clear from the water analysis that various systems exist with depth within the analysed geological units.

The average borehole parameters per geological unit is shown in Figure 31 and a summary of the statistics is presented in Table 12.

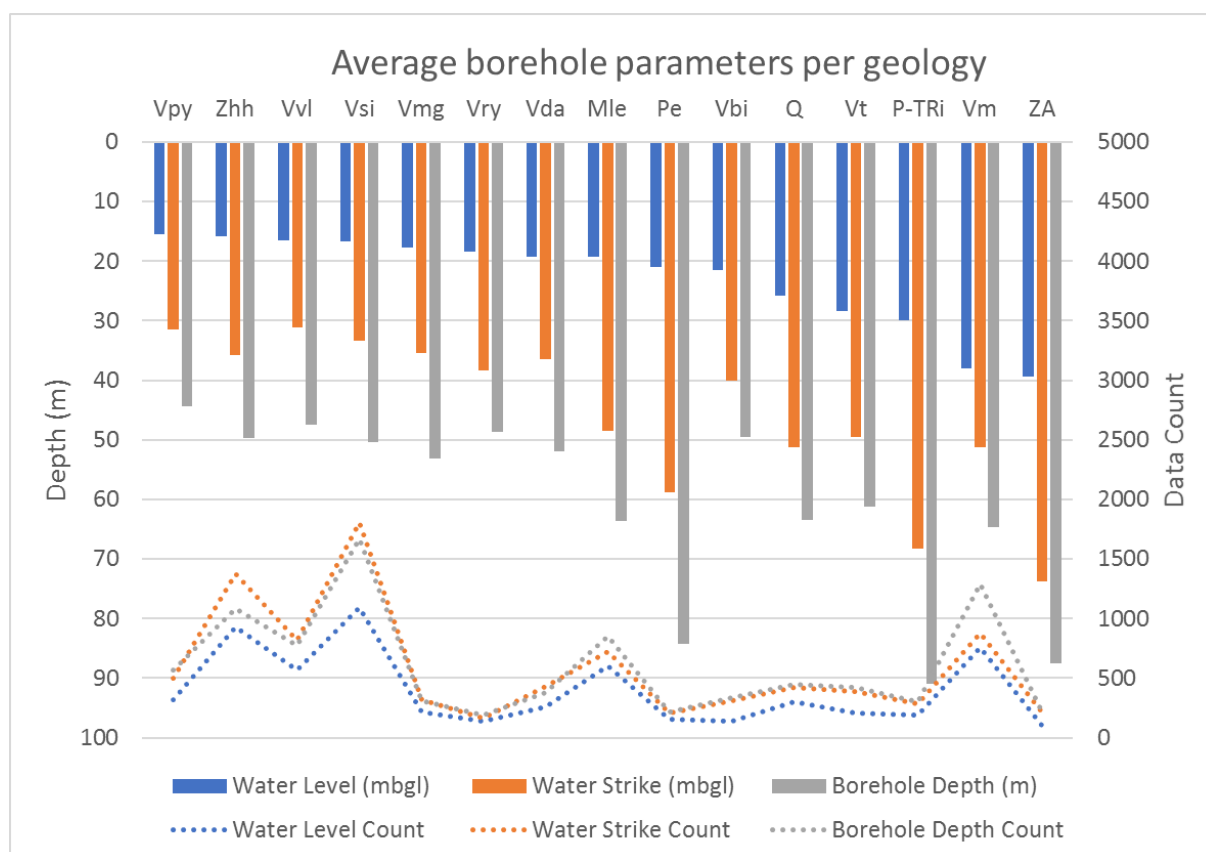


Figure 31 - Average borehole parameters per geological unit

Table 12 - Borehole parameter summary per geological unit

Geological Unit	Average Water Level			Average Borehole Depth			Average Water Strike Depth		
	Avg.	Std. Deviation	Count	Avg.	Std. Deviation	Count	Avg.	Std. Deviation	Count
Mle	19	16	601	64	33	849	48	33	725
Pe	21	16	157	84	47	216	59	47	203
P-TRi	30	20	188	91	37	305	68	39	281
Q	26	16	303	63	35	448	51	29	426
Vbi	21	14	142	50	26	332	40	25	312
Vda	19	13	260	52	30	377	37	24	428
Vm	38	34	758	65	52	1290	51	38	878
Vmg	18	13	213	53	28	306	35	25	319
Vpy	15	10	319	44	25	567	31	23	497
Vry	18	16	136	49	33	186	38	28	161
Vsi	17	12	1090	50	36	1665	33	23	1804
Vt	28	28	204	61	53	420	50	50	386
Vvl	16	10	569	47	24	770	31	21	821
ZA	39	18	99	87	47	207	74	46	210
Zhh	16	10	931	50	18	1082	36	16	1380

5 RESOURCE UNIT DELINEATION

5.1 Preamble

Statistical analysis of borehole information is used to delineate groundwater regions of similar character as groundwater RUs. It has been shown in the previous chapter that the groundwater occurrence is only partially dictated by the geological units and therefore an approach is required that is able to delineate groundwater RUs within a geological unit.

5.1.1 *Skewness of Data*

In probability theory and statistics, skewness is a measure of distributional asymmetry of a real-valued variable about its mean (Von Hippel, 2010). The skewness value can be positive or negative, or even undefined. Many models assume normal distribution; i.e., data are symmetric about the mean. The normal distribution has a skewness of zero. But in reality, data points may not be perfectly symmetric.

For the purposes of this study it is important to understand some of the factors influencing the skewness of the data in question. The two major anthropogenic influences are listed as follows:

- Only records of good yielding boreholes are normally kept e.g. when drilling for water supply takes place, the “dry” boreholes do not get logged as these are not deemed important.
- Borehole density will also affect the proposed delineation as a high concentration of boreholes in certain regions will result in a more detailed delineation as opposed to regions where the borehole distribution is sparse.

5.1.2 *Voronoi Diagram*

A Voronoi diagram is a diagram created by taking pairs of points that are close together and drawing a line that is equidistant between them and perpendicular to the line connecting them. All points on the lines in the diagram are equidistant to the nearest two (or more) source points. A graphic representation of a Voronoi diagram is shown in Figure 32, where the first Voronoi cell was constructed around point A (Bansal, et al., 2011; Luen, et al., 2012; Balakrishnan, et al., 2011).

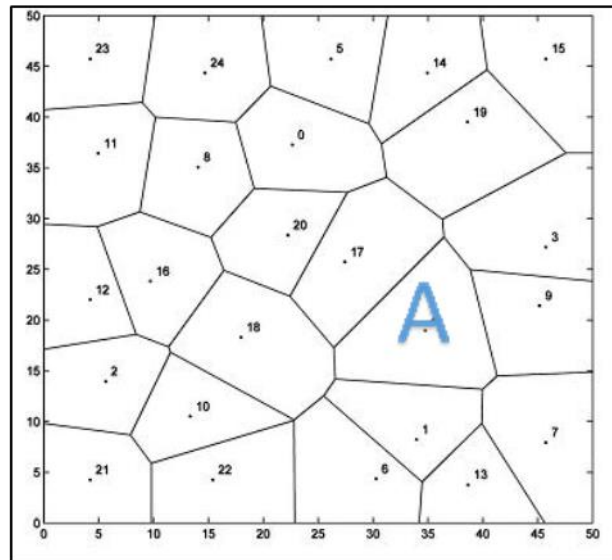


Figure 32 - Creation of Voronoi diagram (adapted from [Bansal, et al, 2011](#))

5.2 Frequency Analysis of Borehole Parameters

A detailed frequency analysis of all available borehole data was done in Chapter 4. Since it was shown that the geological units are not the only governing factor in the occurrence of groundwater, the geological units themselves cannot be used as resources units. It is further postulated that groundwater RUs will not necessarily follow the surface water RUs.

A frequency analysis of all available borehole parameters was conducted on a scale larger than that of the study area to ensure continuity across the surface water RU boundaries. The analysis was extended to the greater Crocodile West – Groot Marico area. The final borehole parameter set considered in the delineation is presented in Table 13.

Table 13 - Borehole parameters considered in the delineation process

Parameter	Comment
Water Level	Average borehole water level measured from surface to water level position.
Blow Yield	During the drilling of a borehole, water strikes are encountered and the “blow yield” measured gives an indication of the sustainable yield of the borehole.
Water Strike Depth	During the process of drilling, water strikes are encountered at specific depths. For the purposes of delineation, the deepest water strike for each borehole was used.
Water Quality (EC)	The EC (Electrical Conductivity) of a borehole is an indication of the salinity of the water. Very saline water is associated with deep stagnant water, but can also be due to the mineralogy of the host rock.

Data availability was a major factor in identifying the borehole parameters used in the delineation. Borehole discharge was also taken into consideration, but was excluded due to the poor distribution of data.

In the frequency analysis (histogram plots) bin sizes were selected for each of the parameters to yield four bins per parameter that describes at least 95% of the total dataset. A bin, for the sake of the study, can be defined as a simplified value that describes different parameters under one numbering convention. A summary of the selected bins per parameter is presented in Table 14 and the resultant frequency analysis of the borehole parameters used is presented in Appendix B. It is clear that the water level information used is an order of magnitude higher than the other parameters due to the fact that water level information is recorded more often as compared to the other parameters.

Table 14 - Summary of selected bins per specified borehole parameter

Bin No	Water Level		Blow Yield		Water Strike		EC	
	Bin	Count	Bin	Count	Bin	Count	Bin	Count
1	20	10825	2	826	40	663	40	721
2	40	6279	4	154	80	478	80	793
3	60	2008	6	78	120	115	120	392
4	80	648	8	45	160	46	160	119
		19760		1103		1302		2025

5.3 Delineation Methodology

A Voronoi diagram was constructed for each of the identified borehole parameters, where the borehole position and bin number were used. The bin number enabled a classification of 1 to 4 for each of the parameters in question. Once the Voronoi diagram was created it was simplified through the grouping of Voronoi cells which has the same bin number as illustrated in Figure 33.

A simplified Voronoi diagram was created for each of the four borehole parameters (Table 14). The final delineation of the groundwater regions was achieved by combining the four Voronoi diagrams in a linear combination as described by the following equation.

$$Delineation\ Class = \frac{Level + (5 - Yield) + Depth + EC}{4} \quad (1)$$

Note the yield bins are reversed in the equation as higher yields generally correspond to shallow water levels and strike depths. The final delineation map is shown in Figure 34. The groundwater sub-region delineation with the borehole sets used that represent the four parameters is shown in Figure 35 to Figure 38.

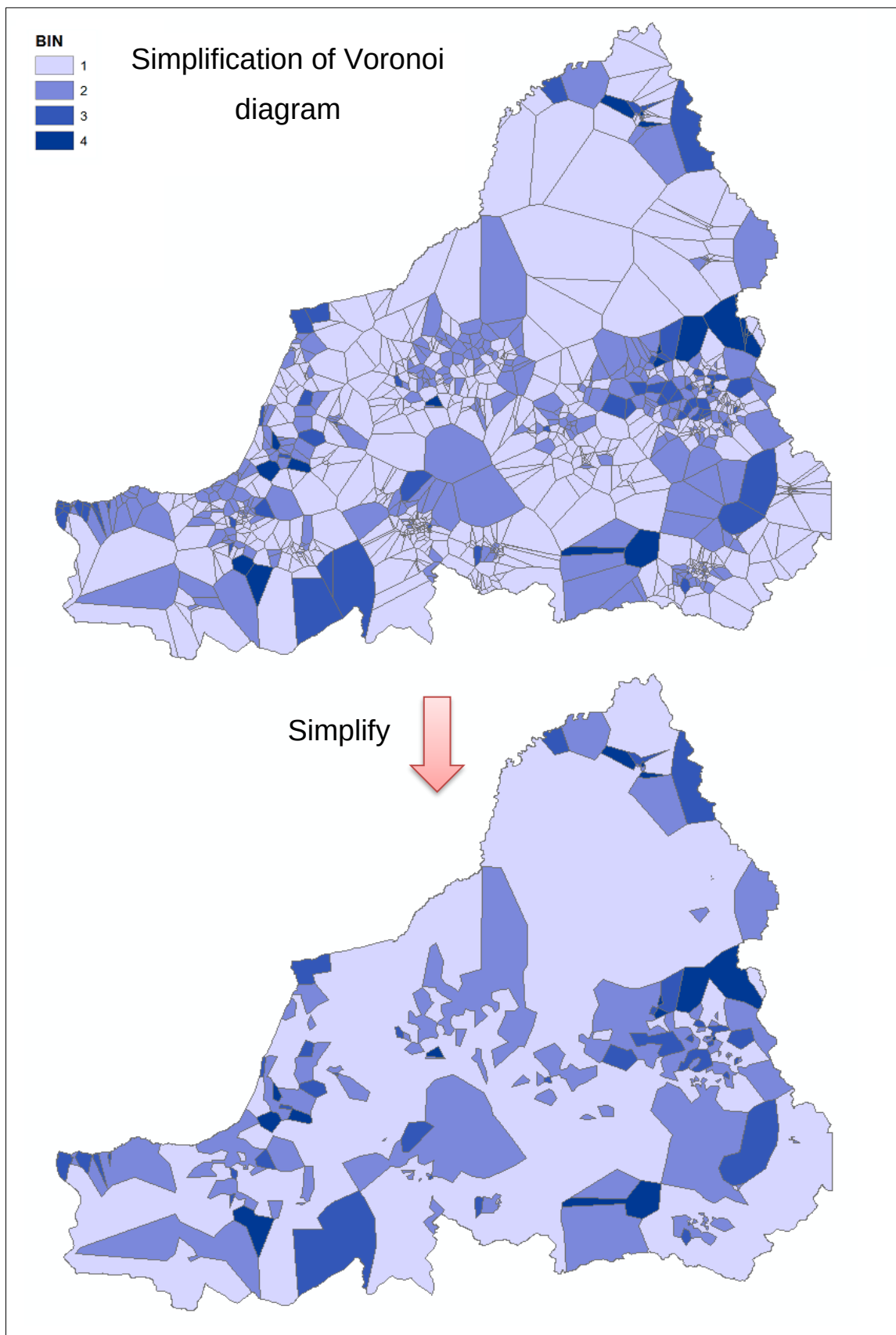


Figure 33 - Simplification of Voronoi diagram based on bin numbers used in frequency analysis

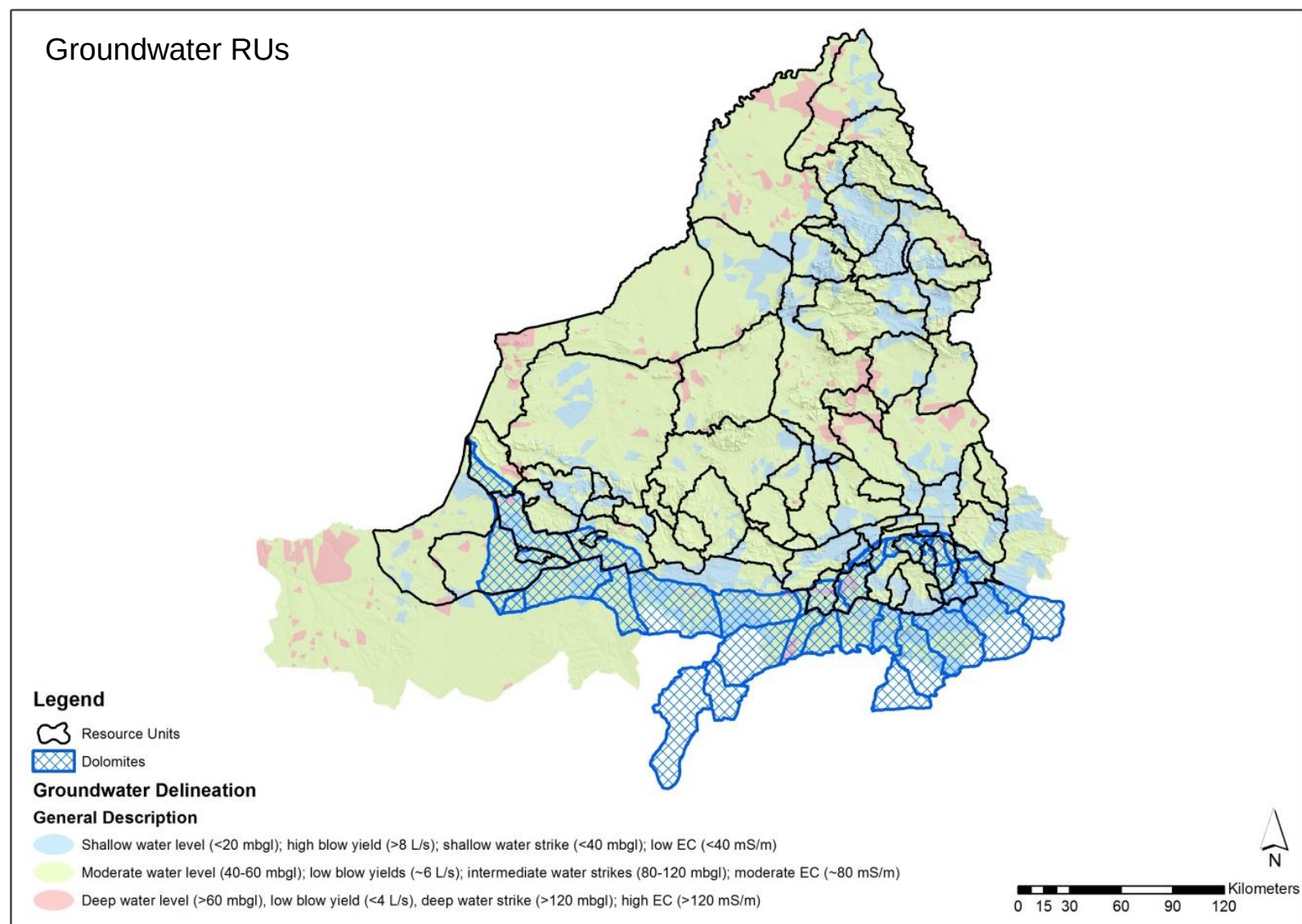


Figure 34 - Groundwater RUs map (extended boundaries)

