

Hydrogeology of Basement aquifers in the Limpopo Province

Report to the
Water Research Commission

by

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Executive Summary

Archaean basement lithologies are distributed extensively in Africa and also underlie large parts of the semi-arid Limpopo Province in South Africa. Groundwater is the only dependable source of water for many users in Limpopo Province. A socio-economic study showed that water supply is chronically short in many rural areas and that households often pay exorbitant prices for water on informal local water markets. The importance of the basement aquifers in the province in meeting water demand makes it important to identify high yielding hydrogeological zones that can be targeted for water supply. Due to the intrinsic low primary permeability and porosity of basement lithologies, the biggest challenge is to understand the factors that determine the secondary permeability and storativity of these aquifers. The focus of this study was therefore to systematically analyse regional factors that may influence borehole yields and aquifer transmissivities.

The study covered two distinct geological and morpho-structural domains within the Limpopo Province, the Limpopo Plateau in the west and the Letaba Lowveld in the east, together covering about 23 500 km². The basement rocks of the Limpopo Province are structurally complex, shaped by multiple tectono-metamorphic events spanning at least 600 million years.

The borehole dataset compiled for the study consisted of over 8 000 boreholes contained in the Groundwater Resources Information Project (GRIP) Limpopo database of the South African Department of Water Affairs. Approximately 3 000 of these boreholes have been hydraulically tested and the lithology has been recorded for 1 200. The basement lithologies of the study area are characterised by a generally thin regolith overlying a primarily structurally controlled fractured aquifer. Compared to the Letaba Lowveld, the Limpopo Plateau is generally characterised by deeper boreholes due to deeper water strikes, water levels, weathering and fracturing depths.

The hydraulic tests in the GRIP dataset were analysed using the Flow Characteristic (FC) method to recommend long term abstraction rates (or “sustainable yields”) for the boreholes. A large number of the pumping tests failed to identify water strikes (fractures) or potential no-flow boundaries, questioning the choice of available drawdown in the abstraction boreholes as one of the most critical parameters for sustainable yield estimates.

The GRIP borehole dataset was analysed in conjunction with spatial information to identify regional factors influencing borehole yields and transmissivities such as weathering, climate, lithology, geological structures including neo-tectonic stresses, thickness of quaternary or alluvial sediments, depth of weathering, age of landforms (erosion surfaces) and relief. Favourable borehole locations from a topographical point of view are predictably boreholes along rivers and valleys. Geology has a clear influence, with boreholes exploiting intergranular aquifers composed of highly permeable material showing generally higher yields. Other identified favourable groundwater targets are the metamorphic aureoles of younger granite intrusions and complexes. Despite the local importance of the regolith as a recharge and storage mechanism for the underlying fractured bedrock, no correlation between borehole yields and depth of weathering was found. A differentiated pattern of lineament, shear zone and dyke orientations in the different domains led to a more complex conceptual model of groundwater occurrence and borehole productivity. This conceptual model is inconsistent with the predicted regime based on regional stress field data and suggests that local variations have a strong influence on groundwater occurrence. A differentiated conceptual hydrogeological model of the basement lithologies in the Limpopo Province has been provided, which can be used in the siting of more productive boreholes.

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1. Introduction

1.1. Basement aquifers

Crystalline Basement rocks are hard, crystalline or re-crystallised rocks of igneous or metamorphic origin, mainly of Precambrian age, such as granites, gneisses and greenstones (Arcworth, 1987; Jones, 1985; Wright, 1992). They can be divided into three main suites in Africa (Key, 1992):

- Ancient rocks of the Archaean cratonic nuclei, including granites, gneisses and greenstones, such as the Halfway House Granite in Gauteng, South Africa.
- Metamorphic rocks of the mobile belts, showing strong deformation and often of Proterozoic age, such as the gneisses of the Limpopo Mobile Belt (e.g. Beit Bridge Complex).
- Anorogenic intrusions of various ages, such as the Cape Granite Suite, South Africa.

Almost the whole continent of Africa is underlain by crystalline Basement rocks, albeit in places under a thick cover of more recent material (Key, 1992). Consequently crystalline Basement rocks form the largest of the four major aquifer domains or “hydrogeological provinces” found in sub-Saharan Africa, covering about 40% of the region’s 23.6 million square kilometers (Figure 1.1). Approximately the same number of rural Africans live on Basement rocks (about 220 million people) as on the other three aquifer domains put together (MacDonald et al., 2001).

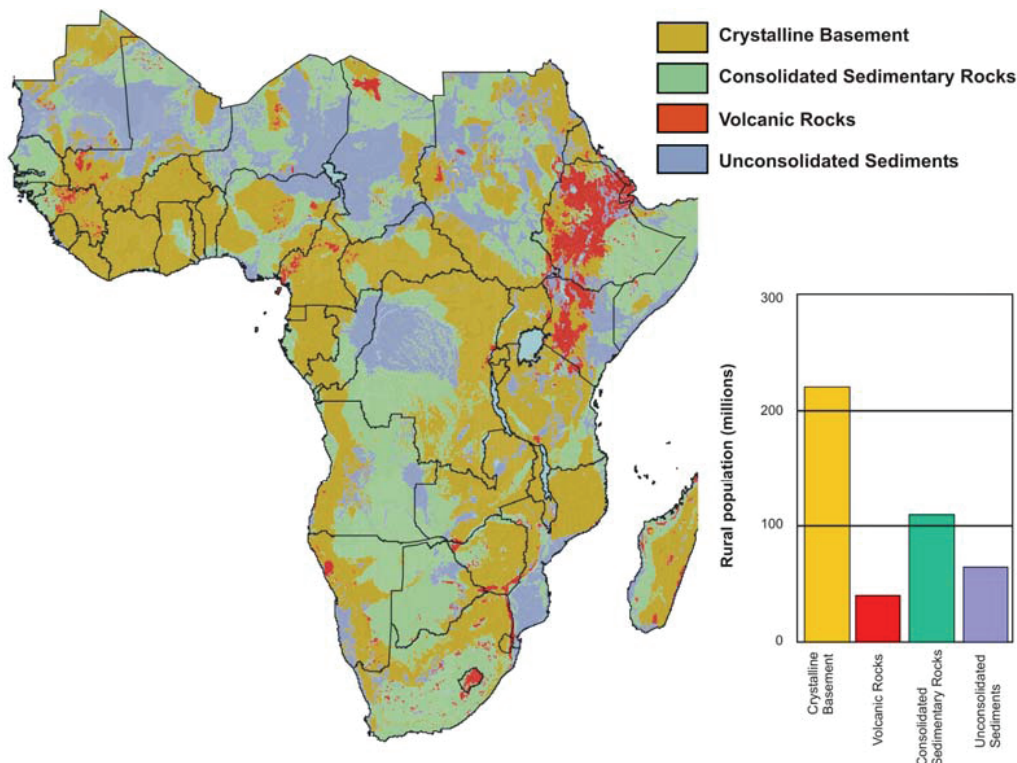


Figure 1.1. Different African hydrogeological environments (after MacDonald, 2005).

Crystalline Basement aquifers differ in important ways from other aquifer types, and demand specific knowledge and techniques if groundwater is to be extracted and managed efficiently. Crystalline rocks are characterised by very low primary porosity (fresh or unweathered crystalline rocks contain virtually no water), and almost all groundwater movement and storage in these rocks takes place via fractures, faults, weathered zones and other secondary features that enhance the aquifer potential only locally (Lloyd, 1999). Whilst fractures (particularly where interconnected) may have high permeabilities they have very little storage potential, and crystalline Basement aquifers usually depend on the presence of higher porosity material, such as weathered regolith or adjacent alluvium, to store groundwater. Hence the “classical” model of a Basement aquifer as a zone of high porosity but low permeability clay-rich weathered material overlying a fractured zone of low porosity but higher permeability. An ideal borehole or well would therefore intercept long or interconnected fractures in the upper part of the solid rock which are in contact with a large volume of low permeability material that provides a consistent resource of water. The practice of targeting for example the shallow aquifer in the weathered overburden regolith (weathered overburden) or the top of the weathered saprock (weathered and fractured bedrock) in topographic lows and/or stopping the drilling once the hard rock or a water strike is encountered may therefore result in frequent failures of boreholes in times of drought due to increased demand on low yielding sources and reduced recharge to the aquifer. In South African Basement aquifers, groundwater drought (when groundwater sources fail as a direct consequence of drought) is uncommon, and according to Du Toit (1996) water supply failures experienced during the 1991-93 drought in Limpopo Province were blamed on maintenance problems made worse by the drought. However it is important to identify hydrogeological zones that have low permeability, boreholes that are low yielding, and areas of high population density with few alternative water sources, i.e. the drought vulnerability.