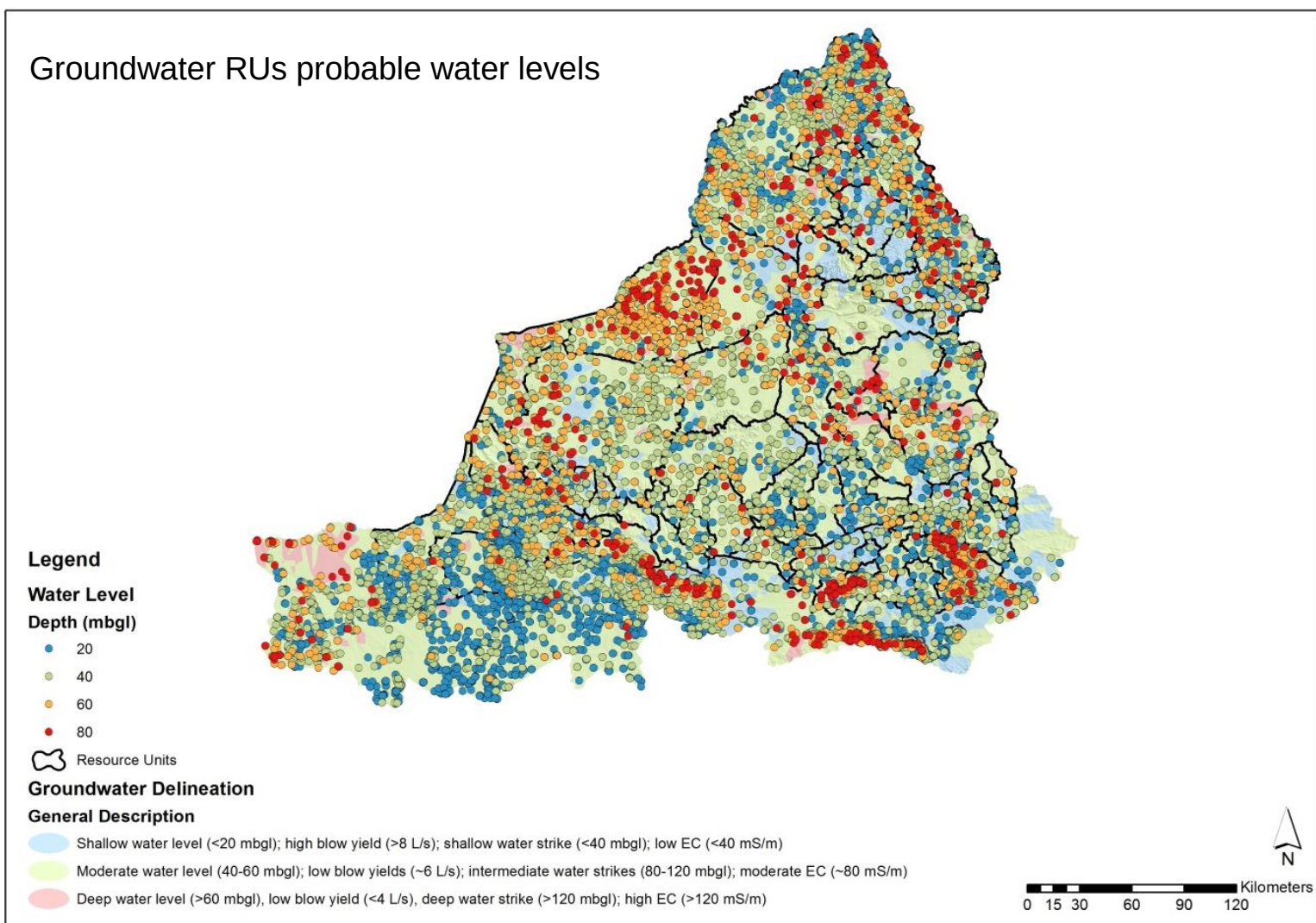


Figure 35 – Groundwater RUs with probable water levels

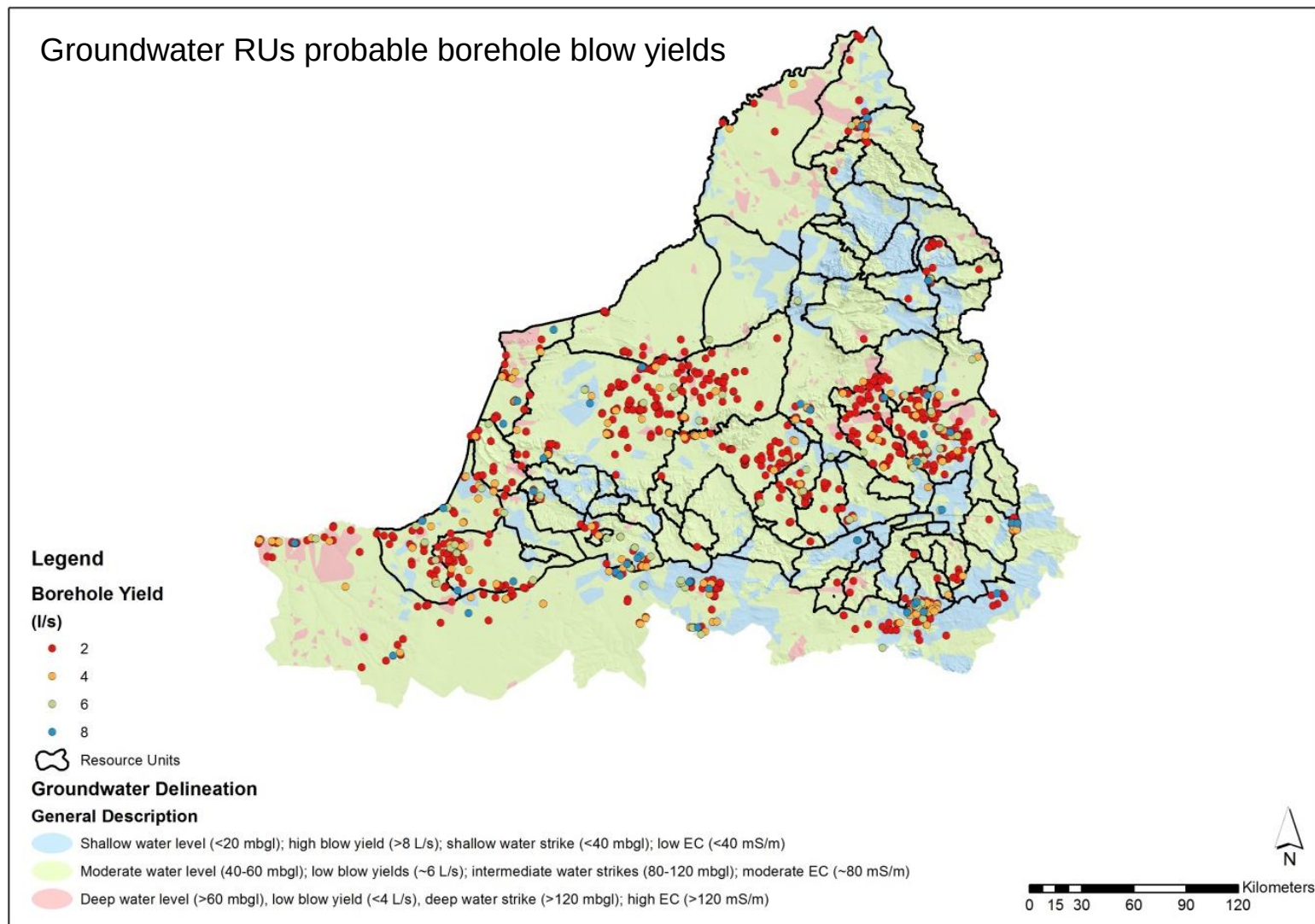


Figure 36 – Groundwater RUs with probable borehole blow yields

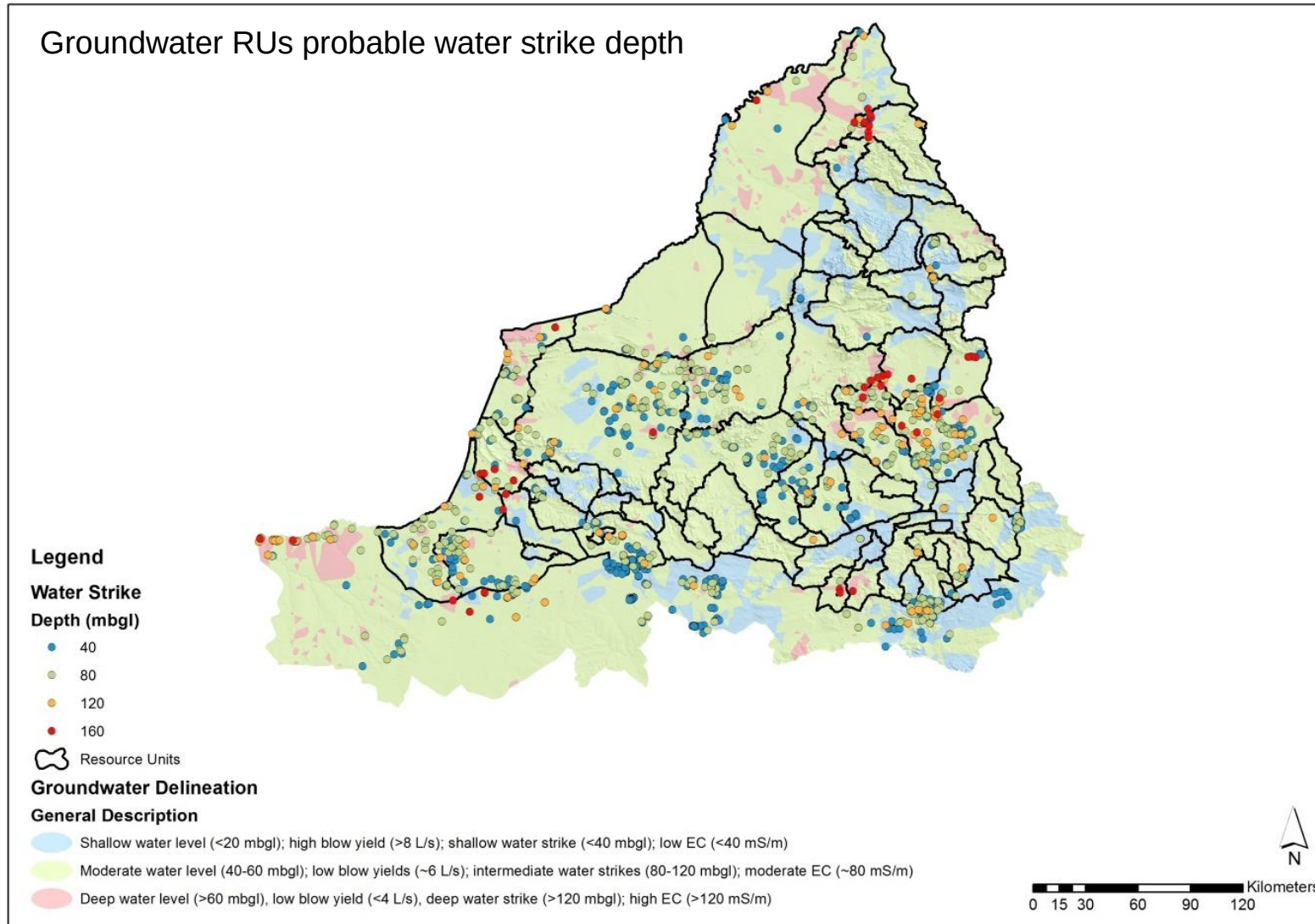


Figure 37 – Groundwater RUs with probable water strike depth

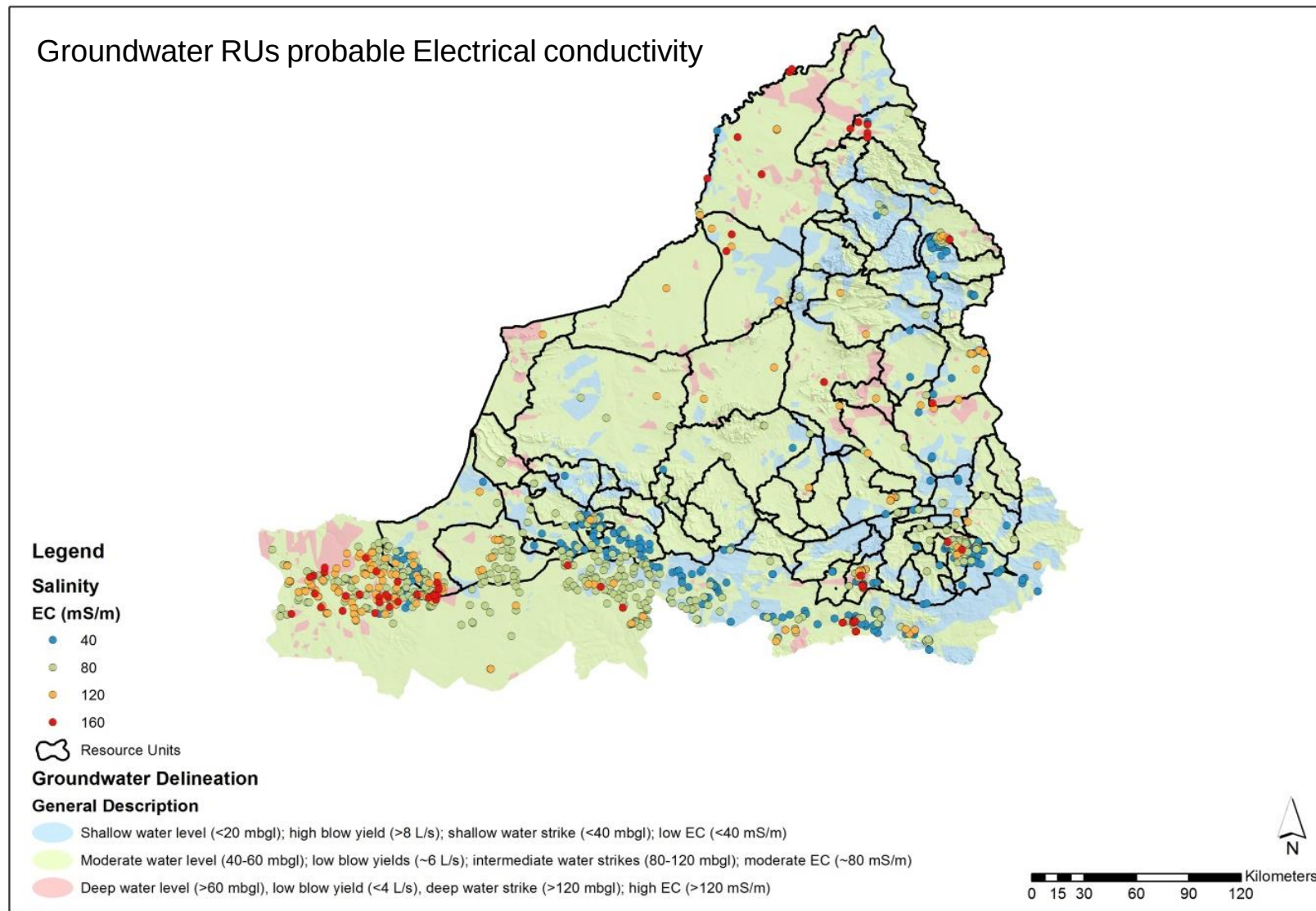


Figure 38 – Groundwater RUs with probable Electric conductivity

The resultant delineation specifying the groundwater profile in the Crocodile-West study area is shown in Figure 39. It is important to note that the delineation is strongly dependent on the specified borehole data and delineation can be refined as more data becomes available.

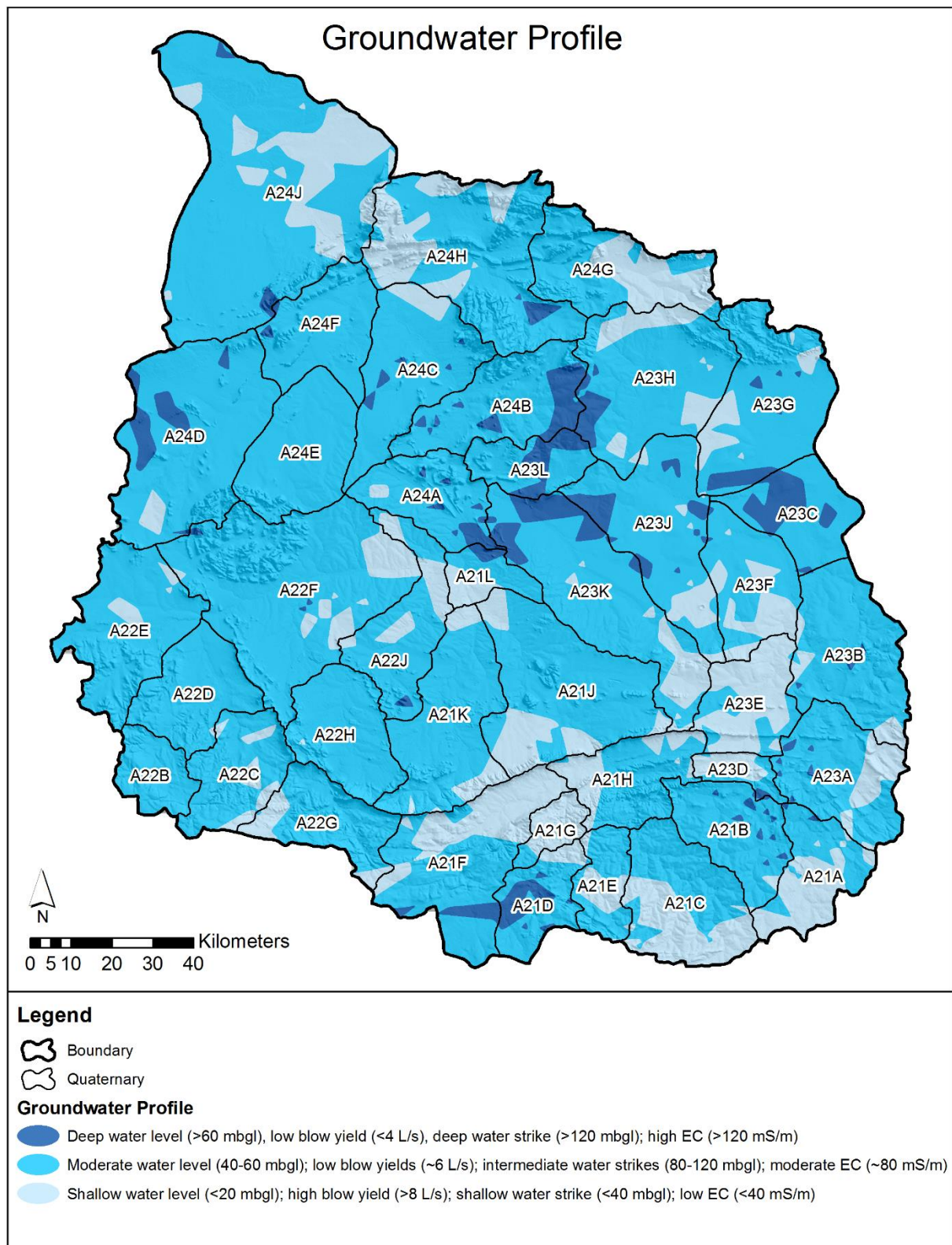


Figure 39 - Groundwater profile map of the Crocodile-West study area

6 CLASSIFICATION

Prior to determining RQOs for the Crocodile-West catchment IUAs need to be classified and the groundwater Reserve for each quaternary catchment calculated. This is an important step as the RQOs will be set to manage the resource against the given class. The classification procedure and groundwater Reserve determination for the study area as it was carried out by the DWA are explained in the sections that follow. This corresponds to the step, establishing vision for the catchment in Figure 2.

6.1 Classification Procedure

To determine the groundwater management class of an IUA in the study area, the same 7-Step process used for surface water as described in Chapter 2 was followed, with a few adjustments.

Separation of groundwater units into Groundwater Management Areas (GMAs), Groundwater Management Units (GMUs) and Groundwater Resource Units (GRUs) was the first step. GMAs are delineated units which may overlap with quaternary catchment areas or the boundaries of dolomitic compartments restricted by dykes (DWA, 2013b). GMAs also may consist of more than one GMU. According to the Groundwater dictionary (DWS, 2015) a GMU is a groundwater area within a catchment that needs to be monitored regularly and action taken to uphold the level of groundwater protection and regulate use. A GMU can consist of several GRUs which can be describes as groundwater resources grouped due to similar/unique hydrogeological characteristics (DWS, 2015).

In Step 1, GMUs were selected and merged with the Integrated Units of Analysis (IUAs) as shown in Figure 39. In some cases, the UA boundaries were changed to take into consideration the flow regime of a group of GRUs. The dolomites on the southern side of the Crocodile-west catchment were treated as such a special case because of their flow patterns, unique boundaries and contribution to base flow. The GMAs which were based on dolomitic compartments in the Crocodile-West catchment do not coincide with the surface quaternary catchments. Other non-dolomitic aquifers were grouped according to the quaternary catchments with the purpose of aligning all water resources with an established framework.

Step 2, the socio-economic and ecological value and condition of water resources in terms of groundwater, refers to the groundwater uses and dependence on groundwater for each IUA. Major groundwater users were identified as domestic water supplies to villages and communities, supply for irrigation and water for mining and industrial use. The socio-economic and ecological value of dolomitic aquifers in the Crocodile-West catchment are high in comparison to other aquifers in the catchment due to the large volumes of water they supply and the quality which is

naturally in a good condition. Flushing due to wet climate cycles are mostly responsible for these conditions. Dolomitic aquifers within the study area have a significant importance and were thus incorporated into the management classification through empirical interpretation. Other non-dolomitic aquifers in the study area are important mainly for supplying water for domestic needs.

Quantifying EWR (Step 3) and changes in ecosystem goods, services and attributes. Dolomitic eyes within the study area play a crucial role in maintaining EWR of surface water downstream in the catchment. Headwater regions in the dolomitic aquifers are significantly important in maintaining these eyes. Examples exist where abstractions from boreholes in the Grootfontein eye had dropped the water Table, which stopped decanting and resulted in a collapse of the downstream ecology as it ran dry.

Step 4 describes the determination of an ESBC scenario (Ecological Sustainable Base Configuration).

Lastly, Step 5 relates to the evaluation of scenarios in the IWRM process. Groundwater-surface water interactions in areas of surface water drainage were identified and included in the ESBC (DWA, 2013c).

Management classes (MCs) for each quaternary catchment, as taken from the DWA (2013c) were based on the quality and quantity of surface water, ground water and wetlands. The percentage contribution of wetlands to the MC of an IUA depends on the presence of wetlands within that IUA. Groundwater occurrence within an IUA determined the percentage contribution groundwater had to the MC of that IUA.

Management classes are defined in three categories:

- Management Class I: Water resources are minimally used and alterations to the resource unit's pre-development ecological state are to a minimum.
- Management Class II: Water resources are moderately used and alterations to the resource unit's pre-development ecological state are moderate.
- Management Class III: Water resources are heavily used and alterations to the resource unit's pre-development ecological state are significant (DWA, 2013c).

Management classes were assigned for each IUA in the Croc-West system (Table 15). The percentage contribution of surface water, groundwater and wetlands to the management class were also included in the Table.

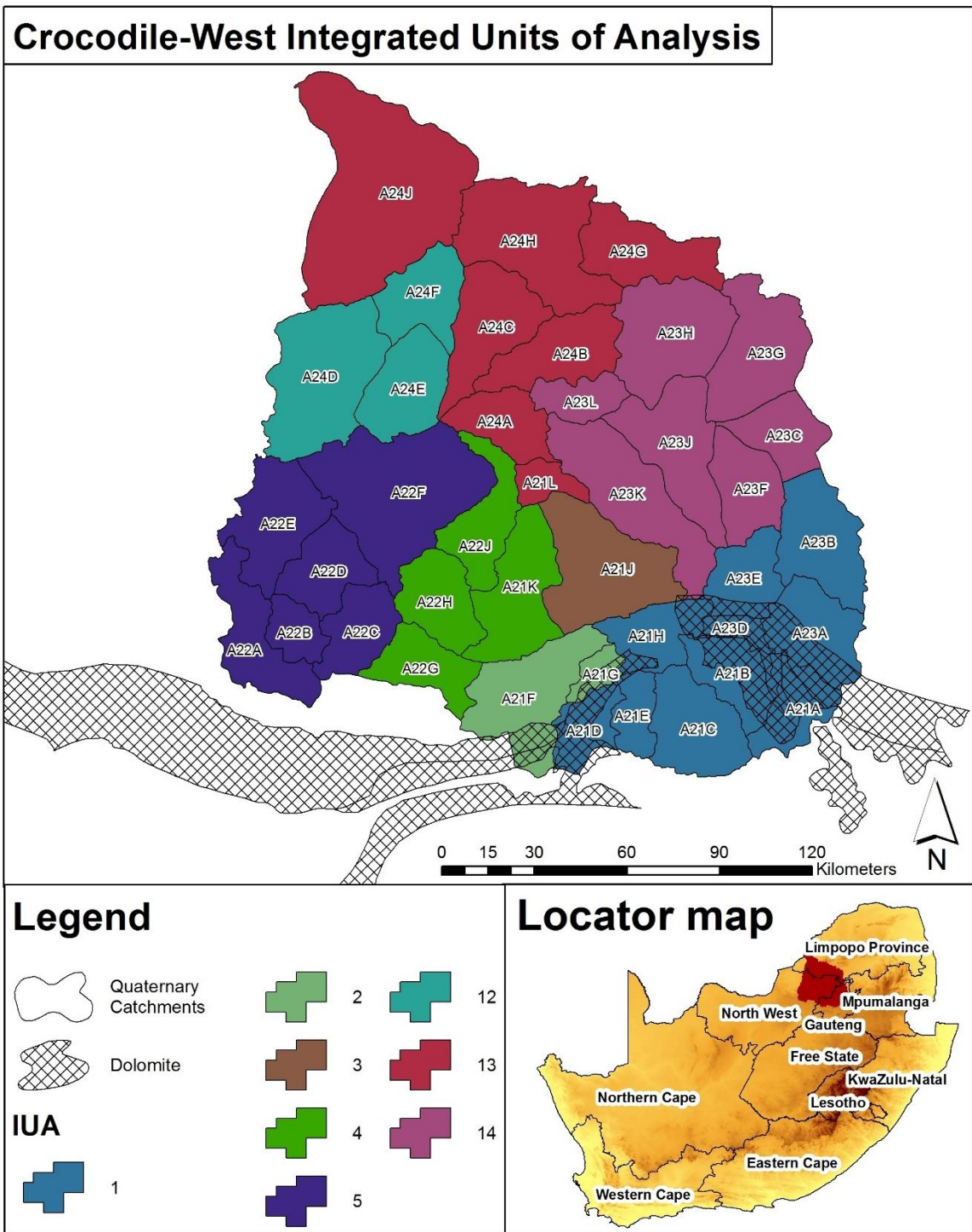


Figure 40 - Crocodile-West IUAs

Table 15 - IUA Management classes (DWA, 2013c)

IUA	Recommended Management Class	% Contribution to Management Class		
		Surface Water	Groundwater	Wetlands
1	III	75	15	10
2	II	60	33	7
3	III	95	5	0
4	II	77	9	14
5	II	75	5	20
12	III	80	20	0
13	III	68	25	7
14	III	65	15	20

To specify the groundwater quantity component for the management class determination a stress index (SI) was calculated as a percentage by dividing groundwater abstraction values with the recharge for each IUA, shown in the following equation:

$$\text{Stress Index} = \frac{Q}{Re} \times 100 \quad (2)$$

where,

$$\begin{aligned} Q &= \text{Groundwater Abstraction} \\ Re &= \text{Recharge} \end{aligned}$$

For groundwater quantity, a ‘present category (impacted)’ was also assessed which is based on the interpreter’s experience of groundwater within an IUA. Groundwater quality for each IUA was statistically evaluated and represents the ‘present category (quality)’ of the groundwater management class (DWA, 2013c). The results of the aforementioned analysis are summarised in Table 16.

Table 16 - Factors contributing to management class (DWA, 2013c)

<i>IUA</i>	<i>Stress Index</i>	<i>Present Category</i>	<i>Present Category (Impact)</i>	<i>Present Category (Quality)</i>	<i>% Contribution to recommended MC</i>
1	34%	I	II	I	15
2	49%	II	II	I	33
3	46%	II	II	I	5
4	35%	II	II	I	9
5	14%	I	II	I	5
12	14%	I	I	II	20
13	41%	II	II	II	25
14	24%	II	II	II	15

6.2 Reserve Determination

The reserve as defined by the NWA (1998) is the quantity and quality of water in a proposed area that is needed to fulfil basic human need requirements now and in the future and to retain ecological sustainability while also developing the water resource for economic growth. Ecological reserve requirements should be the first consideration before any other water consuming activity, as it states how much water of what quality will have to be safeguarded to guarantee that the ecosystem can thrive and will be able to supply us now and in the future with that same quality and quantity of water (NWA, Act No. 36 of 1998).

An intermediate Reserve determination study was initiated by the Chief Directorate: Resource Directed Measures (RDM) for specific and important rivers and wetlands in the Crocodile-West catchment (DWA, 2013b). The Reserve determination study with regards to groundwater was only a rapid assessment based on a quaternary catchment scale. The rapid Reserve determination was aimed at obtaining preliminary results and identifying quaternary catchments with groundwater resources which are stressed due to overuse or contamination. Once determined, prioritised quaternary catchments can be subject to more intensive Reserve determination studies with a higher confidence level. The groundwater Reserve determination results for the study area are expected to be of low confidence as only a rapid assessment was done (DWA, 2010) from which preliminary RQOs will be formulated.

After the completion of the rapid Reserve determination, it was decided that no monitoring was required at that time for any of the study area's quaternary catchments. Prioritised catchments may thus be subject to monitoring after a more detailed assessment in the future (DWA, 2010).

To calculate the Reserve for the study area, BHN requirements were based on the prescribed 25l/p/d requirement and applied to the population figures of each quaternary catchments. It was assumed that BHN was provided for through surface water resources in urban areas with large populations. To limit double accounting in urbanised areas, a maximum population count of 100,000 was chosen as groundwater dependent, while calculating the BHN supplied by groundwater (DWA, 2010). A large portion of the groundwater in some catchments are of such poor-quality due to natural geological features that the BHN reserve for those catchments was chosen to be zero.

For EWR, the environmental flow requirements (EFR) were used. DWA (2010) used EFR data from the SPATISM database for the quaternary catchments of the study area. The lowest proportionate monthly EFR per quaternary catchment was used as the groundwater component for the EWR.

The groundwater Reserve is calculated as follows:

$$Reserve\% = \frac{EWR_{gw} + BHN_{gw}}{Re} \times 100 \quad (3)$$

where,

EWR_{gw}	=	Groundwater ecological water requirement component
BHN_{gw}	=	Groundwater basic human need component
Re	=	Recharge

The groundwater component of the Reserve for the study area as well as the classification for each quaternary catchment as taken from the DWA (2012) is indicated in Table 17. The Reserve determination for quaternary catchment A23A was not available.

Table 17 - Groundwater Reserve determination (DWA, 2012a)

Quaternary catchment RUs	Classification		Recharge		Reserve (million m ³ /annum)			Allocation (million m ³)	
	Present Status Category	Water Resource Category	Effective Area (km ²)	Annual Recharge (million m ³)	Groundwater Component of EWR	Basic Human Needs	Reserve as % of Recharge	Groundwater Allocation	Current Groundwater Use
A21A	E	Poor	483	27.641	0.536	0.611	4.1	26.494	20.345
A21B	C	Fair	527	30.215	0.316	0.913	4.1	28.987	11.575
A21C	B	Good	761	18.684	1.041	0.913	10.5	16.731	1.166
A21D	E	Poor	372	19.655	1.514	0.809	11.8	17.332	11.533
A21E	B	Good	290	9.207	0.411	0.650	11.5	8.146	0.774
A21F	E	Poor	1000	47.399	1.262	0.106	2.9	46.031	33.618
A21G	B	Good	161	6.238	1.735	0.001	27.8	4.502	0.485
A21H	B	Good	514	20.892	2.557	0.614	15.2	17.721	3.226
A21J	D	Fair	1150	29.893	0.285	0.913	4.0	28.696	14.103
A21K	D	Fair	864	23.279	1.514	0.504	8.7	21.261	13.535
A21L	B	Good	213	4.497	0.158	0.000	3.5	4.339	0.612
Total A21			6333	237.600	11.329	6.033	7.31	220.238	110.972
A22A	B	Good	706	21.318	0.347	0.181	2.5	20.790	1.868
A22B	B	Good	284	9.365	0.189	0.000	2.0	9.176	1.800
A22C	B	Good	515	17.303	0.000	0.000	0.0	17.303	1.027
A22D	C	Good	541	14.177	0.095	0.000	0.7	14.082	4.017
A22E	B	Good	812	19.386	0.158	0.037	1.0	19.191	1.903
A22F	B	Good	1688	35.691	0.947	0.000	2.7	34.744	4.022
A22G	B	Good	499	17.989	0.347	0.000	1.9	17.642	1.464
A22H	C	Fair	579	15.612	0.063	0.913	6.2	14.637	6.156
A22J	C	Good	592	8.518	0.221	0.178	4.7	8.119	2.199
Total A22			6215	159.359	2.367	1.308	2.31	155.684	24.456

Quaternary catchment RUs	Classification		Recharge		Reserve (million m ³ /annum)			Allocation (million m ³)	
	Present Status Category	Water Resource Category	Effective Area (km ²)	Annual Recharge (million m ³)	Groundwater Component of EWR	Basic Human Needs	Reserve as % of Recharge	Groundwater Allocation	Current Groundwater Use
A23A	B	Good	682	34.295					5.094
A23B	B	Good	814	10.502	0.284	0.172	4.3	10.046	1.448
A23C	B	Good	491	6.200	0.095	0.051	2.4	6.054	0.791
A23D	E	Poor	252	18.726	1.767	0.913	14.3	16.047	13.731
A23E	D	Fair	490	6.280	0.063	0.913	15.5	5.305	3.098
A23F	C	Good	565	6.476	0.284	0.000	4.4	6.192	0.737
A23G	D	Fair	951	20.580	0.821	0.636	7.1	19.123	10.888
A23H	B	Good	1058	28.124	0.126	0.182	1.1	27.816	2.587
A23J	B	Good	930	6.782	0.820	0.000	12.1	5.962	0.430
A23K	A	Natural	1131	10.964	0.126	0.000	1.1	10.838	0.495
A23L	B	Good	329	3.074	0.347	0.000	11.3	2.727	0.619
Total A23			7012	117.709	4.733	2.867	6.46	110.109	34.824
A24A	D	Fair	493	5.730	0.915	0.097	17.7	4.718	2.912
A24B	C	Good	709	18.594	0.222	0.002	1.2	18.371	1.046
A24C	D	Fair	801	20.297	0.126	0.000	0.6	20.171	11.181
A24D	B	Good	1327	20.547	0.000	0.607	3.0	19.940	1.456
A24E	A	Natural	688	10.585	0.000	0.515	4.9	10.071	0.013
A24F	D	Fair	591	12.090	0.000	0.000	0.0	12.090	6.041
A24G	A	Natural	735	24.662	0.347	0.000	1.4	24.315	0.360
A24H	B	Good	1338	37.309	1.862	0.137	5.4	35.310	4.209
A24J	F	Poor	2516	35.192	0.599	0.055	1.9	34.538	39.497
Total A24			9198	185.006	4.071	1.413	36.1	179.524	66.715

7 PRIORITISATION

7.1 Preamble

For prioritisation (refer to step 3, Figure 2), the same approach was followed as with the Upper Vaal report (DWA, 2014d) but changes were made with regards to the methodology. The scope of the prioritisation of RUs is to compile all available data, information and public participation feedback in a single framework to be used to perform the RU prioritisation. This methodology and framework can then be applied to similar studies based on the same criteria. A schematic representation of the prioritisation is shown in Figure 41.