Borehole yields in Basement aquifers are typically relatively low (usually less than 5 L/s, and often less than 1 L/s), but their importance to human well-being in Africa is far out of proportion to their hydraulic properties. Whilst aquifer properties in Basement rocks may be predictable at an average or regional scale (Jones, 1985), they are highly variable on a local scale (Gustafson and Krasny, 1994) and both yield and water quality may be difficult to predict (Banks and Robins, 2002).

Natural groundwater quality in most Basement environments is generally good (Clark, 1985; Chilton and Foster, 1995), with low salinities and neutral to slightly acid pH values being common. Elevated salinities are typically encountered in areas of low recharge, discharge and/or prolonged residence times in the subsurface. However, natural water quality in Basement can occasionally be detrimental to human health through high levels of trace elements such as fluoride (Smedley et al., 2002). Metals such as aluminum are also mobile in low pH groundwater. High iron concentrations associated with lateritic soils, whilst not harmful to human health, can stain appliances and clothes and make water unpalatable (Clark, 1985). Poor water quality can be as great a constraint on the development of a resource as low quantities.

The complex geology and discontinuous nature of many Basement areas means that natural water quality can change over relatively short distances, both laterally and with depth (Chilton and Foster, 1995).

Basement aquifers are very vulnerable to pollution of the groundwater, particularly where the regolith is thin, since groundwater movement through fractures is rapid and the fractured rock matrix provides little attenuation of contaminants. Furthermore, the existence of a high permeability laterite layer at the base of the soil zone in African Basement areas provides another rapid pathway for contaminant migration. Pollution is therefore a major threat to Basement groundwater quality (Clark, 1985). Numerous village water supply boreholes in Basement areas have been sited close to latrines, and microbial contamination has occurred, since both latrine and borehole penetrate to below the zone of lower permeability regolith.

1.2. The importance of weathering

In-situ weathering of crystalline rocks takes place in the presence of water and air, and is more rapid in warmer, humid conditions. Whilst water alone acts to alter minerals in crystalline rock such as feldspars and is the main weathering agent (Jones, 1985), water and carbon dioxide combine to produce acidity, particularly in the soil zone where carbon dioxide levels are elevated (~1 Vol-% versus 0.035 Vol-% in the atmosphere), and this acidity assists in the weathering process. Crystalline rocks also tend to be more susceptible to weathering than sedimentary rocks of similar age (Wright, 1992).

Fractures appear first at the base of the “weathering front” and the rock may later alter to form a weathered layer or “saprolite” with high clay content (Figure 1.2). If the weathered layer includes material transported from elsewhere, it is referred to as regolith (Jones, 1985). Erosion may remove the weathered material as it is formed, but many parts of the crystalline Basement in Africa are tectonically stable and have subdued topography, hence the thickness of the weathered material can reach 60 m or more in some areas (MacDonald et al., 2005). The porosity of the weathered profile generally decreases with depth, along with clay content, until fresh rock is reached. Leaching of the saprolite may occur, and since it is lighter than the fresh rock the consequent unloading or decompression contributes to the formation of more fractures (often sub-horizontal) in the fresh crystalline rock below. This horizon of fracturing between the fresh rock and the clay-rich saprolite frequently has a higher permeability.

Weathering is more rapid in tropical parts of Africa, whilst in arid areas or higher-lying areas where the rate of weathering is low in comparison with that of erosion, the regolith may be thin or absent. The final regolith thickness and lithology in any particular area depends on an interconnected series of controls, including bedrock characteristics (chemistry, mineralogy, petrography and structure), climate (past and present), age of land surface, and relief (Wright, 1992).