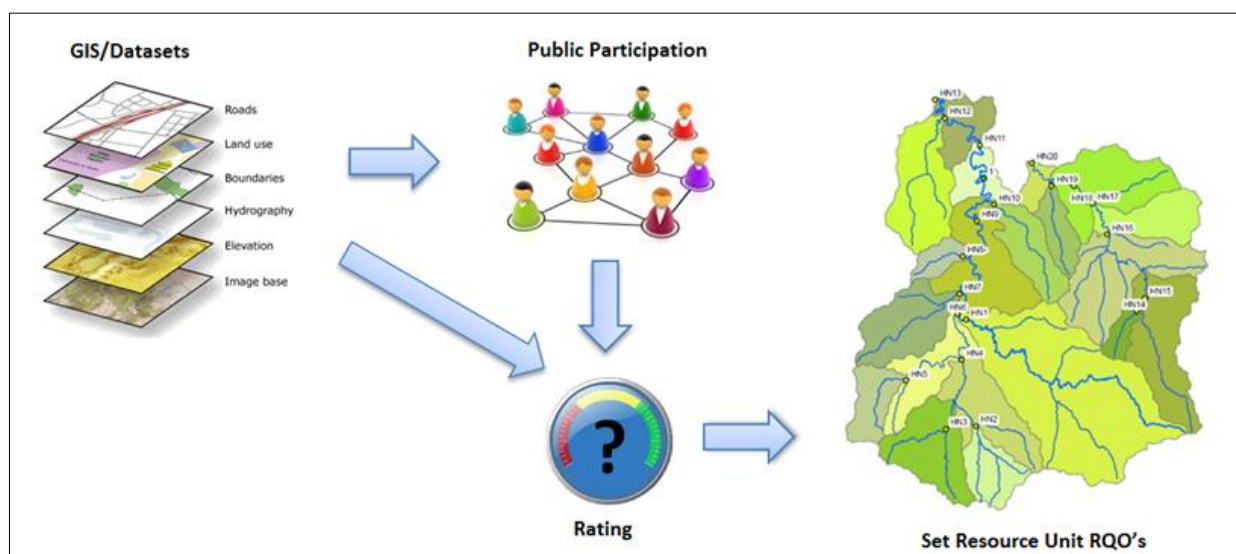


Figure 41 - Schematic representation of the prioritisation process

7.2 Methodology

To prioritise groundwater resources, the framework of an approach developed by the INR (DWA, 2011) to prioritise surface RU's was used. This prioritisation approach requires a set of criteria and sub-criteria that is weighted and rated to calculate a priority rating which is then normalised.

The f criteria and sub-criteria used in this study for the groundwater prioritisation process was chosen due to available datasets. The resultant Table with the selected criteria and the relative weights applied is shown in Table 18. The relative weights assigned, should form part of the public participation process.

Table 18 - Groundwater prioritisation criteria

Criterion	Relative weighting	Sub-criteria	Relative weighting
<i>Importance for users (Current & anticipated future use)</i>	15	Water character of a high quality	30
		Major aquifers	40
		Activities that contribute to economy	30
<i>Threat posed to users</i>	15	Aquifers which are highly stressed	40
		Water quality is currently threatened	40
		Vulnerable aquifers	20
<i>Ecological Importance</i>	20	Groundwater importance to wetlands	40
		Ground-surface water interactions	60
<i>Groundwater Profile</i>	50	Combined groundwater profile	100

Sub-criteria can have a spatial variability across the resource unit extent, but any sub-criteria can only have one rating in the proposed prioritisation model. To address this constraint the following rule set was applied:

- a) The sub-criteria category which covers the largest part of the resource unit is assigned.
- b) Rule (a) can be overridden through public participation if consensus was reached among the relevant role players.

7.3 Importance for Users

The sections that follow discuss the sub-criteria linked to the importance for users and the rating guideline that applies to each of the sub-criteria.

7.3.1 Water character of high quality

All available water quality data (TDS) was obtained from the NGA database for each of the RUs and presented in conjunction with the TDS map of South Africa (Vegter, 1995) as shown in Figure 42. The rating guideline applied to each RU for evaluating the water character is presented in Table 19 and the spatial distribution of the final ratings is presented in Appendix C.

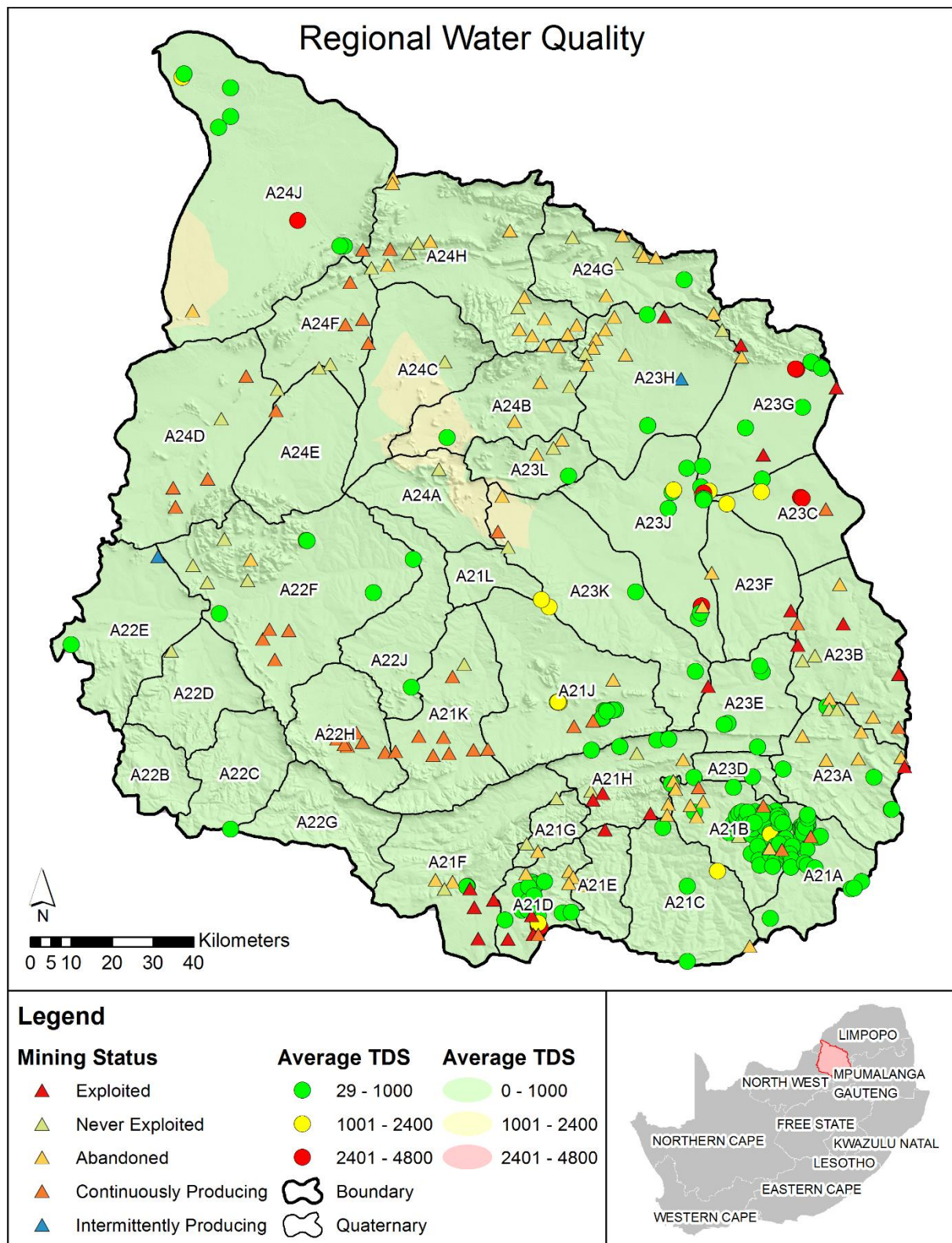


Figure 42 - Water quality map of the study area

Table 19 - Water character rating guideline

Rating	Guideline
0.0	RUs which contain high TDS (>2400 mg/L)
0.5	RUs which contain moderate TDS (1000 – 2400 mg/L)
1.0	RUs which contain low TDS (< 1000 mg/L)

The TDS ratings in Table 19 is based on the DWA drinking water quality guidelines for domestic use (DWAF, 1996).

7.3.2 Major aquifers

Groundwater occurrence was identified using the geohydrological yield map presented in Figure 19. The rating guideline applied to each RU for evaluating major aquifers are presented in Table 20 and the spatial distribution of the final ratings is presented in Appendix C.

Table 20 - Major aquifer rating guideline

Rating	Guideline
0.0	RU's which contain or are dominated by poor aquifers (< 0.5 L/s)
0.5	RU's which contain or are dominated by minor aquifers (0.5 - 2 L/s)
1.0	RU's which contain or are dominated by major aquifers (> 2L/s)

7.3.3 Activities that contribute to the economy

Activities that contribute to the economy that could be dependent on groundwater were identified as farming, parks and mines. The datasets used to depict the aforementioned activities is as follows:

- Protected areas (DWAF, 2006)
- Cultivated lands (SANBI, 2009)
- Registered groundwater use was obtained from the WARMS database 2013
- High Yielding Aquifers as discussed in previous section

The resulting map of the aforementioned covers is shown in Figure 43. The mining activities are not explicitly shown due to the fact that if they utilise groundwater it should be included in the registered use as obtained from the WARMS database.

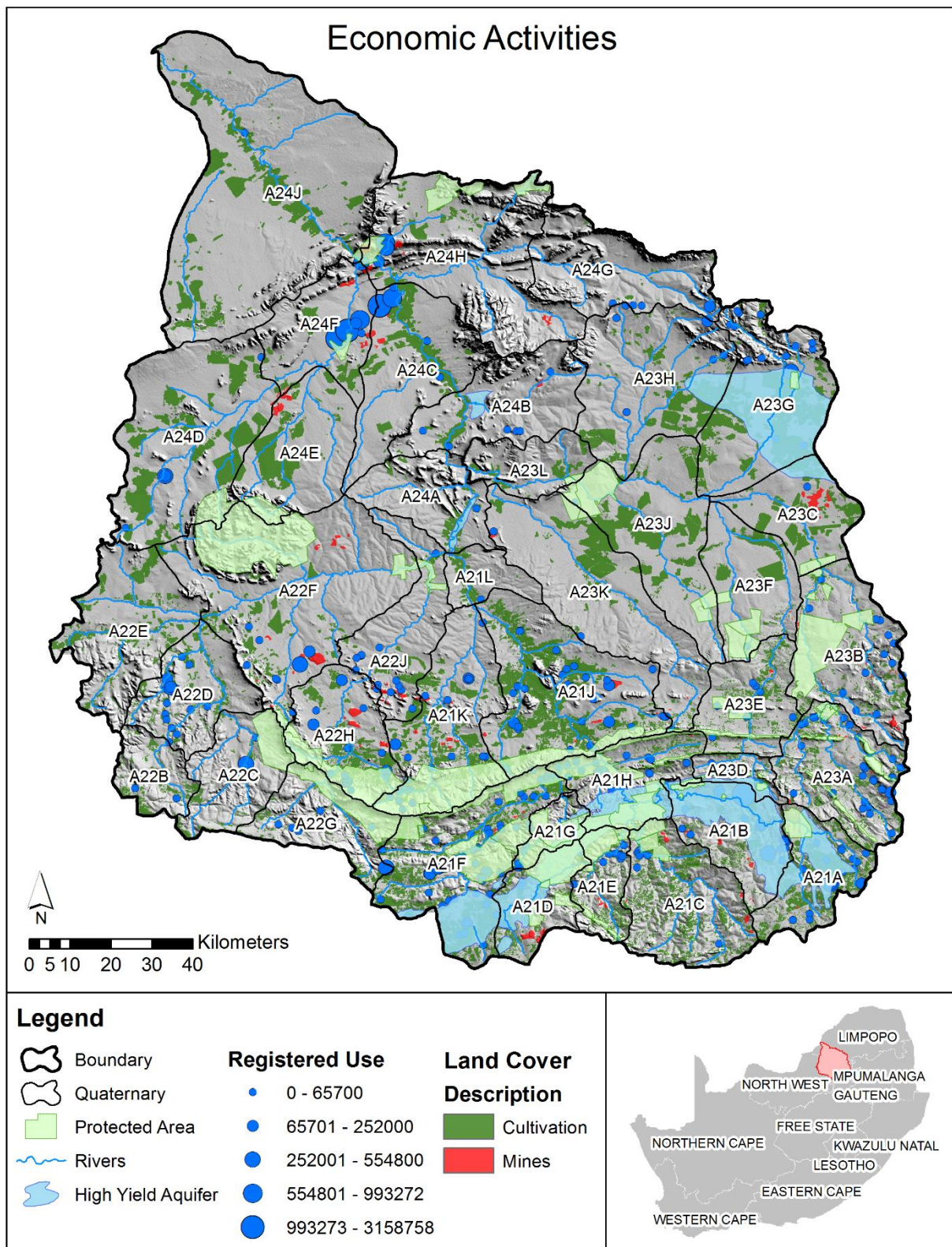


Figure 43 – Activities that contribute to the economy

The rating guideline applied to each RU for evaluating the activities that contribute to the economy is presented in Table 21 and the spatial distribution of the final ratings is presented in Appendix C.

Table 21 - Contribution to economy rating guideline

Rating	Guideline
0.0	RUs which do not directly support any activities which contribute to the economy
0.5	RUs which support activities which provide a moderate contribution to the economy
1.0	RUs which support activities which contribute significantly to the economy

7.4 Threat Posed to Users

The sections that follow discuss the sub-criteria linked to the threat posed to users and the rating guideline that applies to each of the sub-criteria.

7.4.1 Aquifers which are highly stressed

The current stress index of each RU as calculated during the Reserve determination process was used to generate a stress index map as shown in Figure 44.

The rating guideline applied to each RU for evaluating the relative aquifer stress is presented in Table 22 and the spatial distribution of the final ratings is presented in Appendix C. The ranges for the SI was taken from the 2007 GRDM manual (Parsons & Wentzel, 2007).

Table 22 - Relative aquifer stress rating guideline

Rating	Guideline
0.0	RUs with a low stress index (< 20%)
0.5	RUs with a moderate stress index (20 - 65%)
1.0	RUs with a high stress index (> 65%)

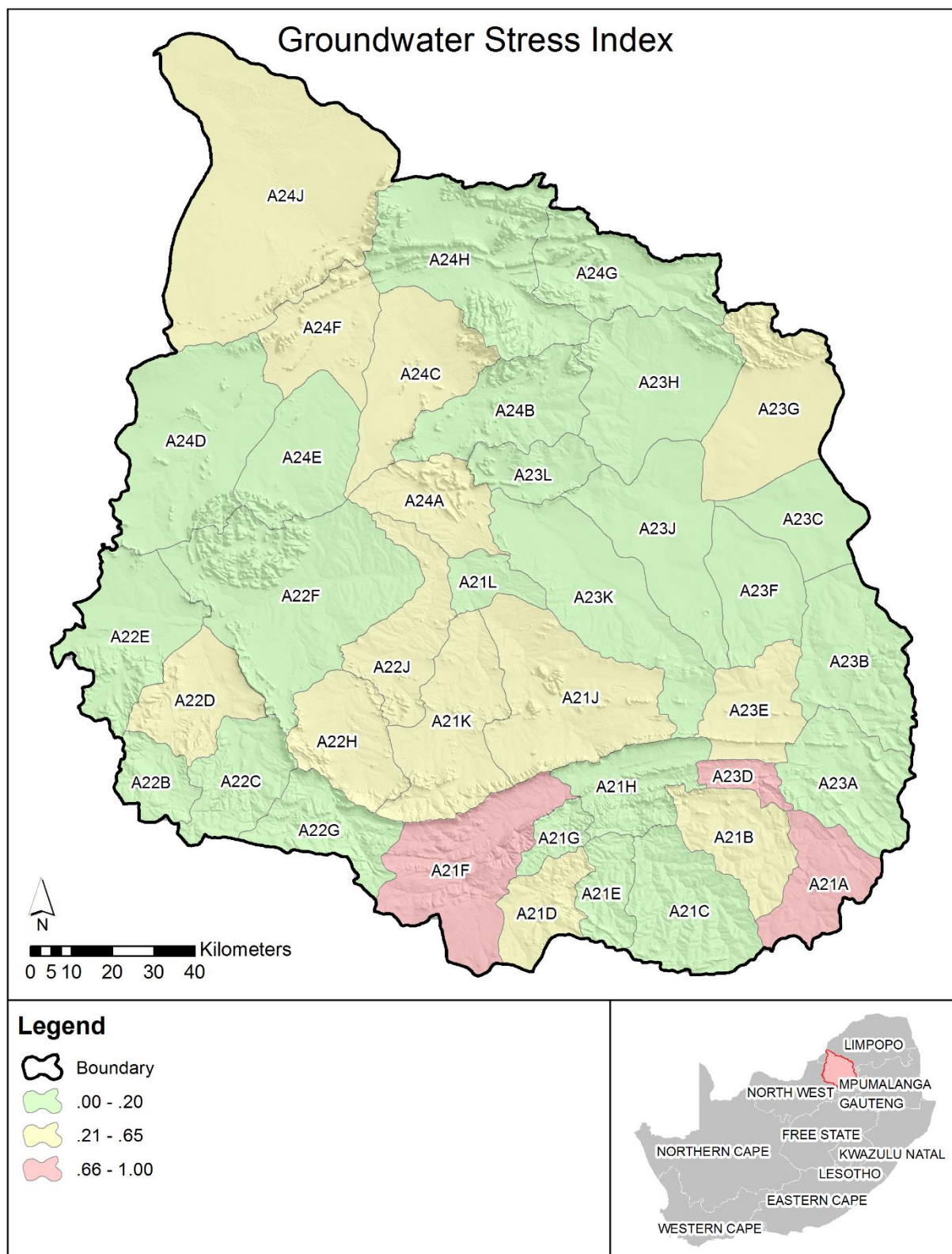


Figure 44 - Stress index map of the study area

7.4.2 Water quality currently threatened

There is not enough historic data available with good distribution across the study area to allow for the generation of a detailed groundwater quality map. The datasets used to visually show the current water quality across the area are:

- The TDS map to give indication of the regional groundwater salinity levels (Vegter, 1995)
- Current and Abandoned Mines

Background groundwater quality is inherently related to the host geology and can be spatially highly variable depending on the geological and physical setting. Although mining operations can be indicative of potential groundwater quality issues, the evaluation of this sub-criterion relies heavily on the public participation process. The resultant map produced is shown in Figure 42, the same map used to determine water of a high quality. During the evaluation the existence of mines are also required to be taken into account.

Typical water quality problems not depicted in the available data set will likely be raised during the public participation process.

The rating guideline applied to each RU for evaluating water qualities that are currently threatened is shown in Table 23 and the spatial distribution of the final ratings is presented in Appendix C.

Table 23 - Water quality that is threatened rating guideline

Rating	Guideline
0.0	RUs where potential threat to water quality is low
0.5	RUs where potential threat to water quality is moderate
1.0	RUs where potential threat to water quality is high

7.4.3 Vulnerable aquifers

Aquifer vulnerability is addressed through the DRASTIC map. The map comprises of the parameters shown in Table 24 as applied to the whole of South Africa. The DRASTIC index has a maximum index of 200 which represents the highest aquifer vulnerability with respect to pollution.

Table 24 - DRASTIC Parameters

Parameter	Input dataset
(D) Depth to water Table	126 263 groundwater levels from the NGA (for 4 280 of these, the mean groundwater level was calculated from time-series data) were interpolated to a groundwater level grid.
(R) Recharge	Recharge calculated as part of GRAII project.
(A) Aquifer material	1:1 million geology from CGS
(S) Soils	WR90 soils data set
(T) Topography and slope	DWAF 20m DTM resampled to 1X1km
(I) Impact of the vadose zone	1:1 million geology from CGS
(C) Hydraulic conductivity	1:1 million geology from CGS

For the purpose of the prioritisation tool, the following classes of DRASTIC index were adopted based on the index range for the study area as presented in Table 25.

Table 25 - Aquifer vulnerability classification

Vulnerability	Index Range
High	121 - 160
Medium	81 - 120
Low	55 - 80

The resultant map generated based on the aforementioned vulnerability ranges is shown in Figure 45. The rating guideline applied to each RU for evaluating aquifer vulnerabilities are shown in Table 26 and spatial distribution of the final ratings is presented in presented in Appendix C.

Table 26 - Aquifer vulnerability rating guideline

Rating	Guideline
0.0	RUs that are least vulnerable to pollution (55 – 80)
0.5	RUs that are moderately vulnerable to pollution (81 – 120)
1.0	RUs that are highly vulnerable to pollution (121 – 160)

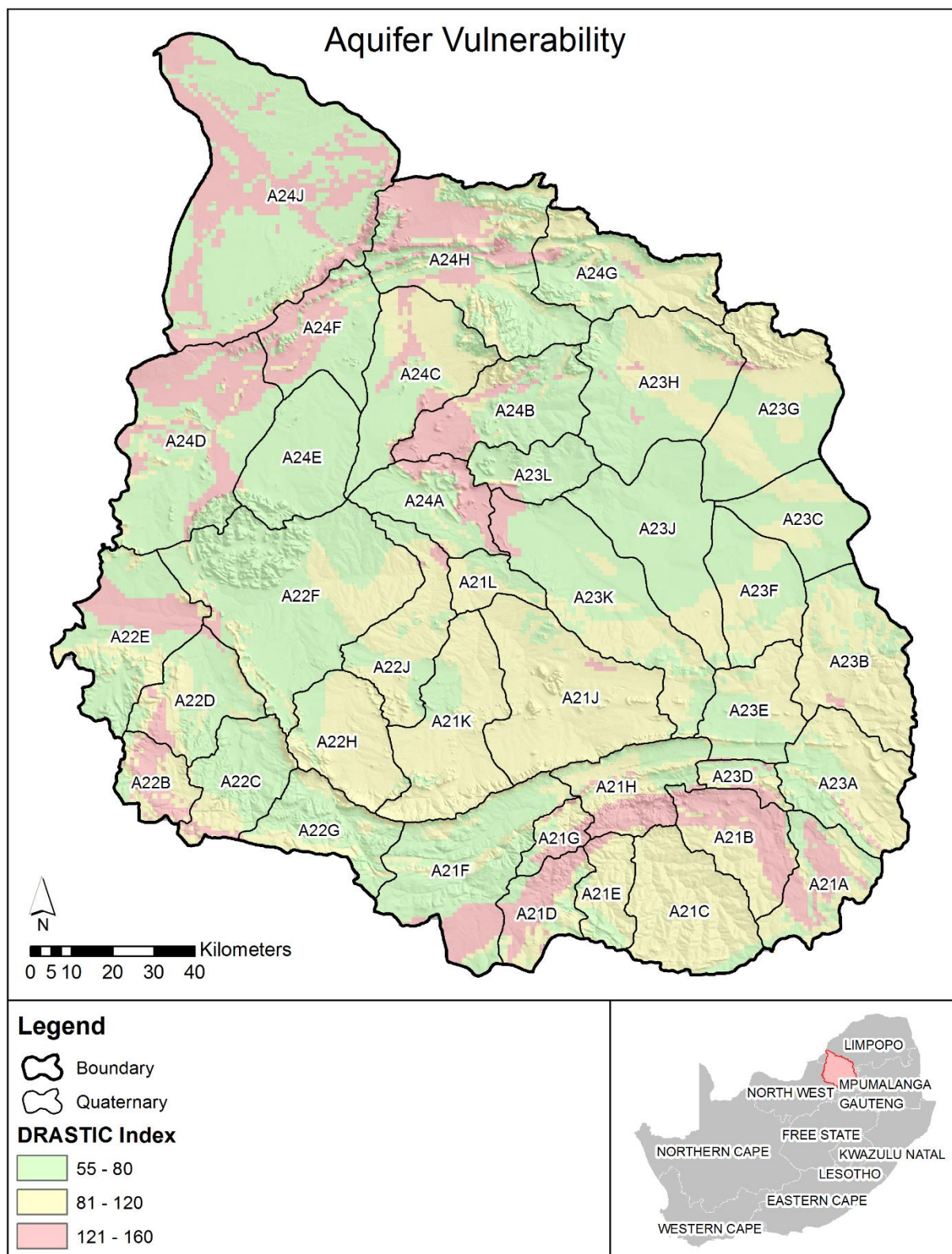


Figure 45 - DRASTIC aquifer vulnerability rating

7.5 Ecological Importance

The sections that follow discuss the sub-criteria linked to the ecological importance and the rating guideline that applies to each of the sub-criteria.

7.5.1 Groundwater importance to wetlands

The wetland cover generated for the study area was used and only wetlands associated with possible groundwater dependence were considered. The spatial distribution of the groundwater wetlands is shown in Figure 46.

Evaluation of the wetlands posed difficult due to the large number and the uncertainty with regard to groundwater, therefore the wetland densities per RU was used in the evaluation. The rating guideline applied to each RU for evaluating groundwater importance to wetlands is shown in Table 27 and the spatial distribution of the final rating is presented in Appendix C.