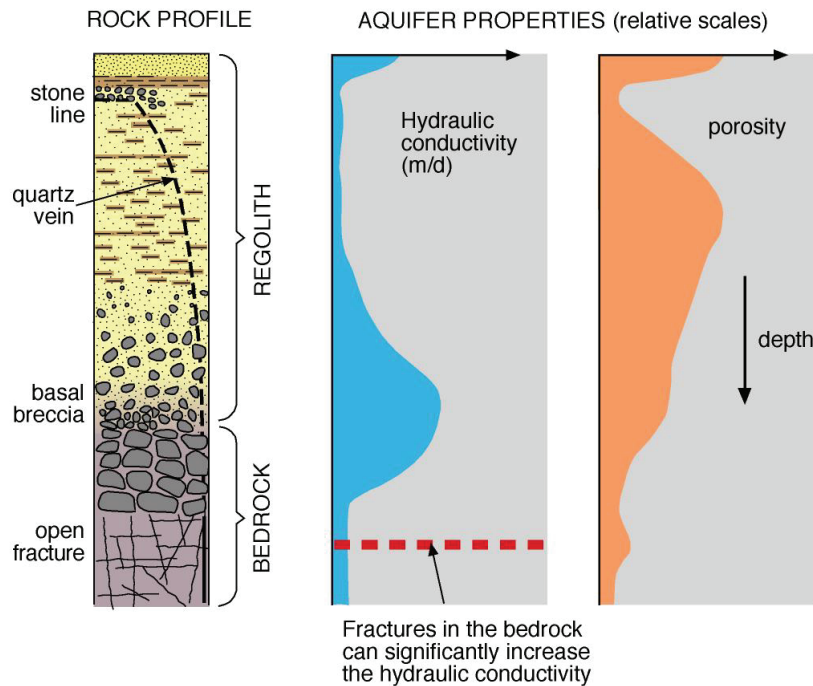


Figure 1.2. Permeability and porosity in Basement aquifers (after MacDonald et al., 2001) based on Chilton and Foster, 1995).

It follows that the presence of weathered material overlying crystalline rocks is often critical to the properties of the Basement aquifer, most importantly to the sustainability of the resource, since this can present a zone in which water is stored. Even where the Basement is fractured, if weathering is thin or absent the groundwater resource is likely to be small and unreliable unless an alternative source of recharge to the fractured Basement such as a river or associated alluvium is present. Sand rivers can perform the storage function in more arid parts of southern Africa.

1.3. Regional characterization of Basement aquifers

Hydrogeological mapping and groundwater exploration in crystalline areas normally pays close attention to locating weathered material, together with the geological and tectonic controls on its occurrence and thickness, typically directly related to structural features which control deeper groundwater flow. Weathering is often related to local feature such as fractures, dykes, river base levels and local topography. In addition, the fracture systems that provide the permeability to Basement aquifers are often discontinuous and localised. Therefore many African Basement aquifers may be better thought of as localised “pockets” rather than as a more uniform regional aquifer. Aquifer properties are discontinuous, and a wide range of yields may be encountered even in otherwise fairly uniform areas (Wright, 1992 and Gustafson and Krasny, 1994). Perched groundwater may also be found, due to the development of discontinuous clay layers and/or impermeable boundaries (Moriarty, 2000). Whilst average regional hydraulic characteristics can be assigned to areas of Basement aquifer, there is a danger in applying these to the local scale, or in anticipating borehole yields on the basis of regional averages. Conversely, aquifer properties gained from a small set of boreholes generally cannot be used to characterise the regional aquifer.

Both the Basement geology and the regional structure must be considered at a regional scale. Different Basement lithologies weather at different rates, and have different propensities for fracturing, depending on crystal size, mineralogy (Key, 1992) and on structural setting. Hence an understanding of the geology of a region is important in developing a conceptual model of groundwater occurrence. Whilst fractures in Basement are often associated with weathering alone, tectonic activities can have a major part in especially deeper fracture development, and regional tectonism has been shown to influence borehole yields (Sami, 2009). In particular, understanding the neo-tectonic stress field and whether fractures are extensional (“open”) or compressional can be important in understanding their hydraulic properties.

1.4. Structure of the report

This report is a summary of the main findings and several interim progress reports of the WRC research project K5/1693/1 “Determining sustainable yields of potential productive well fields in the Basement aquifers of the Limpopo Province (with special emphasis on the Limpopo (WMA 1) and Luvuvhu/Letaba (WMA 2) Water Management Areas)”. Due to the nature of such a document, several specific research outcomes of the project (e.g. detailed structural, geochemical or socio-economic assessment of the study area) are only covered superficially and not in the way they deserve. More detailed interim progress reports are therefore available from the authors on request.