Table 27 - Groundwater importance to wetlands rating guideline

Rating	Guideline
0.0	RUs which contain wetlands with low groundwater importance
0.5	RUs which contain wetlands with moderate groundwater importance
1.0	RUs which contain wetlands with high groundwater importance

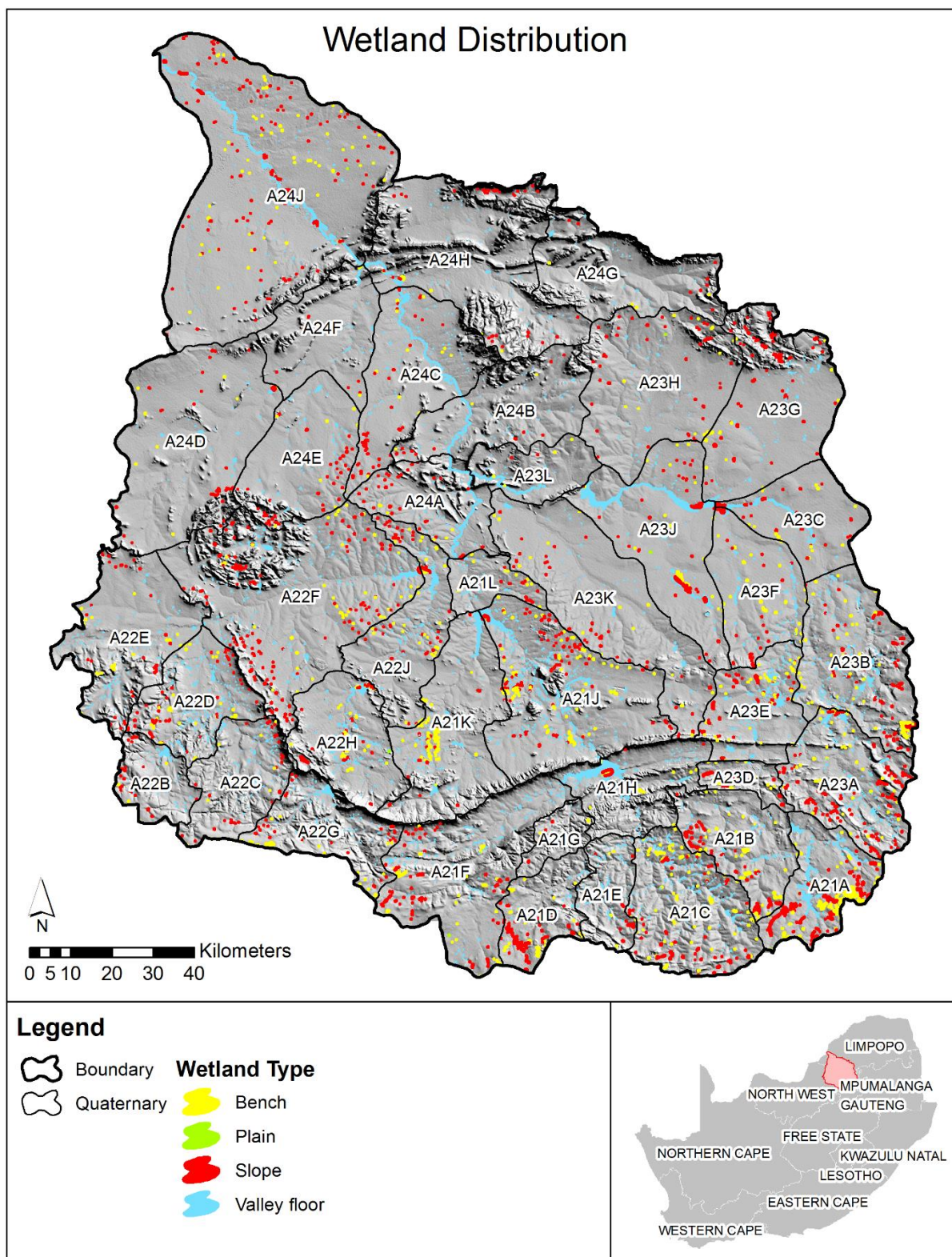
7.5.2 Surface-groundwater water interaction

Surface-groundwater interaction is an on-going field of research and this component is very expensive to measure. This has resulted in models being used to predict the groundwater contribution to baseflow. For the purpose of the prioritisation tool the estimated groundwater contribution to baseflow as calculated during the Reserve determination was expressed as a percentage of the MAR and the resultant map is shown in Figure 47.

The rating guideline applied to each RU for evaluating the surface-groundwater interaction is shown in Table 28 and the spatial distribution of the final ratings is presented in Appendix C.

Table 28 - Surface-groundwater interaction rating guideline

Rating	Guideline
0.0	RUs which contain low GW-SW interaction (< 10%)
0.5	RUs which contain moderate GW-SW interaction (10 - 20%)
1.0	RUs which contain significant GW-SW interaction (> 20%)



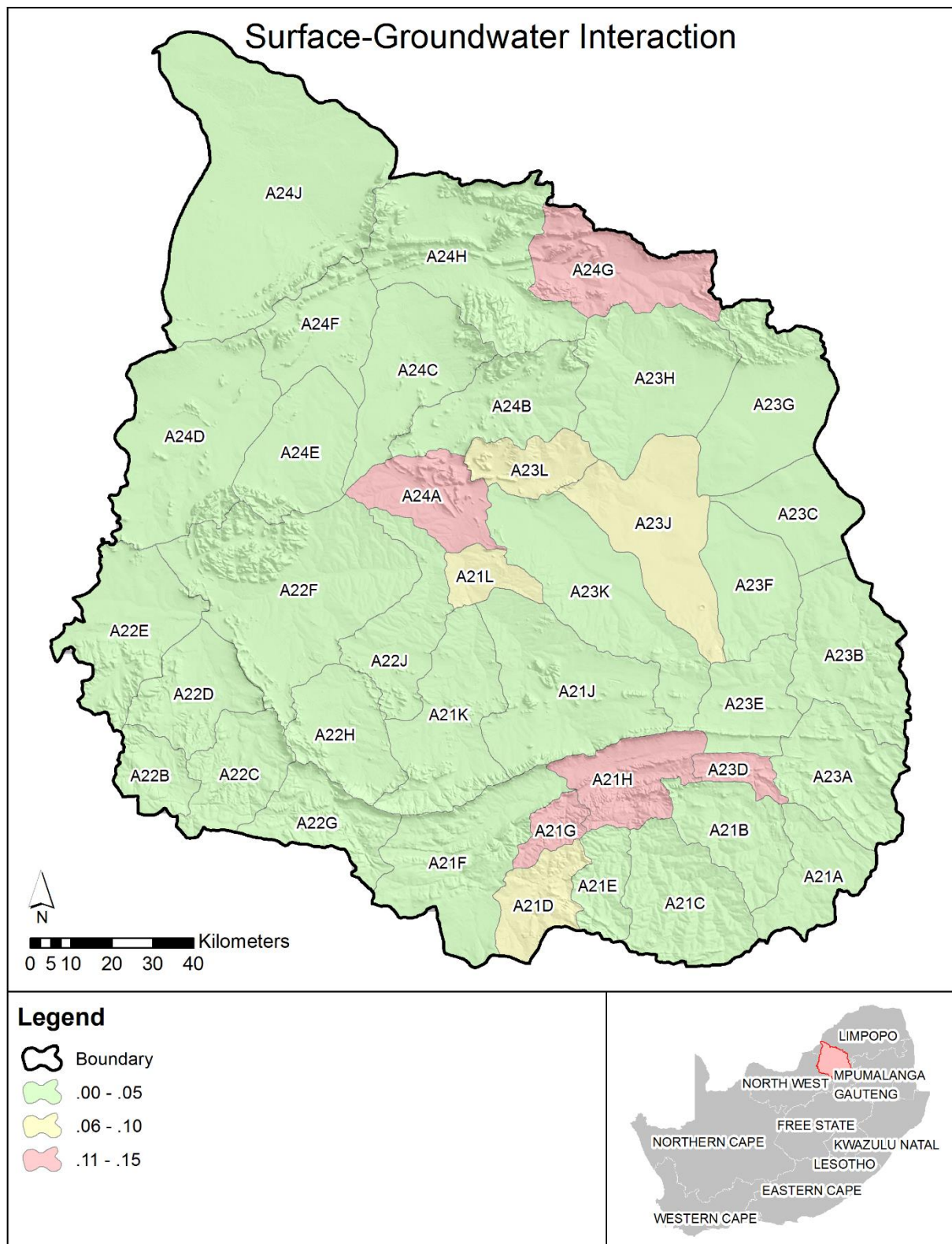


Figure 47 - Groundwater contribution to baseflow expressed as MAR percentage

7.6 Groundwater Profile (Delineation)

The groundwater profile based on the delineation approach discussed in Chapter 5 is included as the final criteria for prioritisation of RUs. The delineation map is shown in Figure 39 and the rating

criteria applied is presented in Table 29 and the spatial distribution of the final ratings is available in Appendix C.

Table 29 – Groundwater profile rating

Rating	Guideline
0.0	RUs with shallow, good quality water
0.5	RUs with moderate water levels and quality
1.0	RUs with deep water levels and poor quality

7.7 Public Participation

Since physical public participation did not take place as part of this research project, all ratings contributing to the prioritisation is solely based on the available data presented in this study. One of the important findings from public participation is that, in general, the participants have intimate knowledge of the area in question, which highlights the importance of this step in the process.

The prioritisation tool presented here and which accompanies this document in Excel format was designed to be used in the public participation process and that the priority rating and associated maps can be updated on the spot to ensure all participants agree with the final outcome.

Instructions on how to use the tool is presented in Appendix D.

7.8 Final Prioritisation

The final RU prioritisation based on the data presented is shown in Figure 48. The main purpose is to use the prioritisation and set RQOs for the highest rated RUs, since it is a vast area and would require a lot of resources to set RQOs for each RU. It is important to note that the RU prioritisation will not necessarily coincide with IUAs or prioritised surface water RUs as the focus is only on groundwater.

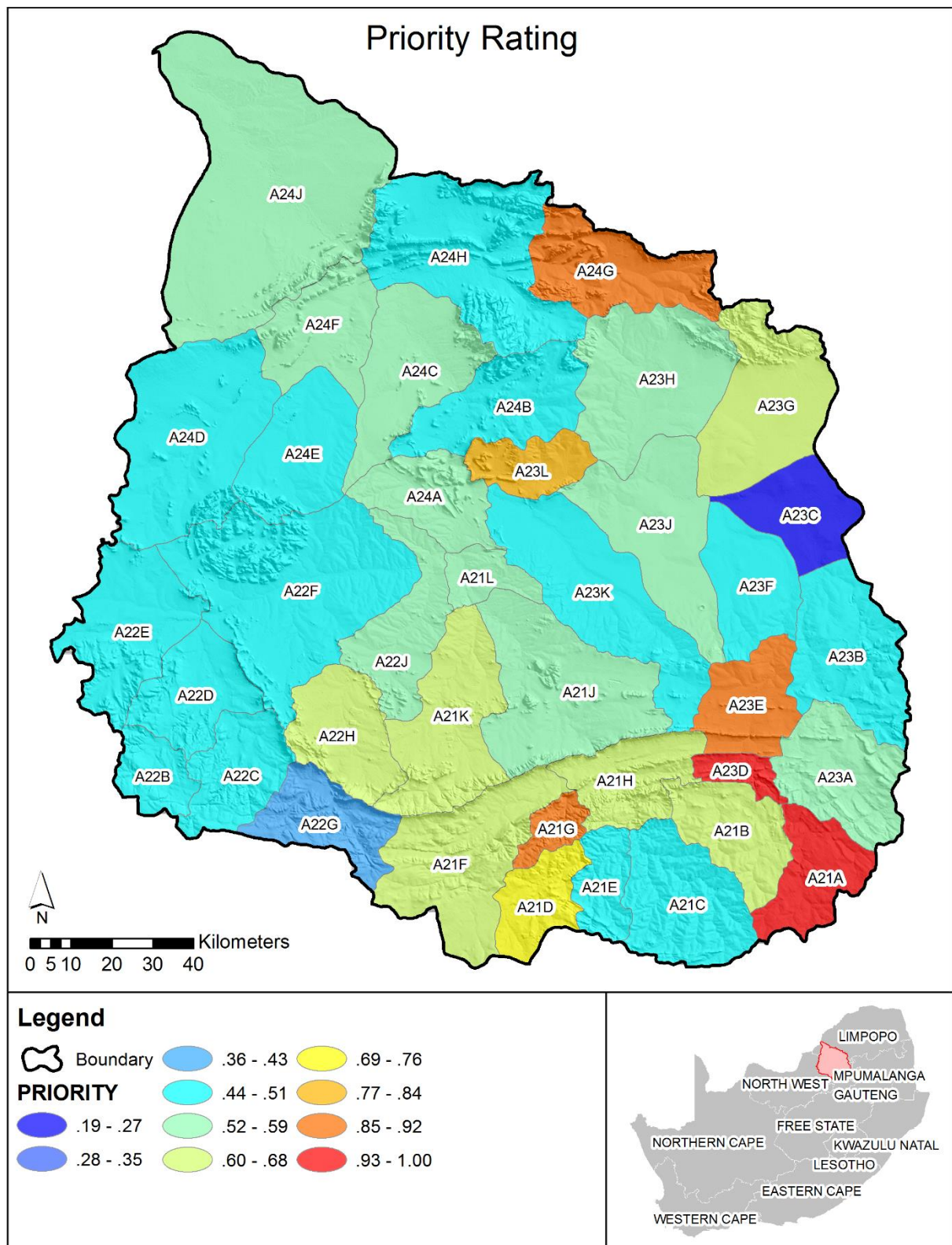


Figure 48 - Final prioritisation of RUs

8 DEVELOPMENT OF RESOURCE QUALITY OBJECTIVES

8.1 Preamble

For development of groundwater RQOs the same approach was followed as with the Upper Vaal report (DWAF 2014c). Because groundwater flows are prone to vary significantly over an area it is impossible to choose a single representative point of groundwater conditions over a RU. This is unlike surface water which can be represented by a single upstream point as indicated in Figure 49.

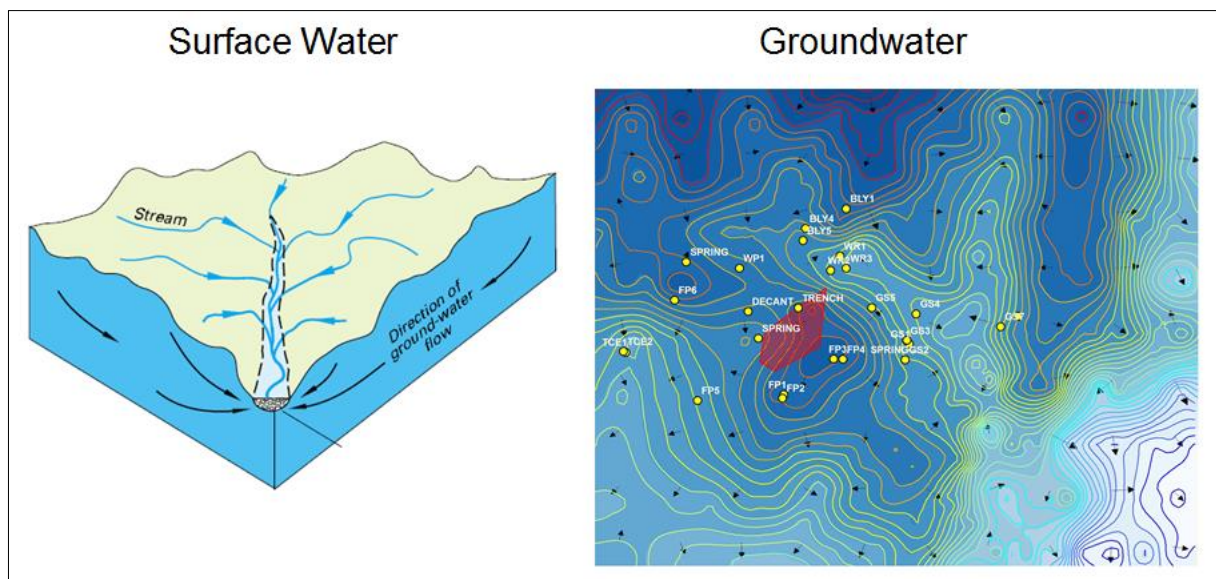


Figure 49 - Surface water catchment vs groundwater

Unfortunately, when setting groundwater RQOs a few individual sites will have to be considered as a single site which will not be sufficient to represent a prioritised RU. Considering the complexity of groundwater systems, certain sub-components and indicators had to be chosen for the prioritisation process in setting groundwater RQOs (step 4, Figure 2). Sub-components include anything that may impact or be impacted by groundwater change in either quality or quantity.

8.2 Approach

Only water level, water quality, and abstraction could be used in the formulation as indicators for RQO development, the reason being that groundwater is a very isolated resource. It can only be accessed if a borehole has been drilled. Biota was disregarded as an indicator, simply because groundwater biota has not been studied extensively enough and not much records for groundwater biota exist.

A list of potential measurable sub-components and indicators for groundwater (Table 30) that might be present now or in the future within the study area was drafted. The potential measurables were classified into a site type which relate to the sub-components used in RQOs.

Table 30 - Potential groundwater sites in the study area

Site Type	Example
Quantity	Production Borehole (Irrigation/ domestic)
	Well Fields
	Mines (Dewatering)
	Afforestation
Ecological	Springs
	Wetlands
	Baseflow (Groundwater)
Aquifer	Aquifer
	Dolomites
	Trans-boundary Aquifer
Quality	Mines (Decant)
	Irrigation Water
	Waste Sites / Landfill
	Burial Sites / Cemeteries
	Feedlots / Animal Dip
	Petrol Stations
	Pit Latrines

The examples listed in the above table are mostly scale dependant. For the purpose of this study definitions were adopted to distinguish between a regional and a local scale:

- Local Scale – defines a site or point source e.g. a borehole or TSF
- Regional Scale – can be defined as the aquifer extent or that of the RU

As a next step Table 30 was extended into Table 31 to include parameters that can be measured for each of the site types and the scale at which they are to be measured.

Table 31 - Site type with measurable parameters

Site Type (Components)	Example	Scale	Abstraction	Water Quality	Water Level
Quantity	Production Borehole	Local	✓	✓	✓
	Well Fields	Local	X	X	X
	Mines (Dewatering)	Local	X	X	X
	Afforestation	Local	X	X	X
Ecological	Springs	Local		✓	
	Wetlands	Local		✓	
	Baseflow (Groundwater)	Local		X	X
Aquifer	Aquifer	Regional	X	X	X
	Dolomites	Regional	X	X	X
	Trans-boundary Aquifer	Regional	X	X	X
Quality	Mines (Decant, Fracking)	Local		✓	
	Irrigation Water, WWTW	Local		✓	
	Waste Sites / Landfill	Local		✓	
	Burial Sites / Cemeteries	Local		✓	
	Feedlots / Animal Dip	Local		✓	
	Agricultural Areas (Pesticides / Fertilizer)	Local		✓	
	Petrol Stations	Local		✓	
	Sanitation Systems / Pit Latrines	Local		✓	

All parameters marked with “✓” are considered as measurable and those where “X” is marked in red are considered impractical to measure. There are various reasons for this and they will be explained in the following section.

8.3 Complexities in Site Types

Having considered the measurable parameters for each example listed in Table 31, impracticalities were identified and are summarised in the following table (Table 32):

Table 32 - Impracticalities with the measurable parameters

Site Type	Description
Well Fields	Well fields, a collection of boreholes, could be distributed widely over an area and may lead to boreholes intersecting different geologies, this in turn could lead to a difference in groundwater chemistry. Thus, it might be difficult to choose representative water quality and quantity BHs in a well field. Another complication is that abstraction rates for well fields aren't readily available because WARMS data only reflect registered use, which isn't the case in well fields.
Dewatering of mines	It will be difficult to associate a single water level with mines as mines are continuously developing. Pumping rates may change to keep working areas dry. Another complication is that groundwater ingress through the different geological features may yield a significant change in groundwater chemistry.
Afforestation	In general abstractions within plantations are estimated through the use of a model which is dependent on the age of the plantation. Water quality and groundwater level can be measured if boreholes are present.
Groundwater contribution to baseflow	As a result of streambed, topographical and geological differences over a water course in a selected area the groundwater contribution to baseflow could vary drastically. Thus it wouldn't be practical to use a single point of reference to characterise the groundwater contribution to baseflow.
Water Aquifer Types	Aquifers cannot be subjected to a single water level or quality. This is because aquifers are very distributed with regards to their geological nature. Modelling the system will be the best estimation of an aquifers characteristics by use of available registered abstraction data.

It should be practical and easy to implement the methodologies for creation of groundwater RQOs therefor detailed modelling of complex systems isn't an option. Cost implications should also be assessed as the development of boreholes and contracting of specialists for these types of studies would be expensive.

Measurable parameters to be used as sub-components include:

- *Quantity (Abstraction)* – this consists of metering of boreholes. The WARMS database isn't updated on a regular basis and only represents registered use. There are not any actual groundwater use Figures available.
- *Aquifer (Water Level)* – groundwater water levels can be easily measured when access is available to a borehole
- *Quality (Water Quality)* – it is easy to estimate pH and EC of groundwater in the field, but lab analysis of chemical constituents could be costly. No chemical constituent can be representative of the groundwater chemical character within a RU as the groundwater character will change in association with the different geological features through which it flows.

8.4 Protection Zones

According to The National Water Act (NWA) (Act No. 36 of 1998) we need to protect basic human need and the ecological reserve; therefore, we need to introduce further measures in the RQOs to meet the aforementioned objective. Due to a lack of sub-components in the groundwater system, protection zones are introduced as a means of protecting the basic human need and the ecological reserve. The four protection zones suggested with the concept of infringements are detailed in the following sections.

8.4.1 Radius of Influence

The protection zone around a borehole (radius of influence) is calculated as follows (Parsons and Wentzel, 2005):

$$r = 1.5 \sqrt{\frac{Tt}{S}} \quad (4)$$

where,

- r = Radius of influence (m)
- t = Time of pumping (days)
- T = Transmissivity (m^2/d)
- S = Storativity

Note: for wellfields a wellfield model is required to verify if a protection zone is violated due to the cumulative effect of multiple boreholes.

8.4.2 Microbial Protection Zone

Groundwater quality must be viable for domestic use and boreholes must be protected from microbial pollution. The protection zone around a borehole to avoid microbial pollution is calculated as follows (Parsons and Wentzel, 2005):

$$r = 2(0.28T) + 53 \quad (5)$$

where,

r = Protection radius (m)

T = Transmissivity (m^2/d)

8.4.3 Wetland Protection Zone

To protect ecological systems that are groundwater fed, it is important to maintain the groundwater gradient to these features. The groundwater gradient can be protected by specifying appropriate protection zones around wetlands (Parsons and Wentzel, 2005).

$$d = \sqrt{\frac{TiL\pi}{R/1000}} \quad (6)$$

where,

d = Distance from wetland (m)

i = Groundwater gradient towards wetland

T = Transmissivity (m^2/d)

L = Wetland perimeter (m)

R = Groundwater recharge (mm/d)

8.4.4 River Protection Zone

To protect ecological systems that are groundwater fed, it is important to maintain the groundwater gradient to these features. The groundwater gradient can be protected by specifying appropriate protection zones around rivers (Parsons and Wentzel, 2005).

$$d = \frac{Ti}{R/1000} \quad (7)$$

where,

d = Distance from river (m)

- i = Groundwater gradient towards river
 T = Transmissivity (m^2/d)
 R = Groundwater recharge (mm/d)

8.4.5 Zone Infringements

The concept of protection zone infringements is proposed for existing infrastructure that will not comply due to their physical position. The RQOs will be implemented with the protection zones, but will allow infringements. Monitoring of the protection zone will be done to ensure no further infringements are incurred with the introduction of new infrastructure.

The advantage of implementing protection zones as RQOs, is that evaluation of RQOs can be done over wide areas through the use of GIS. The protection zone calculations are dependent on certain aquifer parameters and these parameters would need to be determined for each site within a RU where RQOs must be set.

Figure 50 shows an example of a zone infringement between a pumping borehole and river.

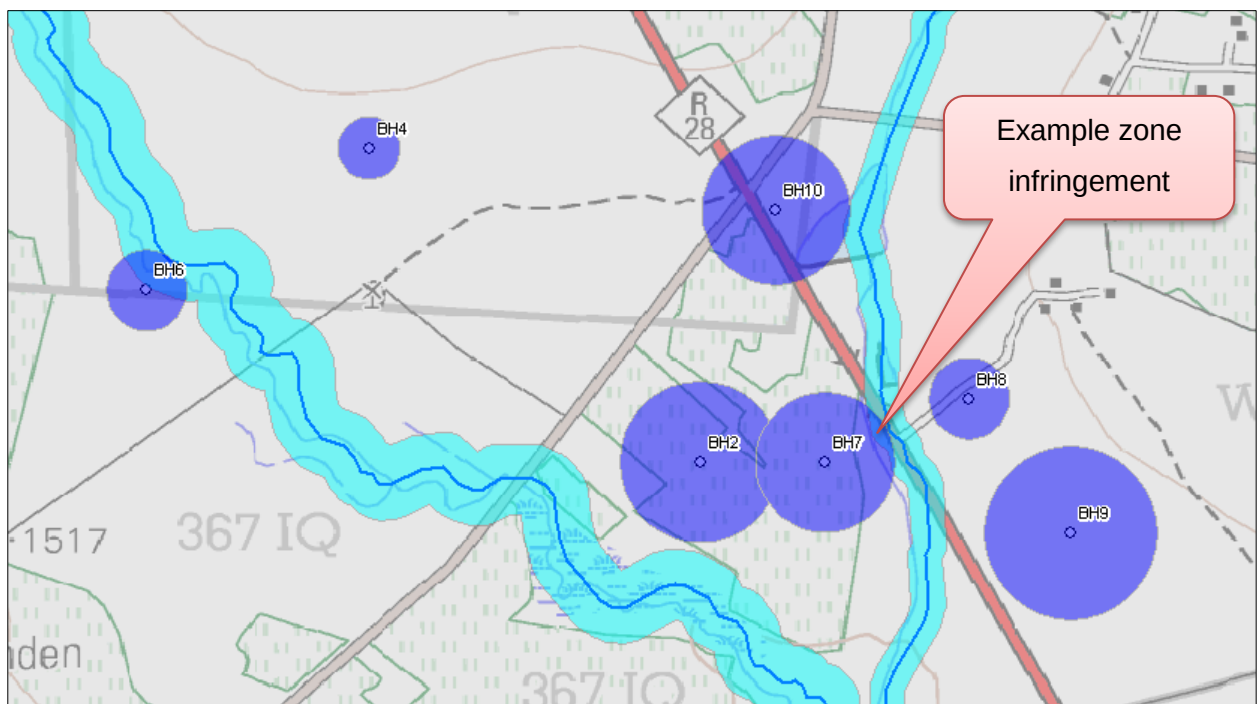


Figure 50 - Example of protection zone infringement

8.5 Generic RQOs

Due to the nature of groundwater and the limited sub-component indicators a generic set of RQOs was formulated (DWA, 2014c). This chapter coincides with step 5, Figure 2. A summary of the sub-components and indicators are given in Table 33.