Following the above brief introduction to Basement aquifers, a general overview of exploration methods, groundwater development and management issues in Basement aquifers is given before the focus shifts to a description of the specifics of these aquifers in the Limpopo province. The characterization of the aquifers includes a description of typical aquifers responses to pumping tests as well as the testing of potential well fields. The comprehensive GRIP database (maintained by the Department of Water Affairs) for the Limpopo Province is analysed using a multidisciplinary hydrogeological assessment approach to identify factors controlling groundwater quantity (i.e. point values of aquifer transmissivity and borehole yield) and quality. Utilizing the insight gained from the analysis above, a conceptual model of the Limpopo Province is developed and utilised to recommend drilling targets for potential productive well fields.

2. Hydrogeological mapping and groundwater exploration in Basement aquifers

2.1. Hydrocensus/ Hydrogeological reconnaissance

The main objective of a hydrocensus of a region in the context of groundwater exploration is to characterise the physical and economic feasibility of meeting water demands through groundwater. A hydrocensus focuses therefore on a hydrogeological characterization of the aquifers rather than a sole identification of discontinuities **as well as** on socio-economic evaluations of the region. Local knowledge gained both from local people and from hydrogeologists accustomed with the area, is important and can save much time (MacDonald et al., 2005). Overlaying the different information layers like geological and structural maps, borehole yields, dry boreholes (!), historic drilling success rates and probability of exceeding specific yield, depth to groundwater and groundwater chemistry using appropriate software (e.g. GIS) will give a good first understanding of the aquifer characteristics, structural and geological influences of successful and unsuccessful boreholes as well as potential drilling targets, i.e. a basic conceptual model of the Basement aquifer(s) in the area. Furthermore, the gathered information should give a good indication of the number of boreholes that need to be drilled to meet the demand together with an idea of their localities (Sami et al., 2002).

While groundwater sampling during a hydrocensus serves primarily the assessment of the physical, organoleptic, chemical and microbiological suitability of the potential drinking water resource (SANS 241, 2006), it can add valuable information with regard to flow paths, recharge mechanisms or potential anthropogenic impacts on the water resource if a complete chemical (once-off) screening (including trace elements, hydrocarbons areas and environmental isotopes) of the water samples is performed (Hiscock, 2005).

2.2. Structural analysis

Exploration in fractured rock environments should be directed towards finding open fracture zones, where permeability is enhanced. Fracture zones are primarily structurally controlled; consequently, an understanding of the deformation events due to tectonic history forming lineaments, joints, faults, folds, synclines, anticlines or graben structures is essential to their characterization. The aim of geodynamics assessment is to highlight the relationship between secondary structures and the stress field that caused them, and furthermore to examine how the orientation of these structures might affect groundwater flow when subjected to a present day 'neotectonic' stress field. Tensile fractures caused by brittle deformation are the most hydrogeological significant types of structural expression of tectonic stress. Boreholes located in tensional zones often have a significantly higher median specific capacity than those in shears or compressional structures (Sami et al., 2002).

2.3. Geomorphologic studies

Studying the geomorphology (relationship between geology and topography together with vegetation) can be an excellent way to identify areas to site wells and boreholes. The relationship between depth of weathering and age of the erosion surface with regard to groundwater occurrence was first reported by Gear (1977) working in Zimbabwe. Jones

(1985) and Houston & Lewis (1989) made similar correlations using data from groundwater development projects in Zambia and Zimbabwe. Taylor and Howard (2000) further investigated the relationship of geomorphology and groundwater occurrence in Uganda. Later, Vegter (2000a) correlated the distribution of erosion surfaces as defined by Partridge & Maud (1987) with geological and borehole data to map zones of groundwater exploitability in South Africa. The weathering fronts associated with the different erosion surfaces would have influenced the regional groundwater levels as well as the creation of groundwater flow paths. However, it is difficult to prove that the older erosion surfaces do indeed offer a more sustainable resource unless sufficient data are available with which to make statistically meaningful comparisons. Six surfaces are recognised: Gondwana (mid to end Jurassic), Post-Gondwana (early Cretaceous), African (mid-Cretaceous to end Oligocene), Post-African (Miocene), Pliocene (Pliocene) and Quaternary (end Pliocene to the present day) (Figure 2.1).