Table 33: Summary of generic sub-components and indicators

Component	Sub-Components	RQO	Indicator / Measure
Quantity	Radius of Influence	The radius of influence should not intersect any other protection zone. In cases where infringements already exist, the infringements will be used as baseline measurement.	Radius of influence (r) ³ . $r = 1.5 \sqrt{(T \cdot t / S)}$, T=Transmissivity(m ² /d), t=Time(days), S=Storativity. Annual sampling via GIS algorithm or on introduction of new borehole
	Abstraction	Where water use is higher than requirements for Reserve, Schedule 1 and General Authorizations, abstraction rates should not exceed the average recharge values of the aquifer based on the licensed area.	Abstraction Rate (Q) per hectare > Reserve, Schedule 1 and General Authorizations
Quality	Microbial Protection Zone	Boreholes require a protection zone from microbial pollution (pit latrines).	Microbial radius (r) ⁴ . $r = 2(0.28 \cdot T) + 53$, T=Transmissivity(m ² /d). Annual sampling via GIS algorithm or on introduction of new borehole
	Groundwater Quality	Groundwater quality should be based on the water use requirement (fit for use ⁵). Sites that exceed the water use requirement should not be allowed to deteriorate in water quality.	Background water quality per borehole using Groundwater Monitoring Guidelines ²
Aquifer	Water Levels	Medium to long-term water trends should show recovery. Dolomitic aquifers must adhere to the Dolomitic Guidelines DWAF (2006)	Depth to Groundwater Level using Groundwater Monitoring Guidelines ² .
Ecological	River Protection Zone	A protection zone along a river/stream is required to protect the ecological reserve. In cases where infringements already exist, the infringements will be used as baseline measurement.	Distance from river (L) ⁴ . $L = (T \cdot i) / R$, T=Transmissivity(m ² /d), i=Groundwater Gradient, R=Recharge(m/d). Annual sampling via GIS algorithm or on introduction of new borehole
	Wetland Protection Zone	A protection zone around a wetland is required to protect the ecological system. In cases where infringements already exist, the infringements will be used as baseline measurement.	Distance from wetland (L) ⁴ . $L = \sqrt{(T \cdot i \cdot W \cdot \pi / R)}$, T=Transmissivity(m ² /d), i=Groundwater Gradient, R=Recharge(m/d), W=Wetland Perimeter (perimeter is based on the Wetland Delineation Guidelines).

General Authorization for the taking and storage of water, DWA (2012b)

A Guideline for the Assessment, Planning and Management of Groundwater Resources in South Africa, DWAF (2008)

The radius of influence is time dependent and the RU statistics is based on borehole pumping of 8 hours/day

A protection zone is defined as a zone where the groundwater gradient is maintained

South African Water Quality Guidelines, DWAF (1996)

Groundwater Resource Directed Measures, Parsons and Wentzel (2005)

All RUs within the Crocodile-West catchment are subject to these generic RQOs.

8.6 Challenges

Numerical limits for RQOs is required before Gazetting can take place and by law a formula e.g. a protection zone calculation cannot be gazetted as a numerical limit. The fact that groundwater is a highly distributed resource that can change chemical character and hydraulic response within a couple of meters complicates the effective assignment of RQOs on a regional scale as this would be required per site.

General practice is still to choose a “representative” groundwater site within a RU and set RQOs based on that particular site, but this is not an effective way to manage and monitor the groundwater resource.

9 CASE STUDY

The aim of the case study is to illustrate the application of the generic RQOs on a local scale problem.

9.1 Background

The case study was conducted on a 220km² area that stretches over quaternary catchments A24D, A24E and A24F as shown in Figure 51. The study area is located near Swartklip and the Sefikile rural area about 15 km west of Northam and 80 km north of Rustenburg.

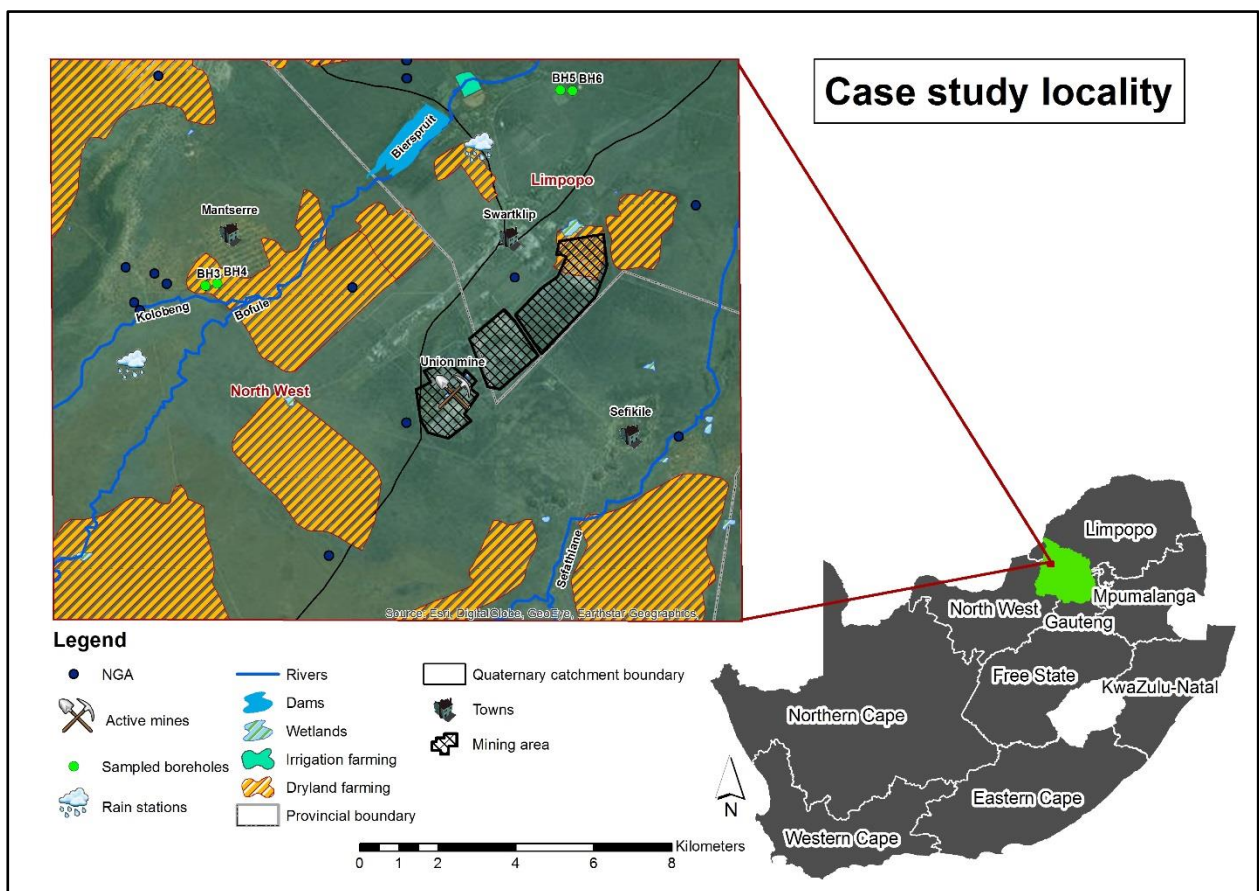


Figure 51 - Locality map of the case study area

Note that the selected case study area represents an intermediate prioritised area based on the priority analysis conducted. The fact that the regional prioritisation for this area doesn't rate high in comparison to the others, does not suggest that there aren't any hotspot areas within that particular RU. This area was also chosen because of availability of up-to-date data.

9.1.1 Climate

Rainfall in the study area averages at about 552 mm/a, most precipitation takes place in the rainfall season during the middle of summer (CRU, 2017). Evaporation rates averages at 2356mm/annum (Golder Associates, 2013). The temperature fluctuates from hot summers of about 21 – 30 degrees Celsius during January and cold frost-free winters at about 2.9 degrees Celsius during nights in July (Golder Associates, 2013). Monthly average MAP and temperatures can be seen in Figure 52 for the period from 1901 to 2015 (CRU, 2017).

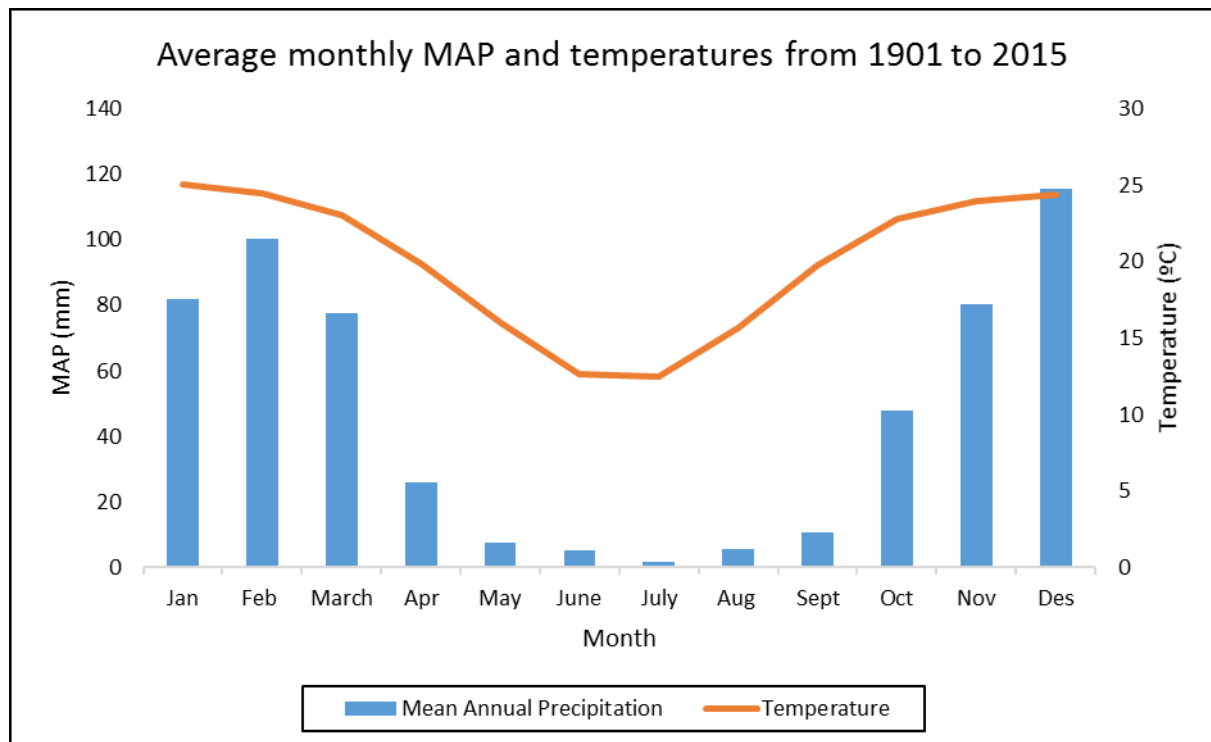


Figure 52 – Average MAP and temperatures from 1901 to 2015

9.1.2 Topography and Drainage

The study area has a fairly flat landscape, between 1000 mamsl and 1200 mamsl, with the exception of some artificial landforms such as tailings dams at the Union mine. A slight slope to the north of the study area promotes drainage through the Kolobeng and Bofule streams- non-perennial tributaries to the Bierspruit dam. From here the Bofule River flows toward the Crocodile River somewhat 35 km to the north of the study area. These small watercourses are mainly visible due to the dense growth of vegetation around them and not the visibility of the streams themselves (Golder Associates, 2013).

9.1.3 Land Cover and Land Use

The land cover in the study area consists largely of natural veld, which could potentially support grazing animals. Dryland farming covers a lot of the study area with the only irrigated land to the north of the study area. A low fauna and flora species diversity is present here thus meaning it has low conservational importance (Golder Associates, 2013).

The main soil types in the area are Arcadia, Bainsvlei and Mispah. Bainsvlei has a high agricultural potential in the area (Golder Associates, 2013).

Sefikile, Mantserre and the town of Swartklip, all present within the study area, show low levels of transformation and has a combined population of about 12094 according to Statistics South Africa (SSA, 2011) census data.

The underground Union mine, situated in the middle of the study area, covers a large area due to tailing dams. Mining is primarily for the platinum group metals (PMG) Platinum, Palladium, Rhodium and Gold. Mining operations covers a total of about 119Km² in the north-western parts of the Bushveld Igneous Complex (BIC) which is also the richest source of PMG. Mining activities for the Union mine are expected to extend through to 2028. There are three vertical shafts and three decline systems in the mine with the mining depth varying from 150m to about 1500m beneath the surface (Union mine, 2017).

9.1.4 Local Geology

The area locality is on the western side of the Bushveld Igneous Complex (BIC) known as the Bierkraal Magnetic Gabbro (BMG), part of the Rustenburg Layered Suite. The Rustenburg Layered Suite within the area boundaries consist mainly of gabbro, diorite, magnetite, arenite, norite and a magnetic layer. There are no major faults in the area although smaller faults and linear structures do occur throughout.

The mafic and ultra-mafic rocks of the Rustenburg Layered Suite can be divided from lower to upper zones, in ascending order, into Marginal, lower, critical, main and upper zones. According to Golder Associates, 2013 the critical zone hosts chromium and other PGM mineralisation in the BIC which is valuable for mining activities.

9.1.5 Geohydrology

Recharge to the groundwater regime is estimated at approximately 3% of the MAP. On a regional scale the geohydrological character is that of a shallow and weathered phreatic unconfined bedrock aquifer system which might be connected to alluvial aquifers and deeper fractured bedrock systems (Golder Associates, 2013). The area is dominated by low to moderate yielding

intergranulated and fractured aquifers of 0.1 – 2 l/s. Groundwater use is low as the communities receive their water mostly through pipelines.

The groundwater levels mostly follow the topography, averaging at 23 mbgl, except for areas of artificial interference. The groundwater level varies from 2.4 mbgl around the Union mine return dam to 7.5 mbgl near Bierspruit dam and 24.25 mbgl at the Mantserre rural area (Golder Associates, 2013).

9.1.6 Ground Water Quality

Piper and Voronoi diagrams were drawn to help evaluate the groundwater chemistry in the proposed study area. These diagrams can act as aids in the development of qualitative RQOs concerning the groundwater chemistry of the study area. To try and describe the quality of the Crocodile-West catchment as a whole will not be effective with use of Piper or Durov diagrams as it is simply too big of an area, thus it's only included within the case study. The data used for the delineation of the diagrams was taken out of (Golder Associates, 2013) and can be consulted in Table 34 together with the South African Water Quality Guidelines (DWAF, 1996).

Table 34: Borehole chemical constituents

Chemical constituent	BH3	BH4	BH5	BH6	SA Water quality guidelines- target water quality range (domestic use)
pH	7.99	8	8.07	7.86	≤6 and ≤9
Total cond (mS/m)	129	152	105	300	
TDS (mg/L)	888	860	692	1980	≤450
P Alk (mg/L CaCO ₃)	<0.6	<0.6	<0.6	<0.6	
M Alk. (mg/L CaCO ₃)	673	652	585	474	
Fe (mg/L)	<0.05	<0.05	<0.05	<0.05	≤0.1
Mg (mg/L)	135	157	158	320	≤30
Mn (mg/L)	<0.05	<0.05	<0.05	<0.05	≤0.05
Si (mg/L)	22.8	24.5	38.1	34.2	
F (mg/L)	0.658	0.643	<0.1	<0.1	≤1
Cl (mg/L)	68.8	116	34.1	636	≤100

Chemical constituent	BH3	BH4	BH5	BH6	SA Water quality guidelines- target water quality range (domestic use)
NO ₂ (mg/L)	<0.2	<0.2	<0.2	<0.2	
NO ₃ (mg/L)	12.2	87.5	38.3	2.74	
PO ₄ (mg/L)	<0.8	<0.8	<0.8	<0.8	
SO ₄ (mg/L)	54.6	63	17	347	≤200
Sum Cations(me/L)	15.5	18.9	14.7	35.8	
Sum Anions (me/L)	16.2	18.7	14.4	35.6	
Total Cr as Cr mg/L	<0.05	<0.05	<0.05	<0.05	
Cr ₆₊ (mg/L)	<0.05	<0.05	<0.05	<0.05	≤0.05

9.1.6.1 Piper diagram

Piper diagrams were created as such to plot the percentages of major cation and anions in two separate ternary diagrams. These points are further projected onto a diamond shape in the center of the diagram. This field provides valuable information on the possible water characteristics and water types of each sample in relation with other samples (Sajil Kumar, 2013).

The top end of the diamond shape indicates a permanent hardness of water with chemical characteristics of $\text{Ca}^{2+} + \text{Mg}^{2+}$ and also $\text{Cl}^- + \text{SO}_4^{2-}$. The right corner of the diamond is indicative of saline water with the constituents $\text{Na}^+ + \text{K}^+$ and also $\text{Cl}^- + \text{SO}_4^{2-}$. The bottom of the diamond is primarily composed of $\text{Na}^+ + \text{K}^+$ and also $\text{HCO}_3^- + \text{CO}_3^{2-}$ alkali carbonates. The left corner means that the water sample is rich in $\text{Ca}^{2+} + \text{Mg}^{2+}$ and also HCO_3^- , this corner is indicative of temporary hardness (Ghoraba & Khan, 2013).

The Piper diagram for the study area is presented in the following Figure (Figure 53).

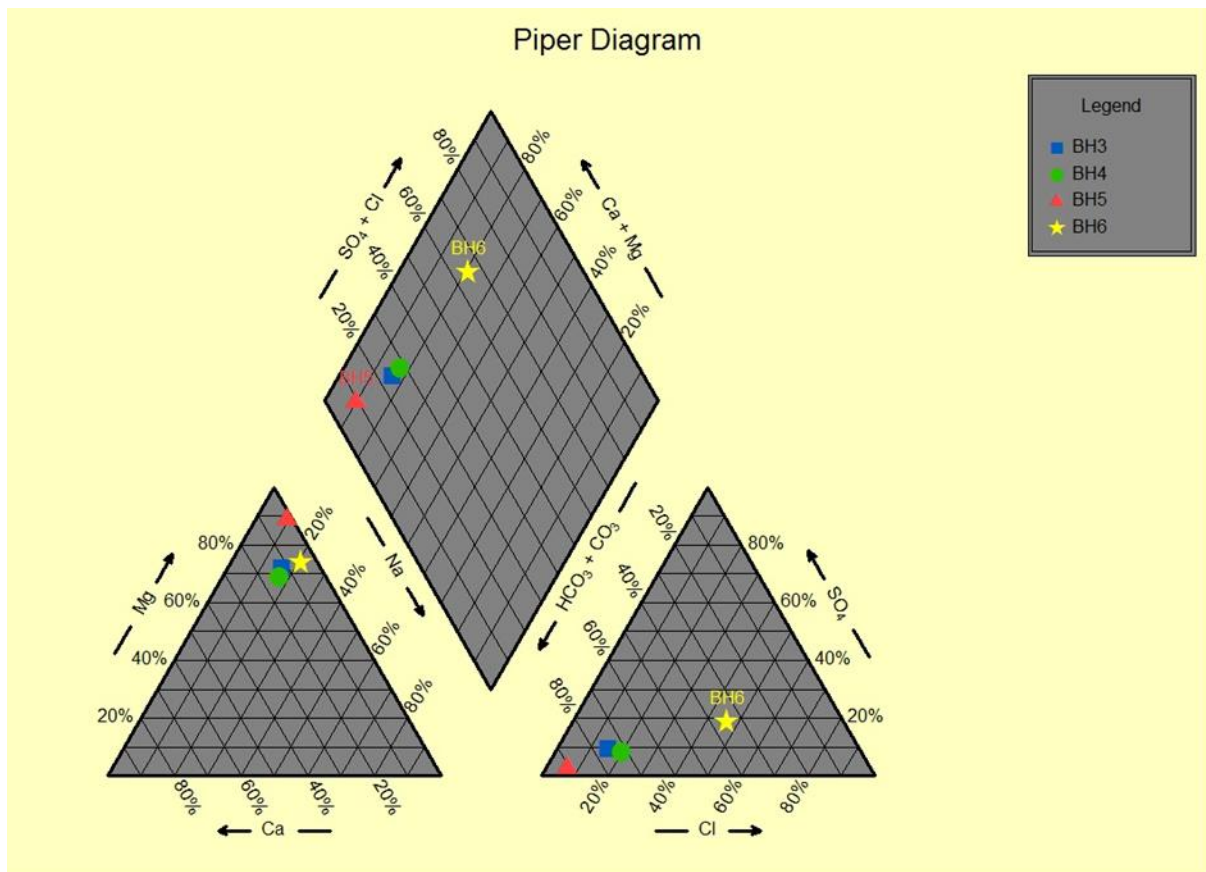


Figure 53: Study area groundwater chemistry- piper diagram

9.1.6.2 Durov diagram

Very much the same as with the Piper diagram the Durov diagram can be used to reveal hydrogeochemical characteristics of groundwater sources i.o.w. to detect the relation between different geochemical elements from various sources (Al-Bassam & Khalil, 2012). The Durov plot helps to identify water types as well as display possible geochemical processes for evaluation of the groundwater quality of a sample.

The Durov diagram consists of two triangular shapes which plot the major cations and anions against each other. Some software is able to create extended diagrams, as done with this case study, to include EC and pH data to the sides of the diagram for further evaluation of the samples (Ghoraba and Khan, 2013).

The Durov diagram for the case study area can be consulted in Figure 54.

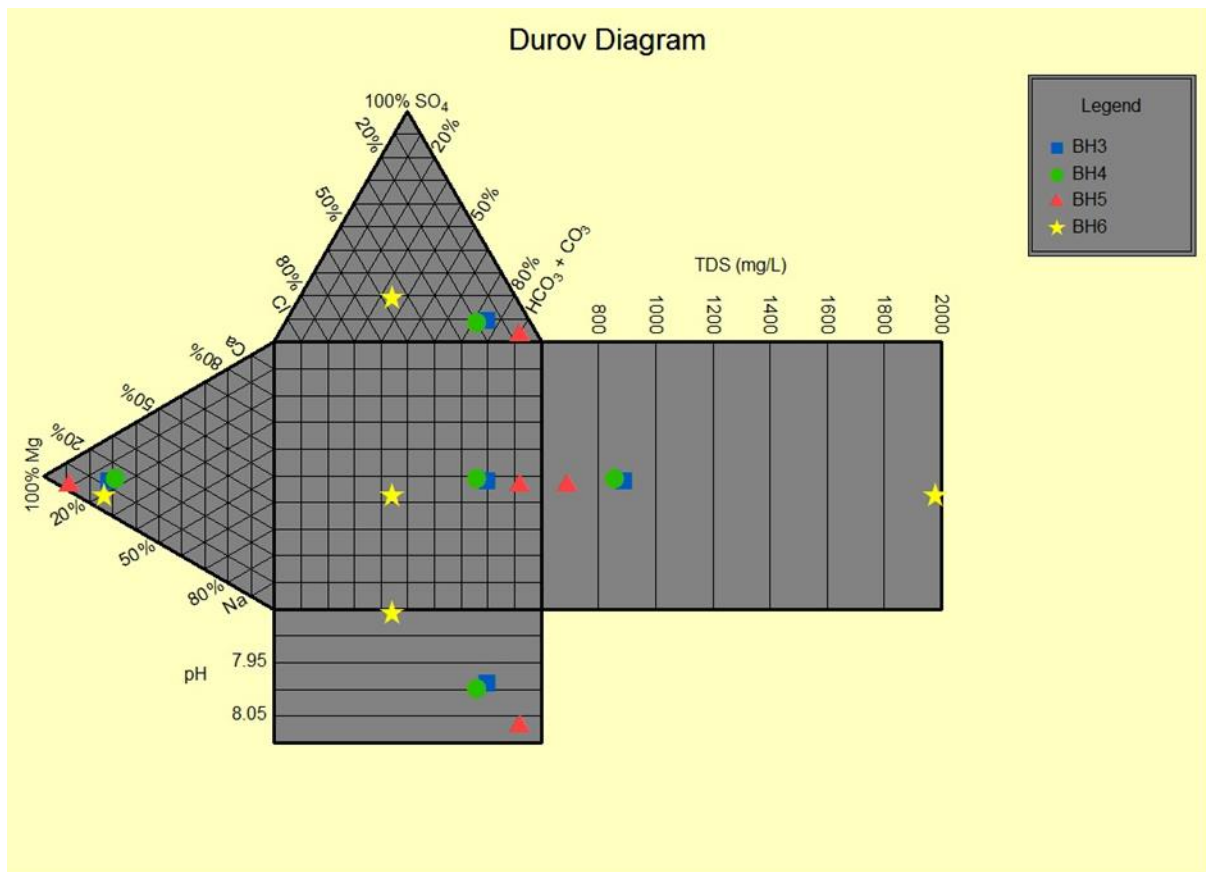


Figure 54: Study area groundwater chemistry- Durov diagram

Together the Piper and Durov diagrams can be used to make an informed conclusion of the groundwater quality and origin thereof in the sampled areas and will be consulted in the process of defining localised RQOs.

All the samples, except for BH6 show similarities in water type and quality. The samples are rich in Ca²⁺ and Mg²⁺ cations and HCO₃, this is indicative of temporary hardness and according to Golder Associates, 2013 relatively recently recharged groundwater. The exception is BH6 which shows more permanent hardness with less HCO₃ and more Cl⁻ anions than the other water samples, this could be indicative of non- natural chloride enrichment either through mine drainage or domestic waste.

The pH values range from 8 to about 8.1 with BH6 at 7.8, which falls well within the acceptable SA Water quality guidelines for domestic use (1996). The TDS in BH6 is excessively more than the rest of the water samples at about 1100 mg/L while the other samples range between about 700mg/L and 900mg/L.

9.2 Parameter Estimation

The first step in calculating protection zones is to estimate the required parameters. The parameters for the case study area, and where they were obtained from will be listed in the Table below (Table 35).

Table 35: Case study parameters

Parameter	Value	Information
Case study area (A)	230 km ²	
Quaternary catchment size within case study area (A)	A24D 123 km ² A24E 90 km ² A24F 17 km ²	
Quaternary catchment recharge (R)	A24D 11.7mm/a A24E 11.5mm/a A24F 12.5mm/a	
Quaternary catchment specific yield (Sy)	A24D 0.004710 A24E 0.001095 A24F 0.005994	
Groundwater gradient (i)	0.0096	Calculated from surface topography since a high correlation exists between surface and groundwater level.
Groundwater recharge (R)	0.032 mm/d	The specific yield was calculated as a fraction contribution of the recharge of the three quaternary catchments.
Storativity (S ₁)	0.0050	Fractured and intergranular (Dennis et al., 2013)
Storativity (S ₂)	0.00345- 0.00442	Obtained from a modeling report at an adjacent mine
Transmissivity (T ₁)	0.5 m ² /d	Transmissivity ranges between 0.5 and 1.5 m ² /d and was obtained from a modeling report at an adjacent mine. Protection zones will be created for each of the extremes.
Transmissivity (T ₂)	1.5 m ² /d	

Specific yield (Sy)	0.0034	The specific yield was calculated as a fraction contribution of the specific yield of the three quaternary catchments.
Wetland 1 perimeter	1583 m	Protection zones were only delineated for significant wetlands within the case study area which had the potential of infringements to occur.
Wetland 2 perimeter	767 m	
Wetland 3 perimeter	597 m	
Bierspruit dam perimeter	6621 m	The Bierspruit dam's infringement zone was calculated the same as for the wetland protection zones.

9.3 Calculate Protection Zones

The radius of influence is time dependent and the RU statistics was based on borehole pumping of 8 hours/day/year. The lower and upper transmissivity values of 0.5 and 1.5 m²/d in the case study area were both used to calculate protection zones, available in Table 36. The calculations were based on the equations in Chapter 8.4. The median between the two extreme storativity values obtained from the adjacent mine was used to calculate the radius of influence as it corresponds more with the average specific yield between the three quaternary catchments than the storativity obtained from Dennis et al., 2013.

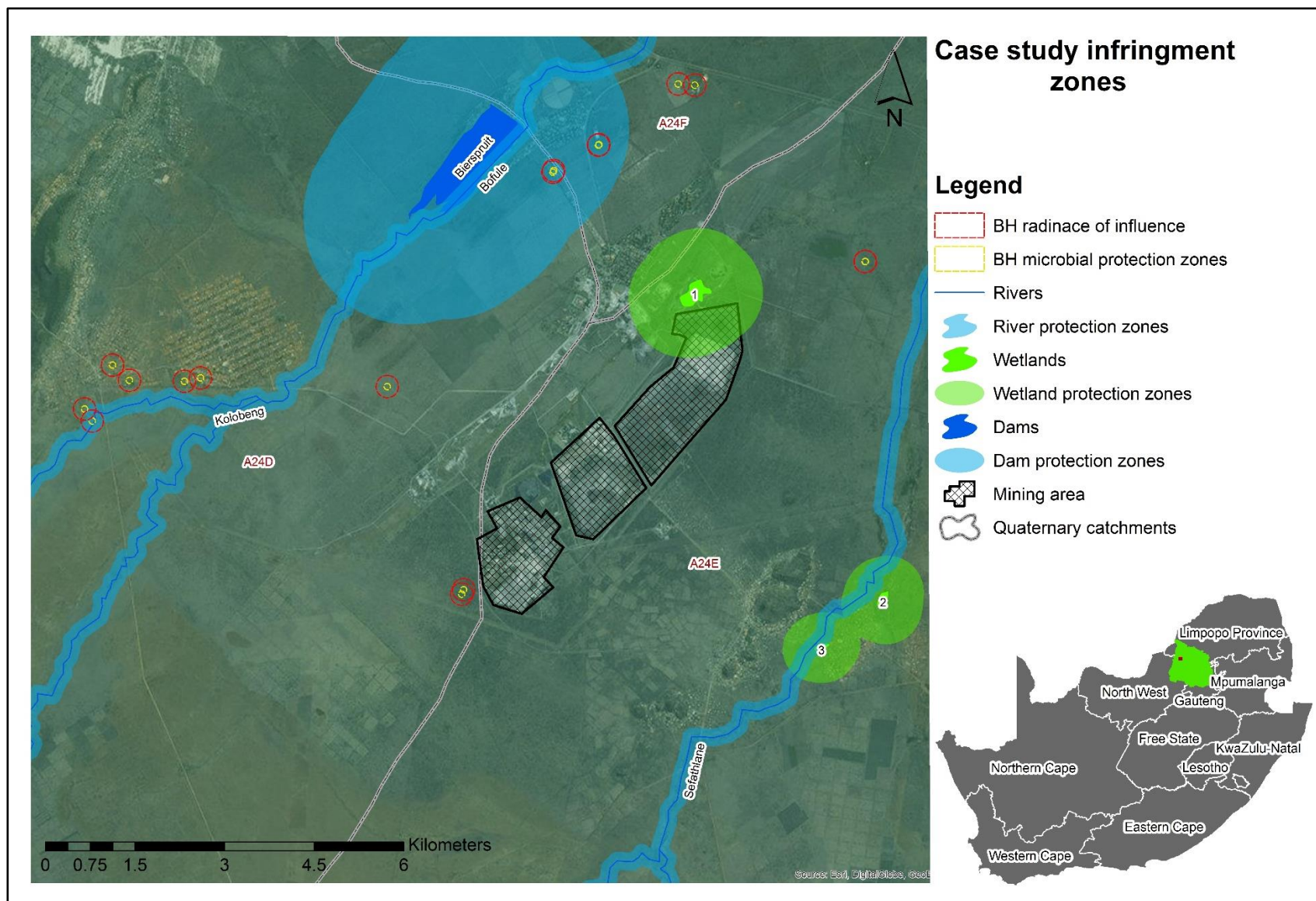
Table 36: Infringement zone calculations

Calculation	T_1	T_2
Radius of influence	$r = 187m$	$r = 325m$
Microbial protection zone	$r = 53m$	$r = 54m$
River protection zone	$d = 150m$	$d = 450m$
Wetland 1 protection zone	$d = 864m$	$d = 1496mm$
Wetland 2 protection zone	$d = 601m$	$d = 1041m$
Wetland 3 protection zone	$d = 530m$	$d = 919m$
Bierspruit dam	$d = 1766m$	$d = 3059m$

Figure 55 illustrates the protection zones as calculated with the transmissivity at $0.5 \text{ m}^2/\text{d}$. On closer inspection it is clear that there are a few borehole infringements at the Kolobeng River and Bierspruit dam. Wetland 1 infringes on the mining area. Protection zones were also delineated for the transmissivity at $1.5 \text{ m}^2/\text{d}$ and can be seen in Figure 56. There is a clear difference in the size of the infringement zones due to the $1 \text{ m}^2/\text{d}$ transmissivity difference between T1 and T2. This highlights the importance for accurate parameters to be taken on site rather than depending on average modelled numbers at a larger scale.

The radiance of influence in Figures 55 and 56 are quite big most likely due to a large draw down. This can be minimized by specifying a certain tolerance with regards to the drawdown curve, which has not been done yet.

Boreholes in the case study area are mostly only for monitoring purposes. They were however treated as pumping BHs for the purpose of implementation.



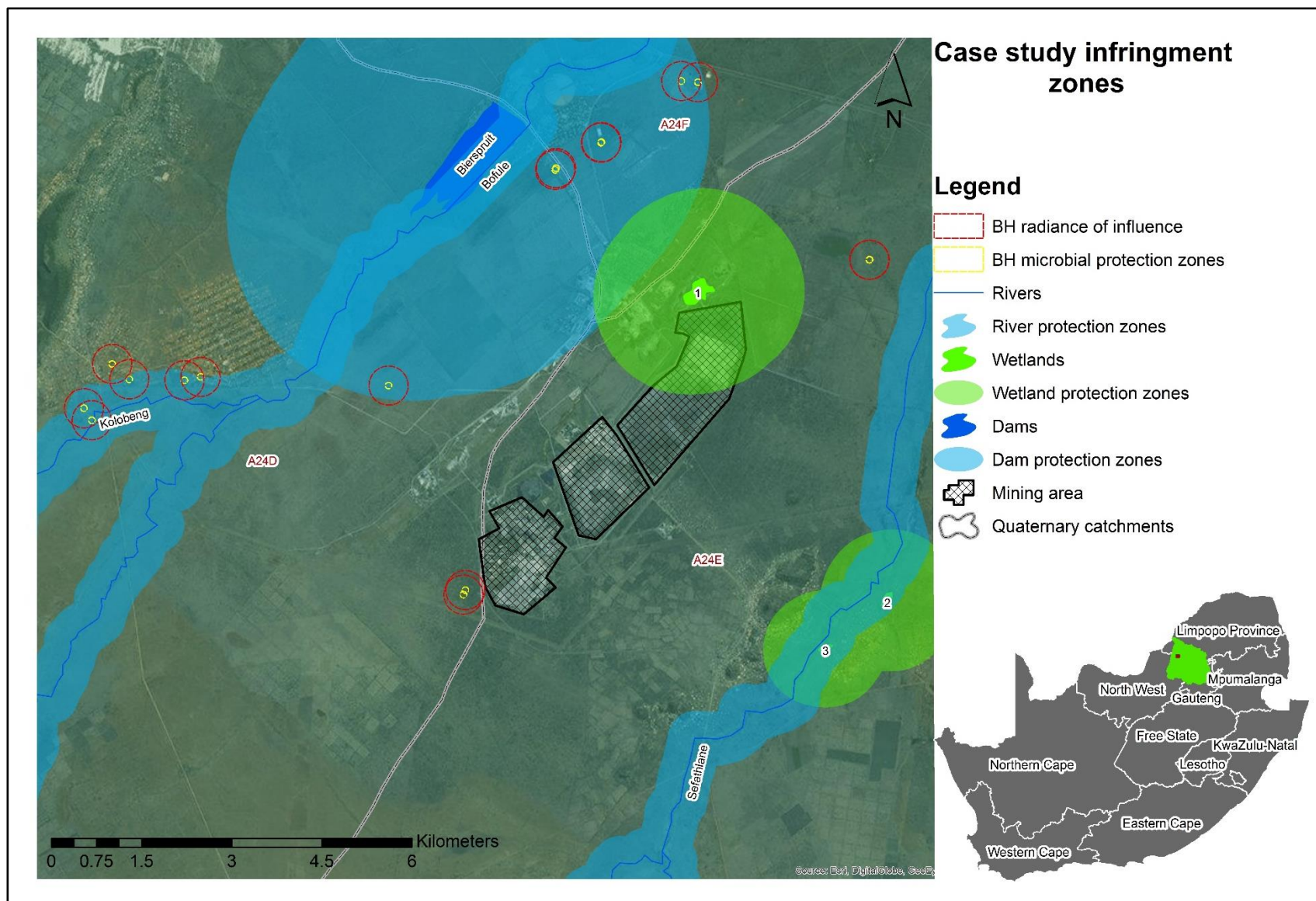


Figure 56: Protection zones for T2

9.4 Resource Quality Objectives

Groundwater RQOs were set up for both cases of transmissivity T1 at 0.5 m²/d and T2 at 1.5m²/d to portray the difference that these values can pose on the groundwater RQOs in the study area (Table 37). The indicator/ measurement used to identify each sub-component can be consulted in Table 33. The study area falls under IUA 12, which has a MC of III- this means water resources are heavily used and alterations to the resource unit's pre-development ecological state are significant. The groundwater had a 20% contribution to the decision of the MC and should not be allowed to deteriorate any further. Before RQOs were assigned for each sub-component the procedures as described in Chapter 2.5.2 were followed.

Table 37: Case study localised RQOs

Component	Sub-Components	RQOs for T1	RQOs for T2
Quantity	Radius of Influence	The radius of influence was estimated at 187m and should not intersect the protection zones of other BHs, wetlands or rivers in the study area. The minimum distance between to BHs should be 374m to prevent intersection of protection zones. In cases where infringements already exist, the infringements will be used as a baseline measurement.	The radius of influence was estimated at 325m and should not intersect the protection zones of other BHs, wetlands or rivers in the study area. The minimum distance between to BHs should be 650m to prevent intersection of protection zones. In cases where infringements already exist, the infringements will be used as a baseline measurement.
	Abstraction	General authorisation for the case study area is estimated 45m³/a/hectare . Where water use is higher than requirements for Reserve, Schedule 1 and General Authorizations, abstraction rates should not exceed the average recharge values of the aquifer based on the licensed area.	General authorisation for the case study area is estimated 45m³/a/hectare . Where water use is higher than requirements for Reserve, Schedule 1 and General Authorizations, abstraction rates should not exceed the average recharge values of the aquifer based on the licensed area.
Quality	Microbial Protection Zone	The safety radius around boreholes to prevent microbial pollution was estimated at 53m . Pit latrines or any other potential source of microbial pollution shouldn't be allowed to breach this radius.	The safety radius around boreholes to prevent microbial pollution was estimated at 54m . Pit latrines or any other potential source of microbial pollution shouldn't be allowed to breach this radius.
	Groundwater Quality	Groundwater quality at the vicinity of BH6 is unsafe for use. BH6 exceeds the water use requirement for TDS by 1530mg/L ; Mg by 290mg/L ; Na by 74mg/L ; Cl by 536mg/L ; SO ₄ by 147mg/L and has a high conductivity of 130 mS/m . BHs 3, 4 and 5 have overall good chemical balance except for Mg and TDS levels which exceeds the water use requirement of 30mg/L and 450 mg/L respectively at all these sites. BH 4 exceeds the water use requirement limit for Cl	Groundwater quality at the vicinity of BH6 is unsafe for use. BH6 exceeds the water use requirement for TDS by 1530mg/L ; Mg by 290mg/L ; Na by 74mg/L ; Cl by 536mg/L ; SO ₄ by 147mg/L and has a high conductivity of 130 mS/m . BHs 3, 4 and 5 have overall good chemical balance except for Mg and TDS levels which exceeds the water use requirement of 30mg/L and 450 mg/L respectively at all these sites. BH 4 exceeds the water use requirement limit for Cl

		by 16mg/L . Sites that exceed the water use requirement should not be allowed to deteriorate in water quality by any type of activity.	by 16mg/L . Sites that exceed the water use requirement should not be allowed to deteriorate in water quality by any type of activity.
Aquifer	Water Levels	Medium to long-term water trends should show recovery. Time series data isn't available for the study area, but the water levels mostly follow the topography, which could be an indicator for good water levels.	Medium to long-term water trends should show recovery. Time series data isn't available for the study area, but the water levels mostly follow the topography, which could be an indicator of good water levels.
	River Protection Zone	A protection zone along a river/stream is required to protect the ecological reserve. Any new possible influences should be at least 150m away from the rivers in the study area. In cases where infringements already exist, the infringements will be used as baseline measurement.	A protection zone along a river/stream is required to protect the ecological reserve. Any new possible influences should be at least 450m away from the rivers in the study area. In cases where infringements already exist, the infringements will be used as baseline measurement.
Ecological	Wetland Protection Zone	A protection zone around a wetland is required to protect the ecological system. Wetland protection zones for the case study area are as follows: - Wetland 1, 864m - Wetland 2, 601m - Wetland 3, 530m - Bierkraal dam, 1766m In cases where infringements already exist, the infringements will be used as baseline measurement.	A protection zone around a wetland is required to protect the ecological system. Wetland protection zones for the case study area are as follows: - Wetland 1, 864m - Wetland 2, 601m - Wetland 3, 530m - Bierkraal dam, 3059 In cases where infringements already exist, the infringements will be used as baseline measurement.

General Authorization for the taking and storage of water, DWAF (2012)

² *A Guideline for the Assessment, Planning and Management of Groundwater Resources in South Africa, DWAF (2008)*

³ *The radius of influence is time dependent and the RU statistics is based on borehole pumping of 8 hours/day*

⁴ *A protection zone is defined as a zone where the groundwater gradient is maintained*

⁵ *South African Water Quality Guidelines, DWAF (1996)*

⁶ *Groundwater Resource Directed Measures, Parsons and Wentzel (2005)*

10 CONCLUSIONS AND RECOMMENDATIONS

It is difficult to specify groundwater RQOs at quaternary catchment level as groundwater is not bound to the quaternary drainage regions at deeper levels. The opposite is true for surface water which has a representative downstream point. One of the objectives of this thesis was to delineate groundwater RUs for the Crocodile-West catchment based on available hydrogeological parameters even though final reporting was done on surface water RUs for IWRM purposes.

A detailed geostatistical analysis was done on significant geological units covering 73% of the total area. A frequency analysis was done on these geological units with regards to water level. Out of the analysis it became clear that the majority of groundwater movement through the catchment, except for minor variances, correlated highly with the topography. Thus, there wasn't any noteworthy justification to report RQOs on any specific groundwater RUs. Groundwater RU delineation was successfully done based on a frequency analysis of borehole water levels, blow yield, water strike and water quality parameters yielding a groundwater profile to be used in the prioritisation tool for prioritising groundwater to be reported on surface water RUs.

The formulation of a prioritisation strategy was needed as implementation of RQOs on a scale such as the Crocodile-West catchment will be costly and time consuming. A prioritisation strategy was created for GRDM RUs based on groundwater related criteria and sub-criteria. These criteria were weighted and rated to produce a priority rating per RU which was then normalised. The criteria included was largely dictated by available data. The main criteria were:

- Importance for users
- Threat posed to users
- Ecological importance
- Groundwater profile

After normalisation, RUs A21A and A21D were specified as the highest groundwater priority rated areas within the Crocodile-West catchment.

The final aim of the study was to formulate groundwater RQOs for the Crocodile-West catchment. Generic groundwater RQOs were set for the entire catchment and groundwater RQOs with numerical limits were set on a local scale case study with use of available geohydrological data. The components and their sub-components which were used to define groundwater RQOs are set out in the below table, Table 38:

Table 38: Components for defining RQOs

Component	Sub-Components
Quantity	Radius of Influence
	Abstraction
Quality	Microbial Protection Zone
	Groundwater Quality
Aquifer	Water Levels
Ecological	River Protection Zone
	Wetland Protection Zone

The local scale case study RQOs were successfully quantified and drafted. Protection zones were created around boreholes and ecological key features. The groundwater quality of the case study area was evaluated with use of Piper and Durov diagrams and compared to the South African water quality guidelines for domestic use.

All the objectives were completed for this study. During the study it became apparent that there are challenges in the determination of groundwater RQOs. They were identified as follows:

- Data was either unavailable or outdated.
- Public participation should be a contributor to the setting of RQOs. Local people could have valuable information on the groundwater state of an area.
- The RUs from which the case study was done had a moderate priority rating. Even though a RU isn't highly prioritised, doesn't mean that there aren't any highly prioritised localised hot spots within the RU.
- It will be near to impossible to set numerical RQOs at regional scale as evident in the difference between BH chemistry values of BH5 and BH6 that are seen on a local scale already.
- Quality and quantity of water and the geology within a RU can differ significantly. It will take a lot of labour to estimate parameters and draft RQOs at this scale. RQOs are meant to be easily set and implemented. It won't be efficient to try and set numerical RQOs on a regional scale.

The way forward:

- Implementation of groundwater RQOs in a pilot study on a local scale.
- Onsite verification of geohydrological data (hydro-census) should be done for up-to-date data and higher confidence levels of the RQOs set.

With the local scale case study, it is seen that groundwater RQOs can be quantified to a certain measure, although a lot more research will have to be done as local scale groundwater RQOs can contribute greatly to the protecting our precious resource- groundwater.

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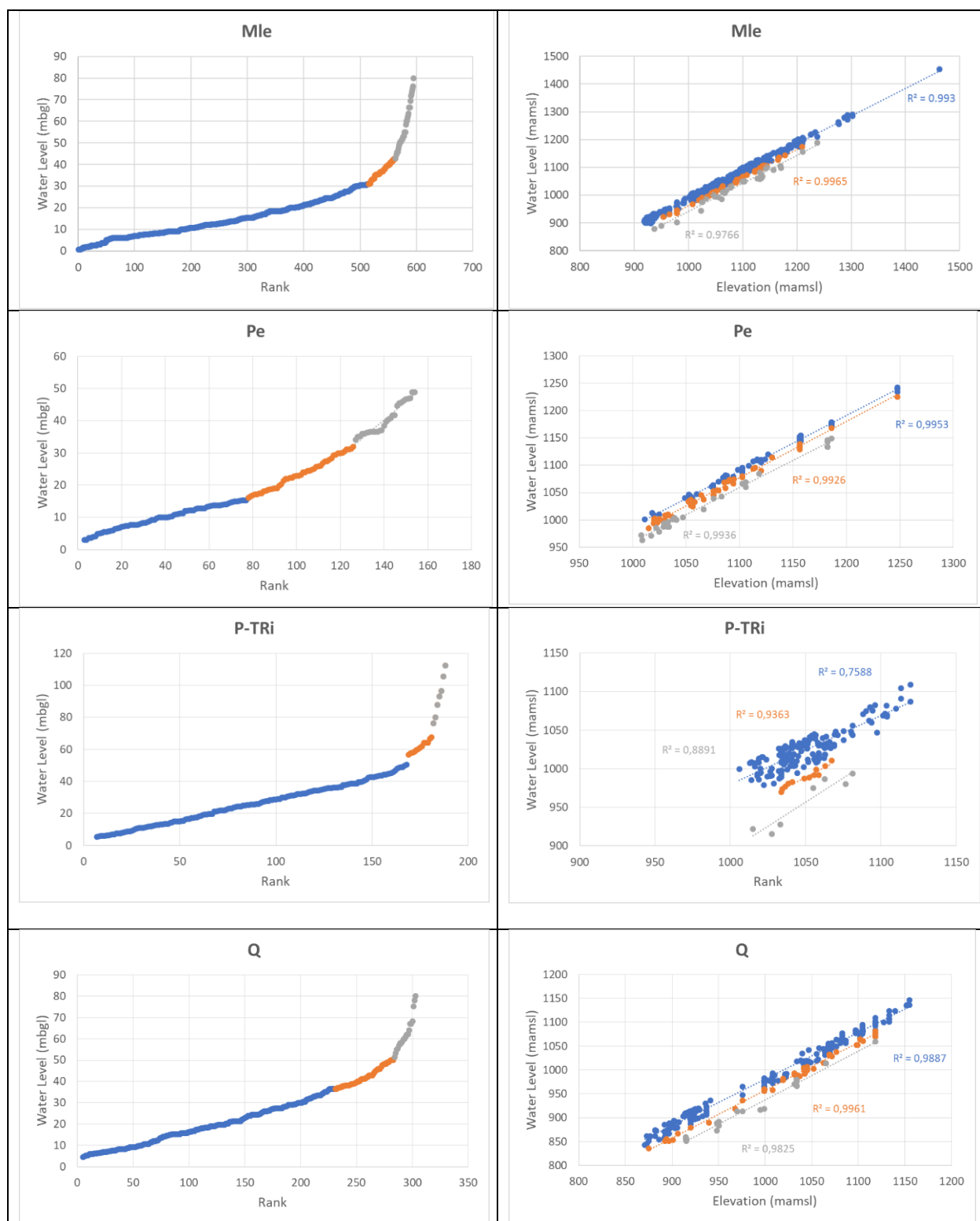
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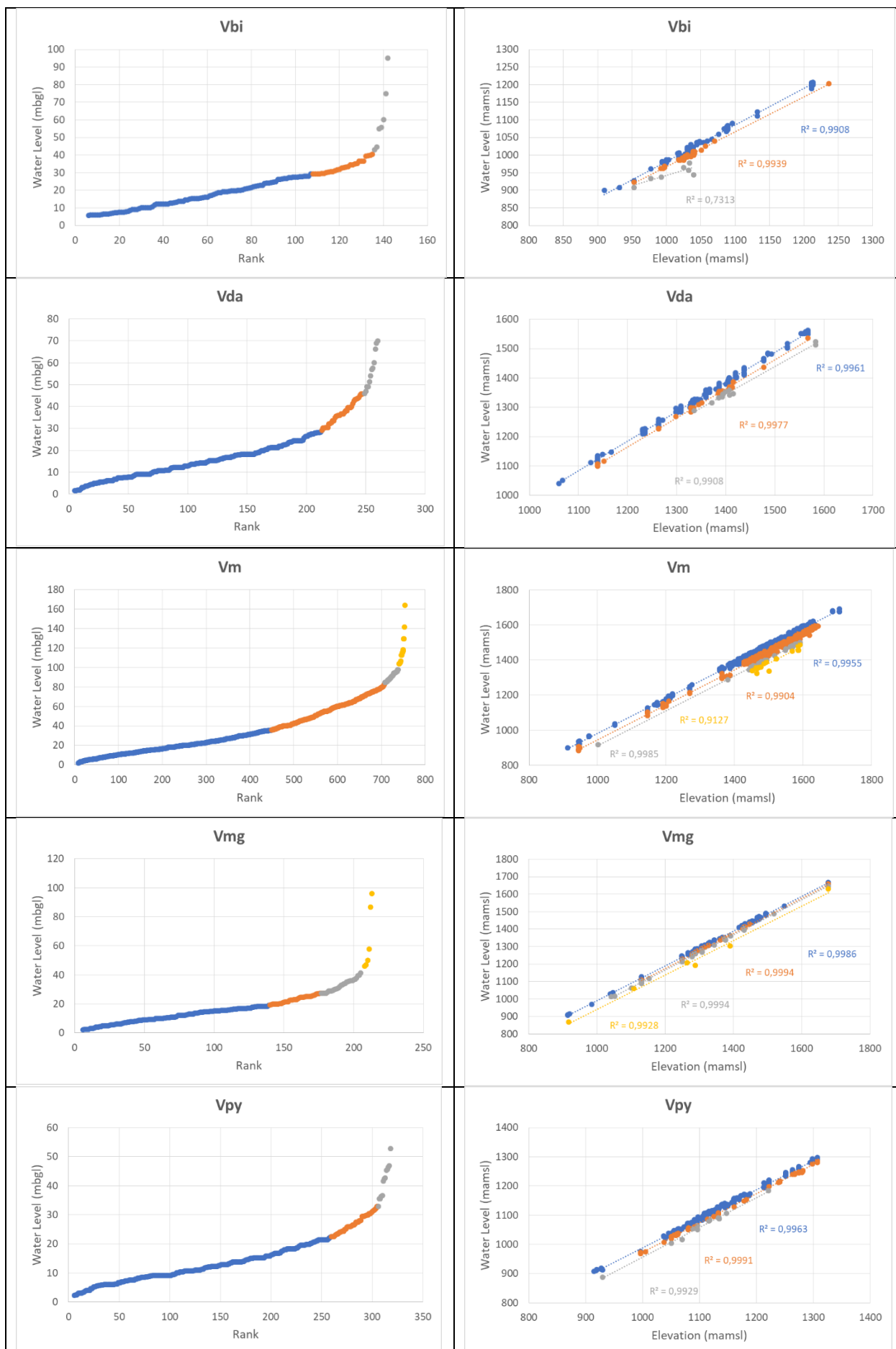
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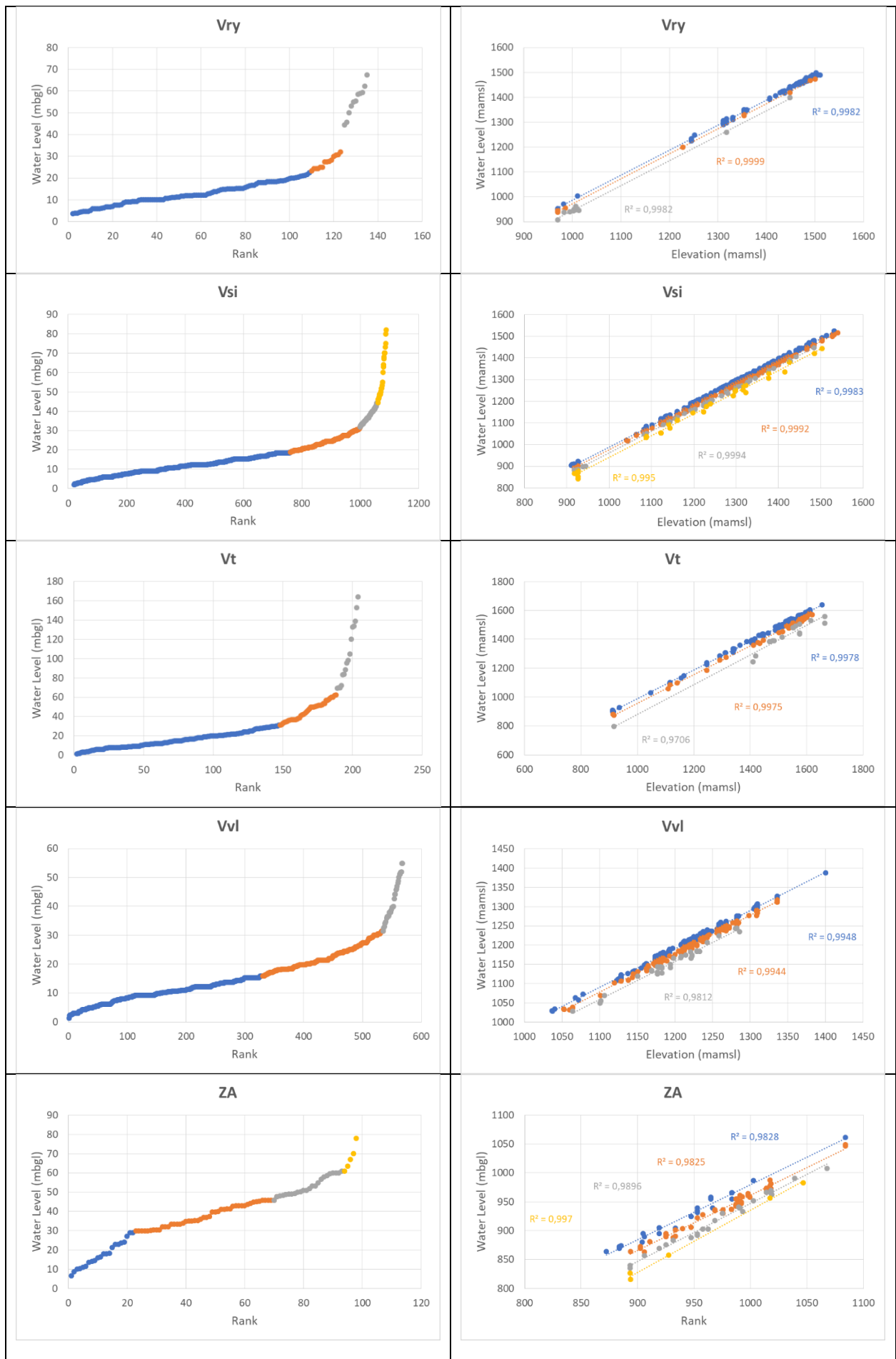
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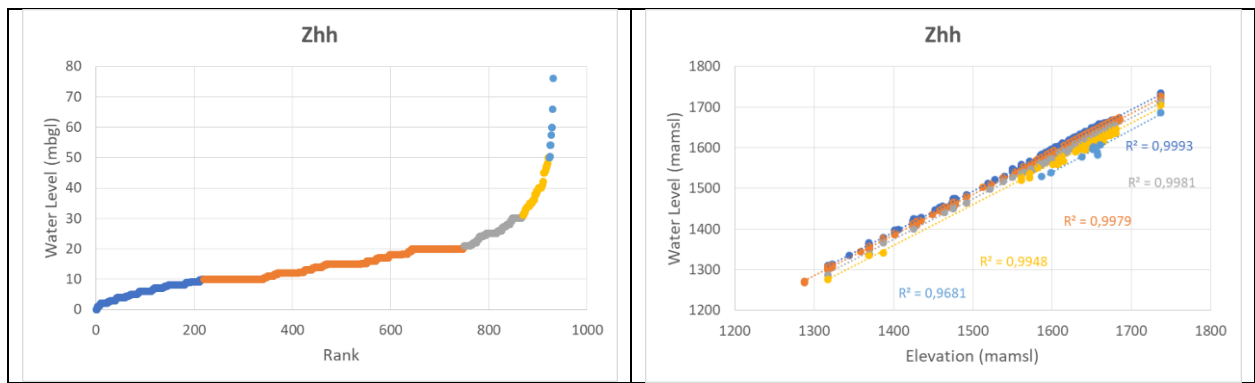
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APPENDIX A – WATER LEVEL ANALYSIS