Figure 2.1. The distribution of erosion surfaces in southern and eastern Africa (adapted from Jones, 1985; Partridge and Maud, 1987; Lister, 1976, Lister, 1987, Taylor and Howard, 2000 and UNDP, 1990).

2.4. Remote sensing

Surface and sub-surface hydrogeological features such as lithology, geological structures, geological and structural lineaments, landforms, drainage density, water bodies and weathered/fractured thickness of overburden material play an important role in groundwater recharge and flow. The idea of remote sensing methods is to identify such structures that cannot be seen in the field or have not been mapped yet (Sami et al., 2002). Remote sensing techniques include:

- Radar Image and aerial photographs
 - ▣ Excellent reconnaissance tool to map out the landforms, rivers, geological features, land use and vegetation.
- LANDSAT Imagery
 - ▣ Can be used to identify rock types, fractured zones, drainage patterns, unconsolidated deposits, vegetation patterns and lineaments (fracture, fault, dykes, sills show up as linear features).
- Airborne geophysics (Aeromagnetic survey)
 - ▣ Because different rock types differ in their content of magnetic minerals, the magnetic map allows a visualization of the upper crust in the subsurface, particularly the spatial geometry of bodies of rock and the presence of faults and folds. Aeromagnetic data maps are ideal for mapping dykes due to its magnetic signature (Figure 2.2).

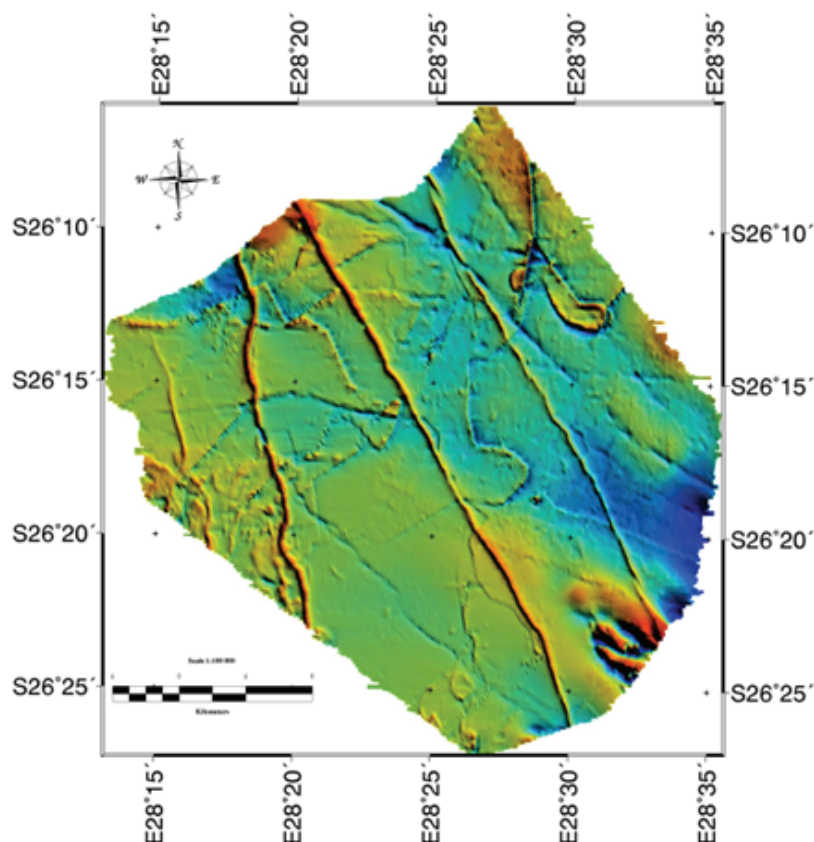


Figure 2.2. Example of an aeromagnetic image with linear magnetic dykes.

2.5. Geophysical methods

Geophysical methods are by far the most common methods for siting wells and boreholes in Basement rocks for rural water supply. The aim of geophysics is to measure the properties of rocks, making it possible to interpret the underground occurrences of joints, fractures, overburden and thus groundwater (MacDonald et al., 2005). However, geophysically-derived sites in a weathered Basement type environment can be achieved in numerous different ways (Table 1). Among the surface geophysical methods, the electrical resistivity method is commonly used, primarily for local groundwater problems, whereas gravity and seismic refraction methods are used for regional basin studies and delineation of buried river channels and valley fills (Murty and Raghavan, 2002). Magnetic surveys are particularly effective at detecting basic intrusions such as dolerite dykes, which can be associated with a groundwater resource.