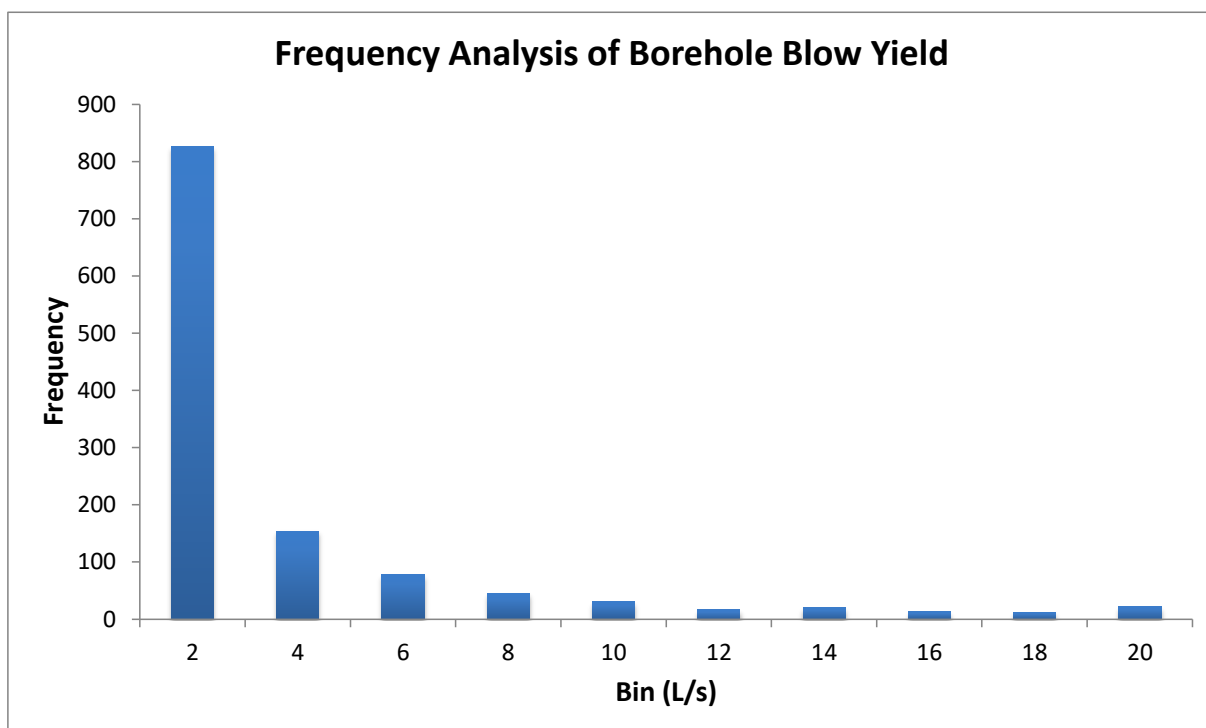
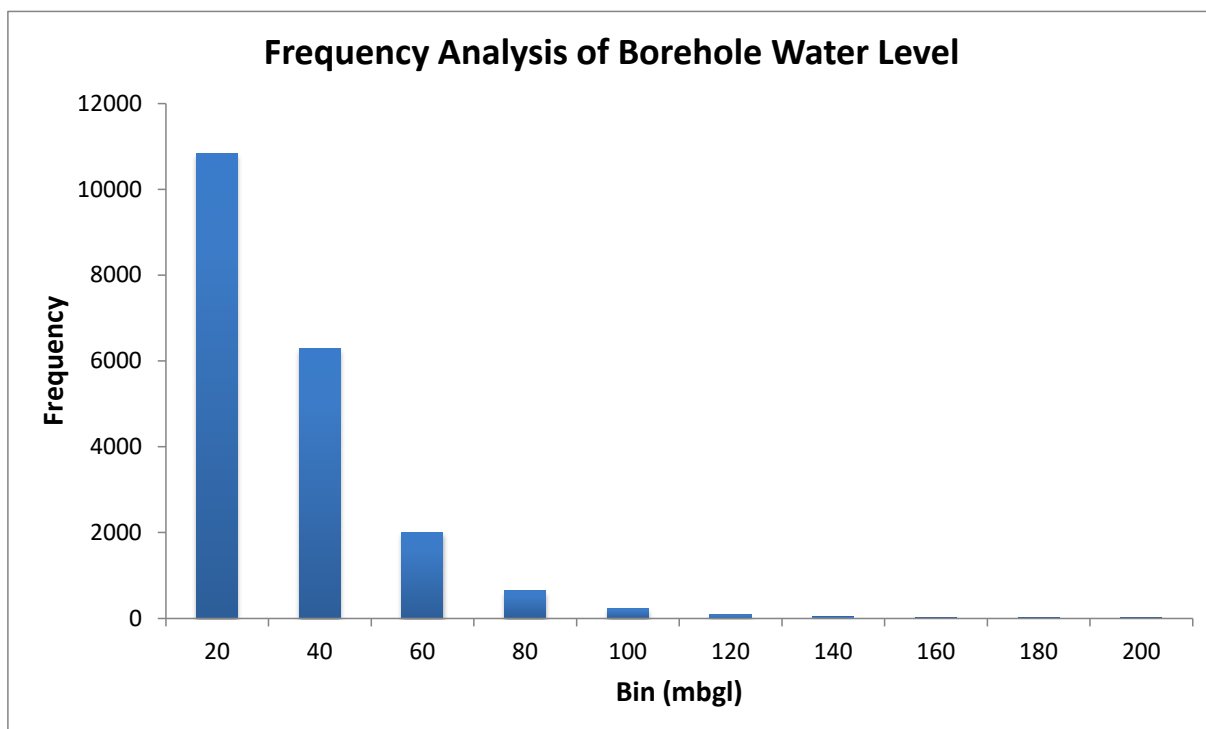


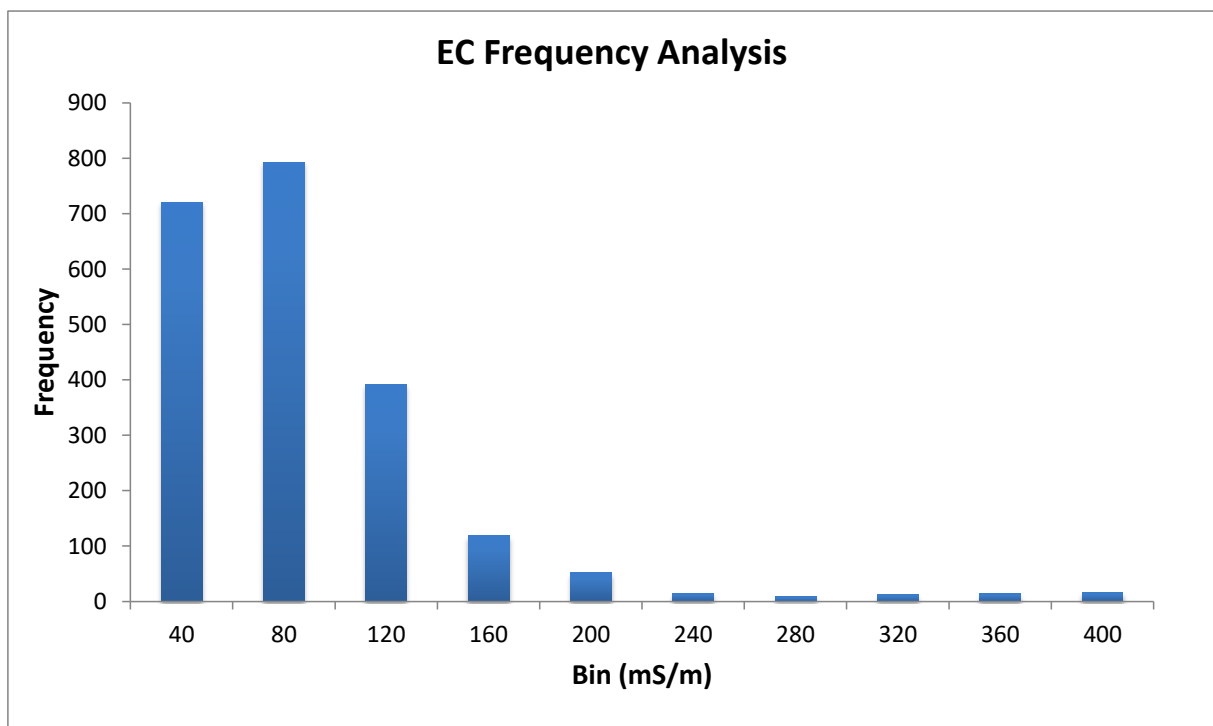
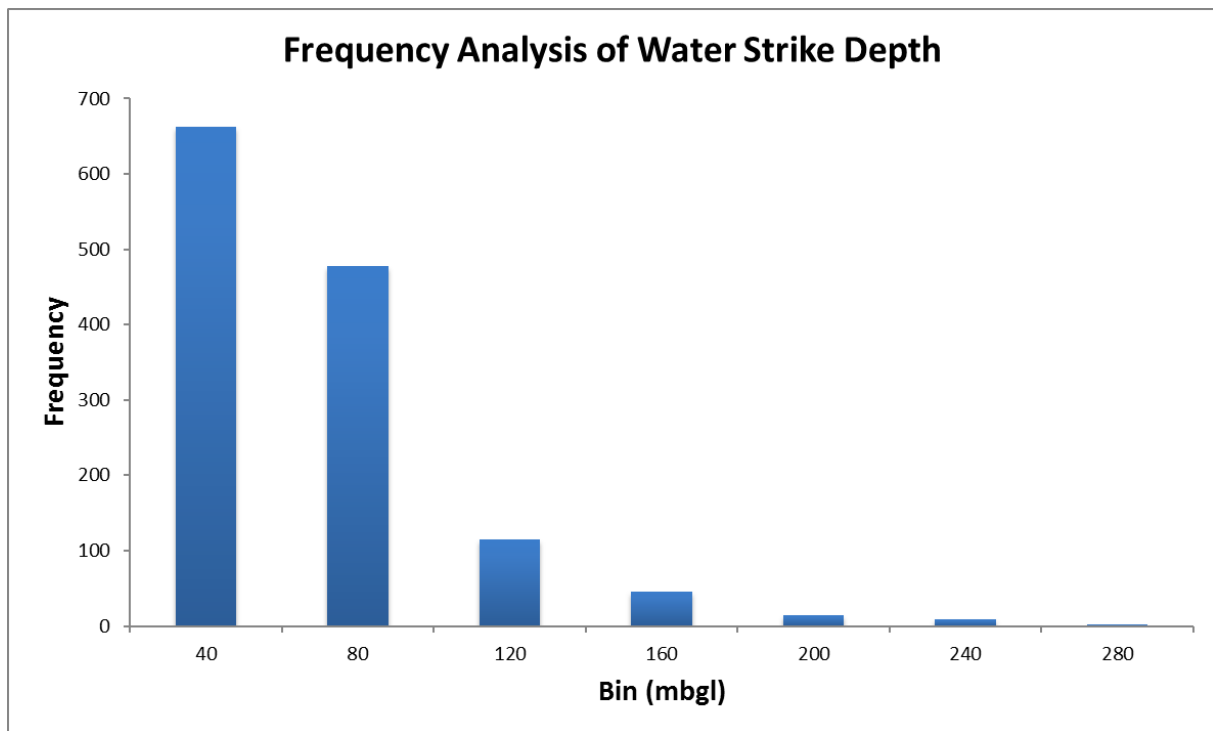




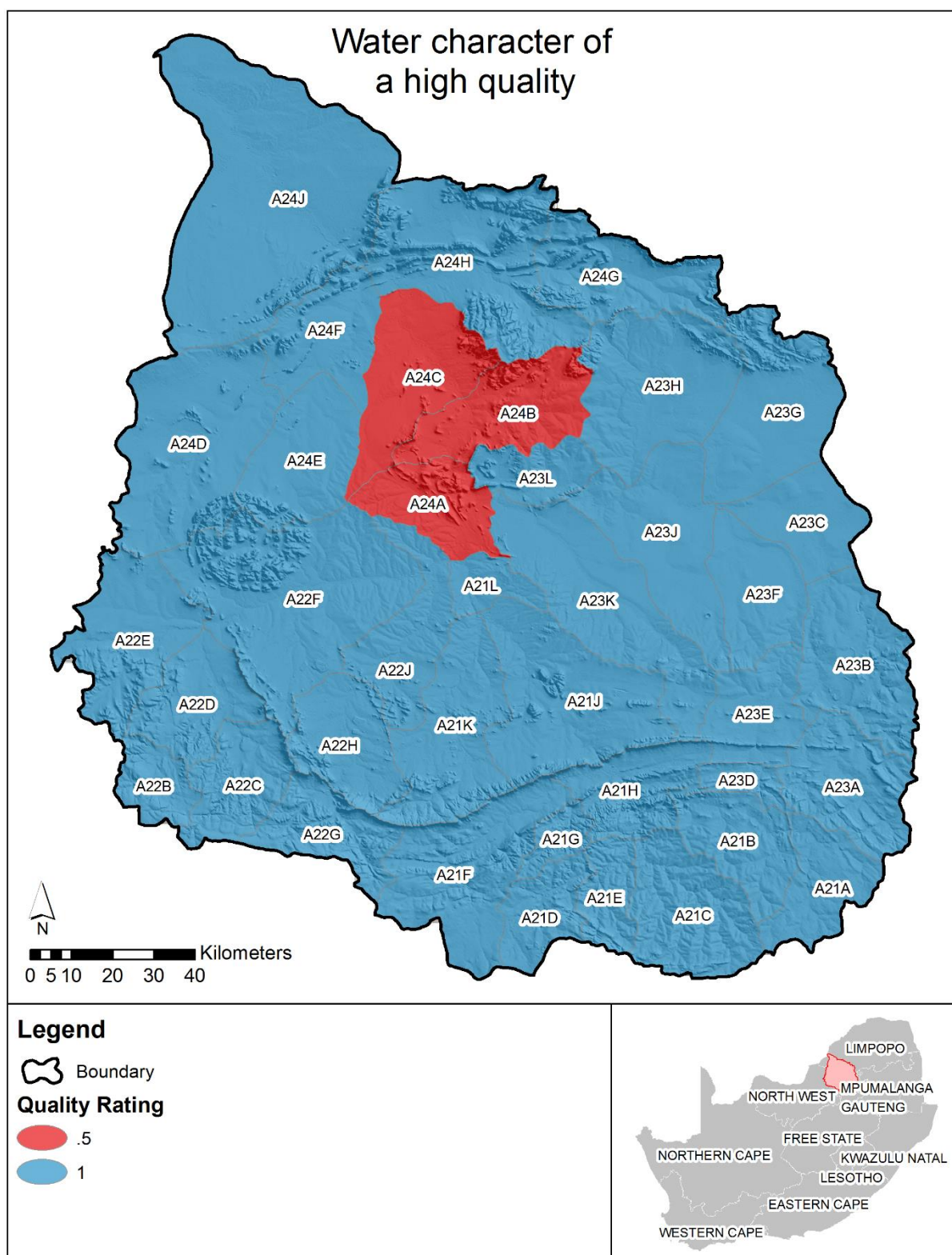


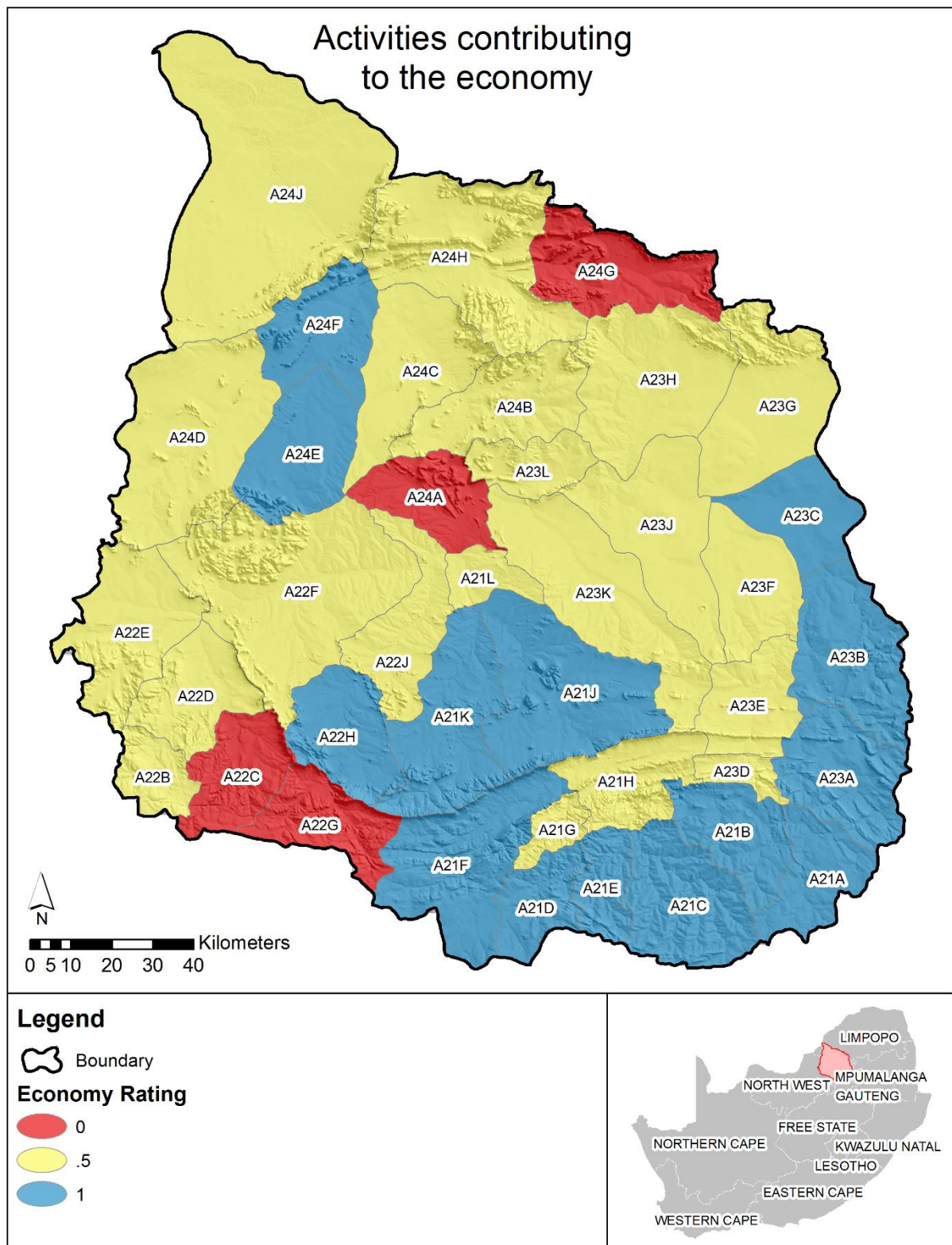
APPENDIX B – FREQUENCY ANALYSIS OF BOREHOLE PARAMETERS

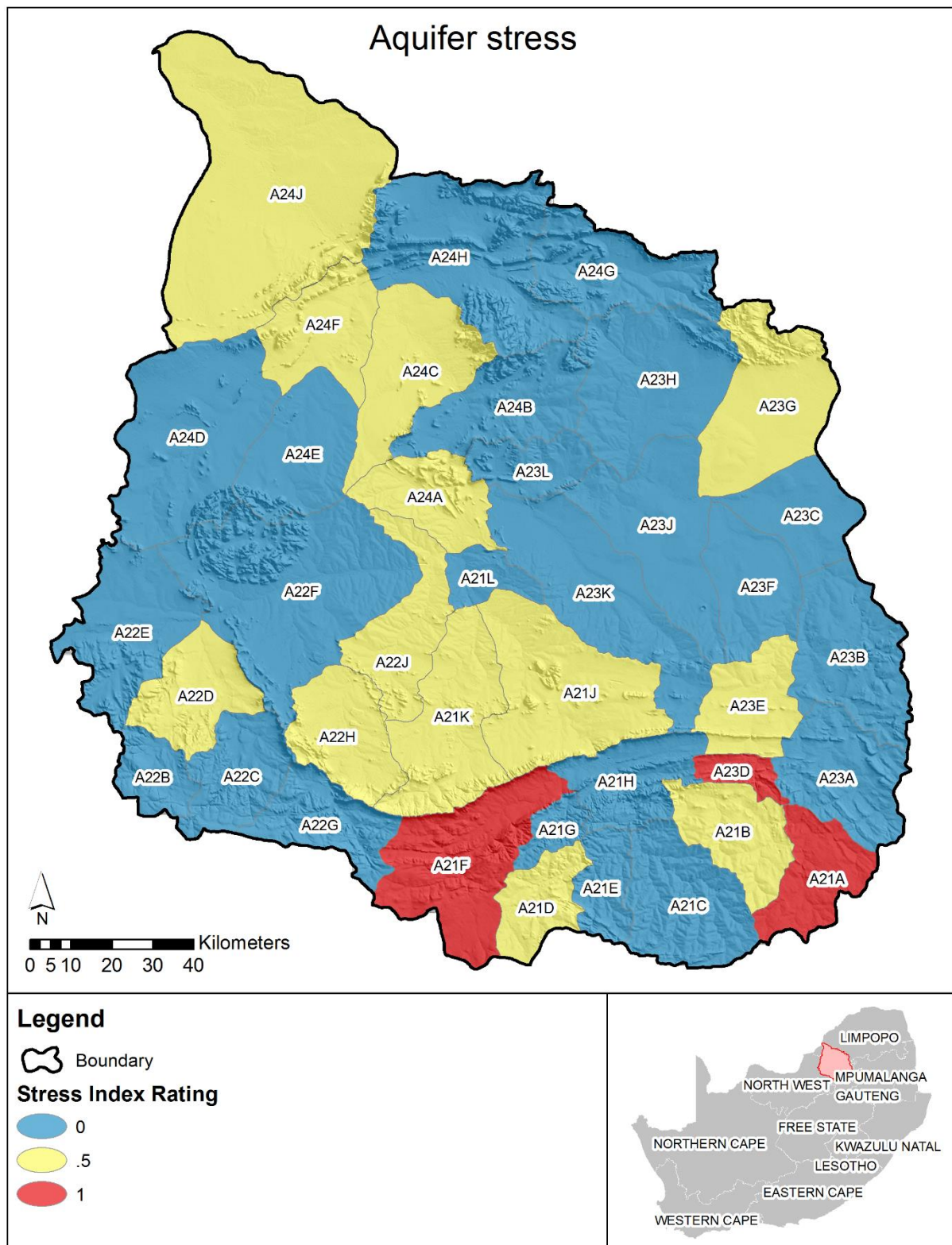


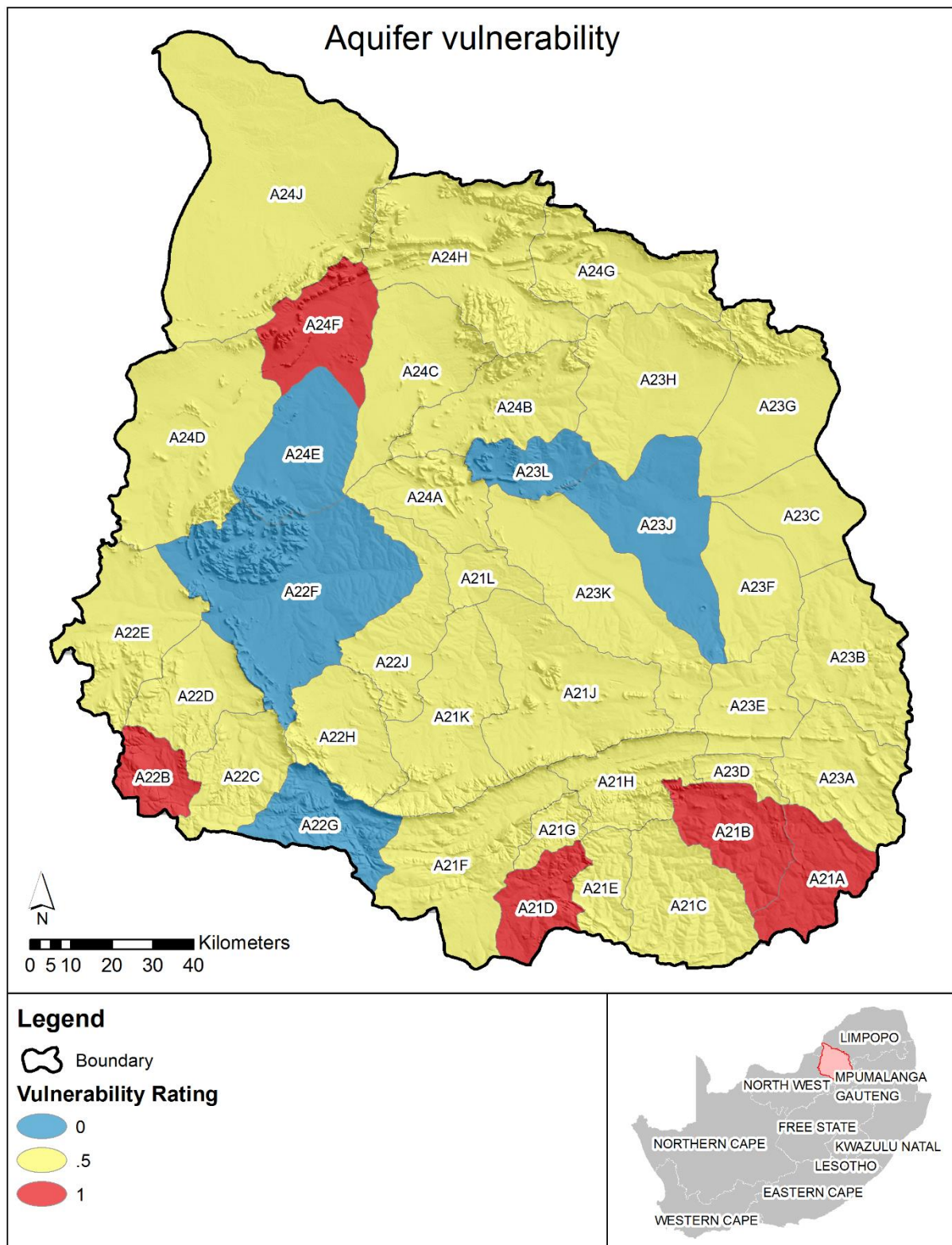


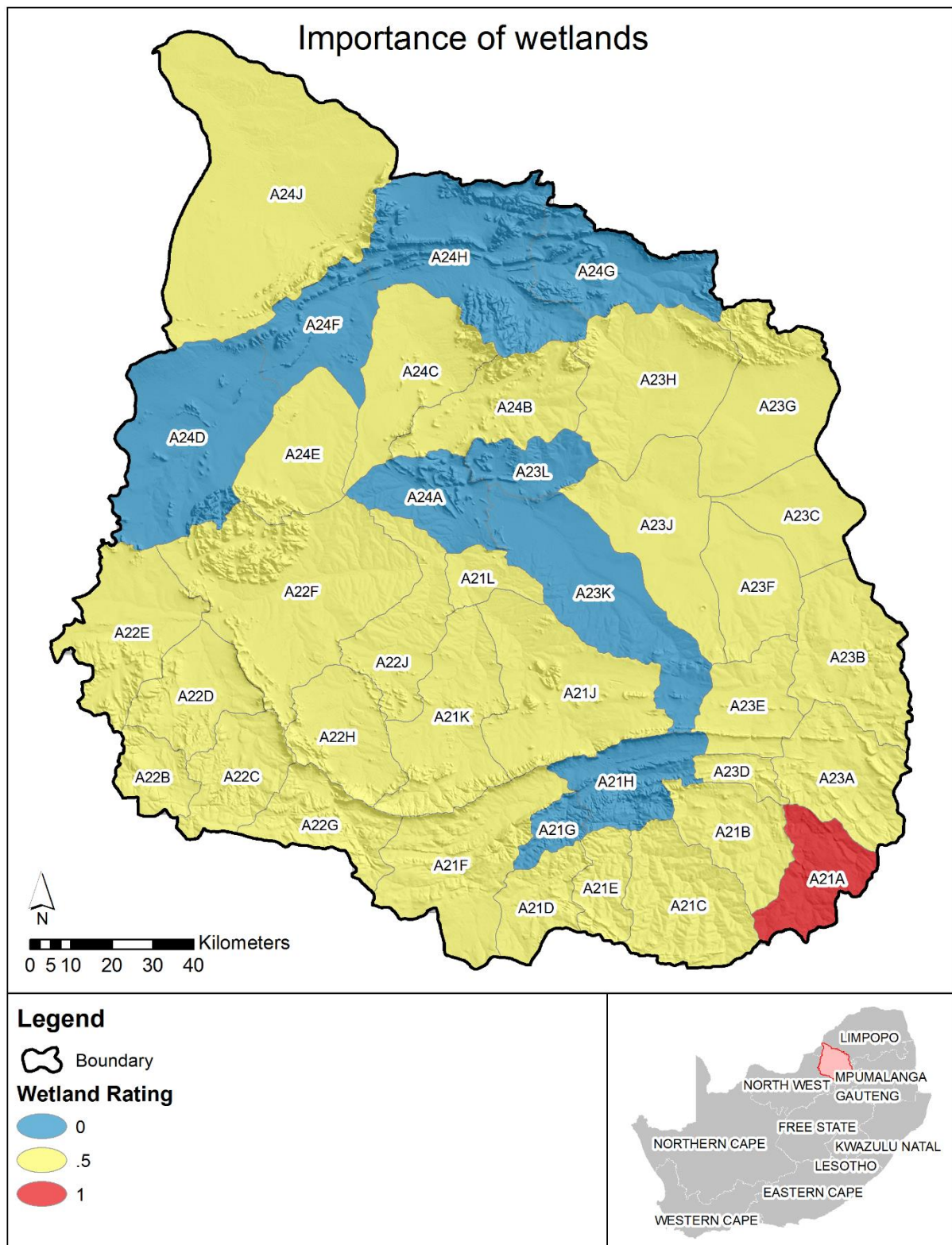
APPENDIX C – PRIORITISATION RATING MAPS

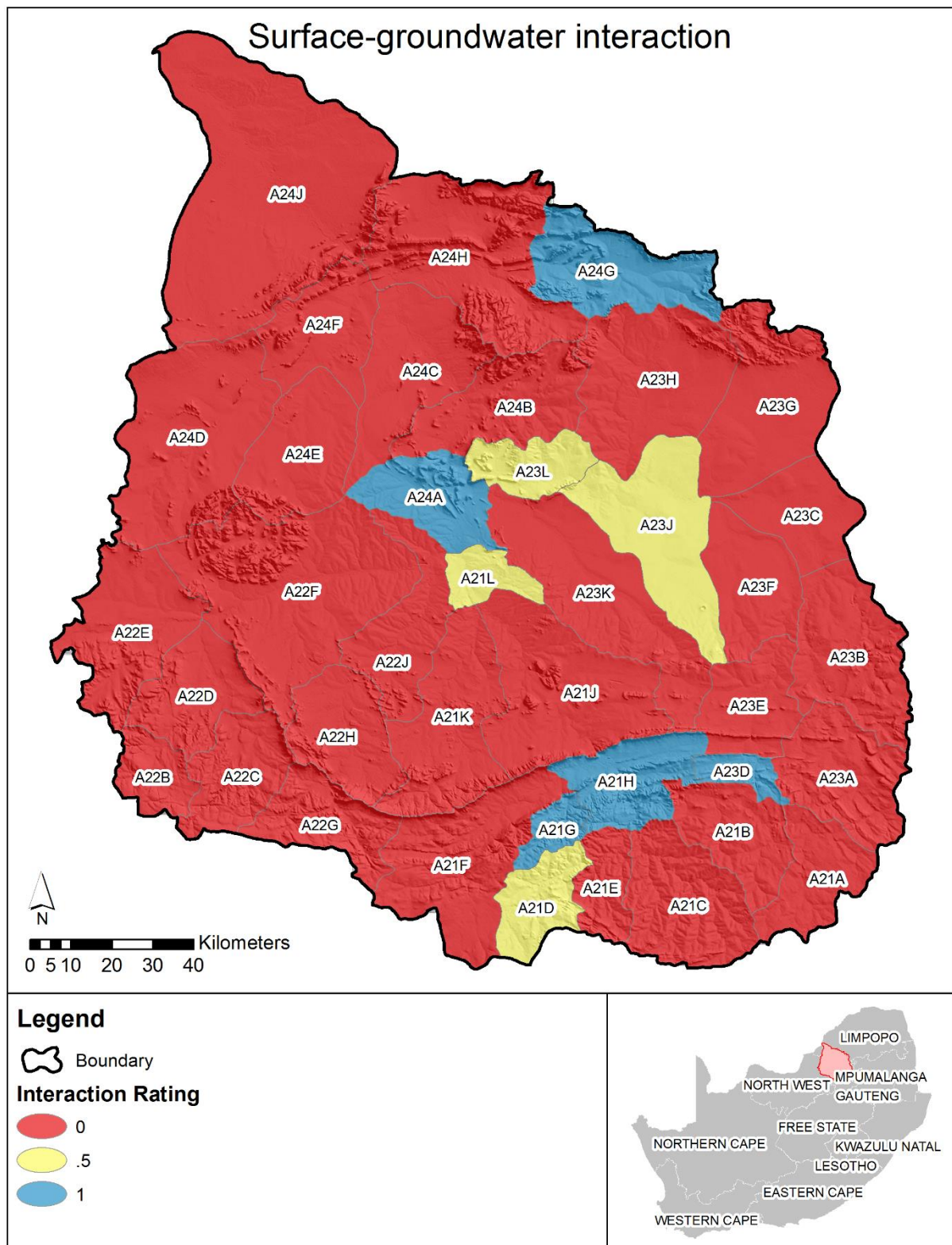


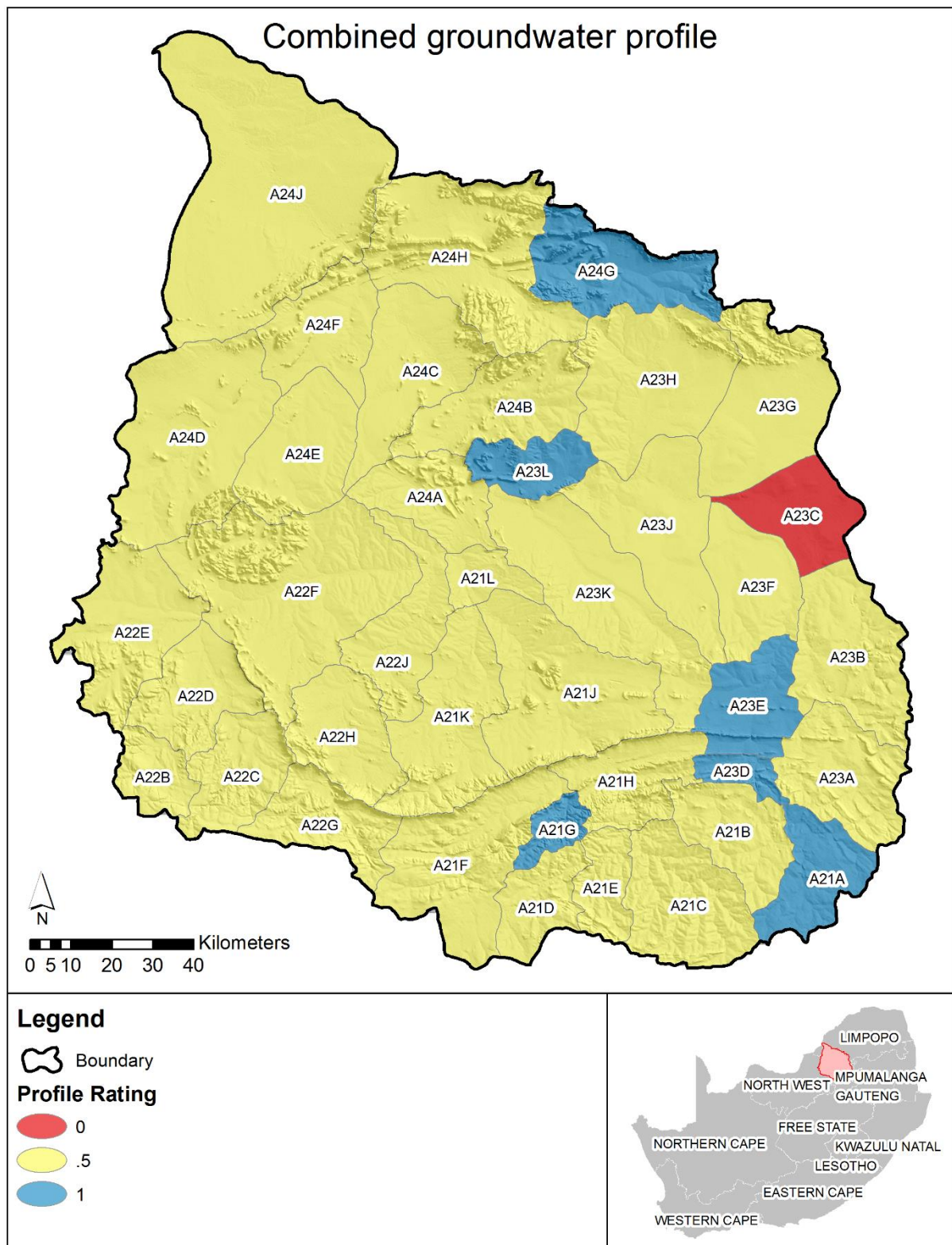








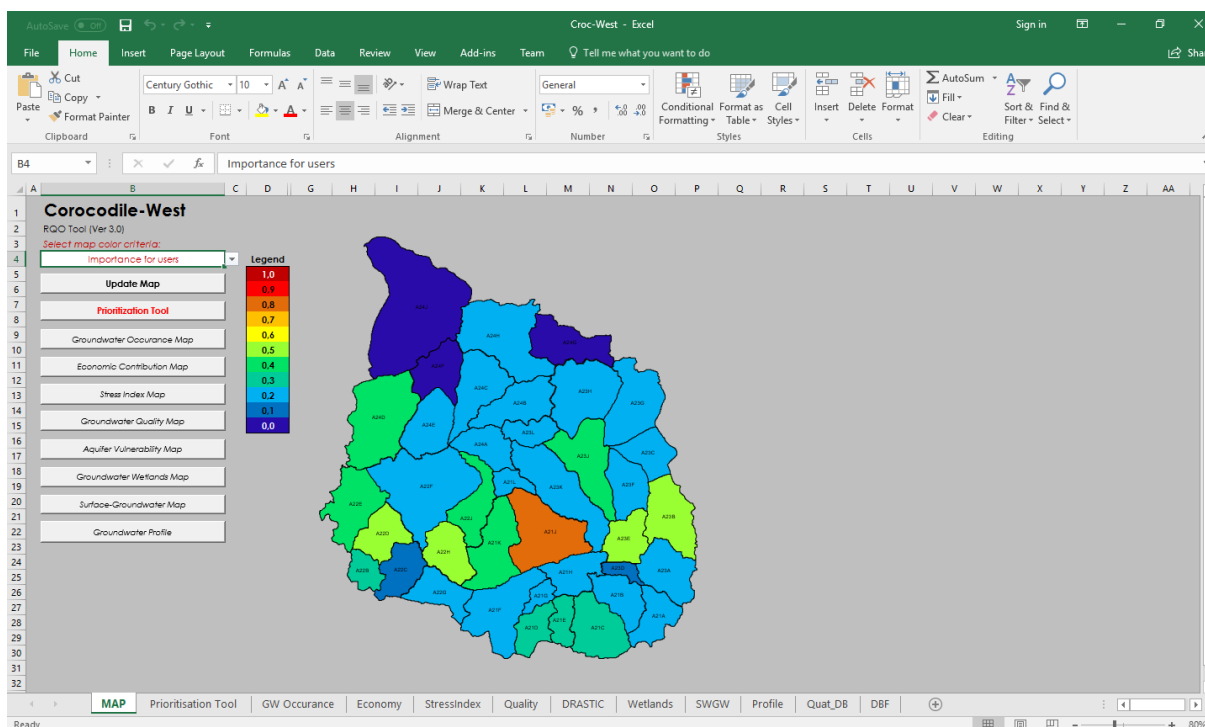




APPENDIX D – RQO TOOL INSTRUCTIONS

Navigating the RQO tool

The main page in the RQO tool, see Figure below, represents a coloured map with its legend which ranges between 0 and 1 indicating the priority of each RU based on the chosen criteria. The buttons on this page act as shortcuts for the rest of the tabs in the document which include the prioritisation tool and detailed criterion maps. Each page has a simple “Home” button which will take the user back to the main page. To view a different criterion simply click on the drop-down list under “Select map colour criteria”, choose the desired criteria, and click on the “update map” button.



Understanding the RQO tool

RUs in the study area are prioritised based on four main criteria (See the following Figure for the prioritisation tool). These criteria are accompanied by a weight, i.o.w. a percentage contribution to the overall priority rating. These criteria with their weights in brackets are:

- Importance for users (25)
- Threat posed to users (25)
- Ecological Importance (30)
- Groundwater Profile (20)

The four criteria are each defined by a set of sub-criteria with their respective weights or percentage contribution to that criterion. Every sub-criterion is accompanied by a rating guideline, which describes the sub-criterion between 0.0, 0.5 or 1.0 for a RU.

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A1 : X ✓ fx GROUNDWATER RESOURCE UNIT PRIORITISATION TOOL

Criterion	Weighting	Sub-criteria	Rating Guideline	Weighting	A24J	A24H	A24G	A24F	A24C	A23G	A23H	A24D	A24B	A24E	A23L
Importance for users (Current & anticipated future use)	25	Water character of a high quality	0.0 - RUs which contain high TDS (> 2400 mg/L) 0.5 - RUs which contain average TDS (1000 - 2400 mg/L) 1.0 - RUs which contain low TDS (< 1000 mg/L)	30	0	1	0	0	1	1	1	1	0	1	1
		Major aquifers	0.0 - RUs which contain or are dominated by poor aquifers (< 0.5 L/s) 0.5 - RUs which contain or are dominated by minor aquifers (0.5 - 2 L/s) 1.0 - RUs which contain or are dominated by major aquifers (> 2 L/s)	40	0	0	0	0	0	0	0	0.5	0	0	0
		Activities that contribute to economy	0.0 - RUs which do not directly support any activities which contribute to the economy 0.5 - RUs which support activities which provide a moderate contribution to the economy 1.0 - RUs which support activities which contribute significantly to the economy	30	0	0	0	0	0	0	0	0	1	0	0
Threat posed to users	25	Aquifers which are highly stressed	0.0 - RUs with low stress index (< 20%) 0.5 - RUs moderate stress index (20 - 65%) 1.0 - RUs with high stress index (> 65%)	40	0	0	0	0	0	0	0	0	0	0	0
		Water quality is currently threatened	0.0 - RUs where potential threat to water quality is low 0.5 - RUs where potential threat to water quality is moderate 1.0 - RUs where potential threat to water quality is high	40	1	1	1	1	0	1	1	1	1	1	1
		Vulnerable aquifers	0.0 - RUs that are least vulnerable to pollution (55 - 80) 0.5 - RUs that are moderately vulnerable to pollution (81 - 120) 1.0 - RUs that are highly vulnerable to pollution (121 - 160)	20	0.5	0.5	0.5	0.5	0.5	0.5	0	0	0.5	0.5	0.5
Ecological Importance	30	Groundwater importance to wetlands	0.0 - RUs which contain wetlands with low groundwater importance 0.5 - RUs which contain wetlands with moderate groundwater importance 1.0 - RUs which contain wetlands with high groundwater importance	40	1	1	1	1	1	1	1	1	1	1	1
		Ground-surface water interactions	0.0 - RUs which contain low Gv-Sv interaction (< 10%) 0.5 - RUs which contain moderate Gv-Sv interaction (10 - 20%) 1.0 - RUs which contain significant Gv-Sv interaction (> 20%)	60	0.5	1	1	1	1	1	1	1	1	1	1
Groundwater Profile	20	Combined groundwater profile	0.0 - RUs with shallow, good quality water 0.5 - RUs with moderate water levels and quality 1.0 - RUs with deep, poor quality water	100	1	1	1	1	0	1	1	1	1	1	1
Priority score	100	Importance for users			0.00	0.30	0.00	0.00	0.30	0.29	0.29	0.48	0.28	0.28	0.28
		Threat to users			0.50	0.50	0.50	0.50	0.10	0.50	0.40	0.40	0.50	0.50	0.50
		Ecological importance			0.70	0.99	0.97	0.95	0.93	0.91	0.90	0.88	0.87	0.85	0.84
		Groundwater profile			1.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
Total Prioritisation Score					0.54	0.70	0.61	0.61	0.38	0.67	0.64	0.68	0.66	0.65	0.65
Priority Rating					0.69	0.90	0.80	0.79	0.49	0.87	0.83	0.89	0.85	0.84	0.84

MAP Prioritisation Tool GW Occurance Economy StressIndex Quality DRASTIC Wetlands SWGW Profile Quat_DB DBF

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Determining the priority per RU

Specific criterion maps were created based on existing geohydrological data. These maps were inserted into the RQO tool, see the following Figure as an example. They were evaluated with use of the rating guidelines as assigned to each sub-criterion. A value (rate) of 0.0, 0.5 or 1.0 was then assigned for each RU in the prioritisation tool for each sub-criterion. Note that the rating guideline that covers most of a RU's area determined the rate.

A priority score for each of the main criteria were then calculated per RU. This was done by multiplying each of the relevant sub-criteria weights with their respective rates as assigned per RU and adding the results together. The resultant value was then divided by 100 (combined sub-criteria weights).

Next the "Total prioritisation score" was calculated per RU. The "Total prioritisation score" for each RU is determined by:

$$\begin{aligned} &(((\text{Priority score: Importance for users} \times \text{weight}) + (\text{Priority score: Threat posed to users} \times \text{weight}) \\ &\quad + (\text{Priority score: Ecological Importance} \times \text{weight}) \\ &\quad + (\text{Priority score: Groundwater Profile} \times \text{weight})) / (100 (\text{combined criteria weights})) \end{aligned}$$

The priority rating per RU was then determined by dividing the "Total prioritisation score" of each RU by the "Total prioritisation score" of the RU with the highest score. This will produce a priority rating of between 0 and 1, 1 being the highest prioritised RU.

A map was then delineated to represent the priority of each RU.