Table 1. Summary of common geophysical techniques used in groundwater investigations (adapted from MacDonald et al., 2005).

Geophysical method	What it measures	Output	Approximate depth of penetration (m)	Comments
Frequency domain EM (FEM)	Apparent terrain electrical conductivity (calculated from the ratio of secondary to primary EM fields)	Single traverse lines or 2D contoured surfaces of bulk ground conductivity	50 m	Quick and easy method for determining changes in thickness of weathered zones or alluvium. Interpretation is non-unique and requires careful geological control. Can also be used in Basement rocks to help identify fracture zones.
Transient EM (TEM)	Apparent electrical resistance of ground (calculated from the transient decay of induced secondary EM field)	Output generally interpreted to give 1D resistivity profile	100 m	Better at locating targets through conductive overburden than FEM, also better depth of penetration. Expensive and difficult to operate.
Ground penetrating radar (GPR)	Reflections from boundaries between bodies of different dielectric constant	2D section showing time for EM waves to reach reflectors	10 m	Accurate method for determining thickness of sand and gravel. The technique will not penetrate clay, however, and has a depth of penetration of about 10 m in saturated sand or gravel.
Resistivity	Apparent electrical resistivity of ground	1,2- or 3-D vertical geoelectric sections	50 m	Can locate changes in the weathered zone and differences in geology. Also useful for identifying thickness of sand or gravel within superficial deposits. Often used to calibrate EM surveys. Slow survey method and requires careful interpretation.
Magnetic	Intensity (and sometimes direction) of earth's magnetic field	Variations in the earth's magnetic field along a traverse or on a contoured grid	30 m	Can locate magnetic bodies such as dykes or sills. Susceptible to noise from any metallic objects or power cables.

2.6. Drilling exploratory boreholes

Random or “wildcat” drilling in Basement commonly has success rates of around 40% or lower, unlike in other hydrogeological domains such as unconsolidated sediments where boreholes may be sited almost anywhere (unless the regolith is uniformly thick, when wildcat drilling may be much more successful). However, a less expensive way of exploration by drilling is through the drilling of narrow diameter boreholes. Trial boreholes are often used to find sites for high yielding boreholes (MacDonald et al., 2005) and are typically drilled at several sites that have been identified using other siting techniques, at sites preferred by the community or randomly within the community. Trial boreholes will give an indication of the water quality, quantity and the geology.

2.7. Multidisciplinary exploration approaches

The outcome of a hydrogeological reconnaissance study should be a basic conceptual model of the Basement aquifer(s), given a broader overview of the regional groundwater occurrence in the area. Individual boreholes will still need to be sited carefully, and this is usually done by means of geophysical techniques. One way to improve a geophysical interpretation and the confidence in borehole siting is to combine the use of maps, field observations and geophysics in a method known as geological triangulation (MacDonald et al., 2005) (Figure 2.3).

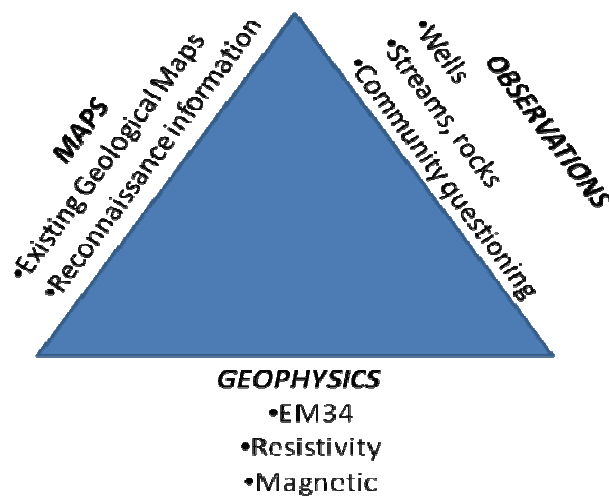


Figure 2.3. The geological triangle method (MacDonald et al., 2005).

Sami (2009) proposed a multidisciplinary exploration approach to identifying drilling targets in Basement aquifers and placed special emphasis on a comprehensive geodynamic / strain analysis, highlighting the structural control of groundwater flow in the fractured aquifer (Figure 2.4).

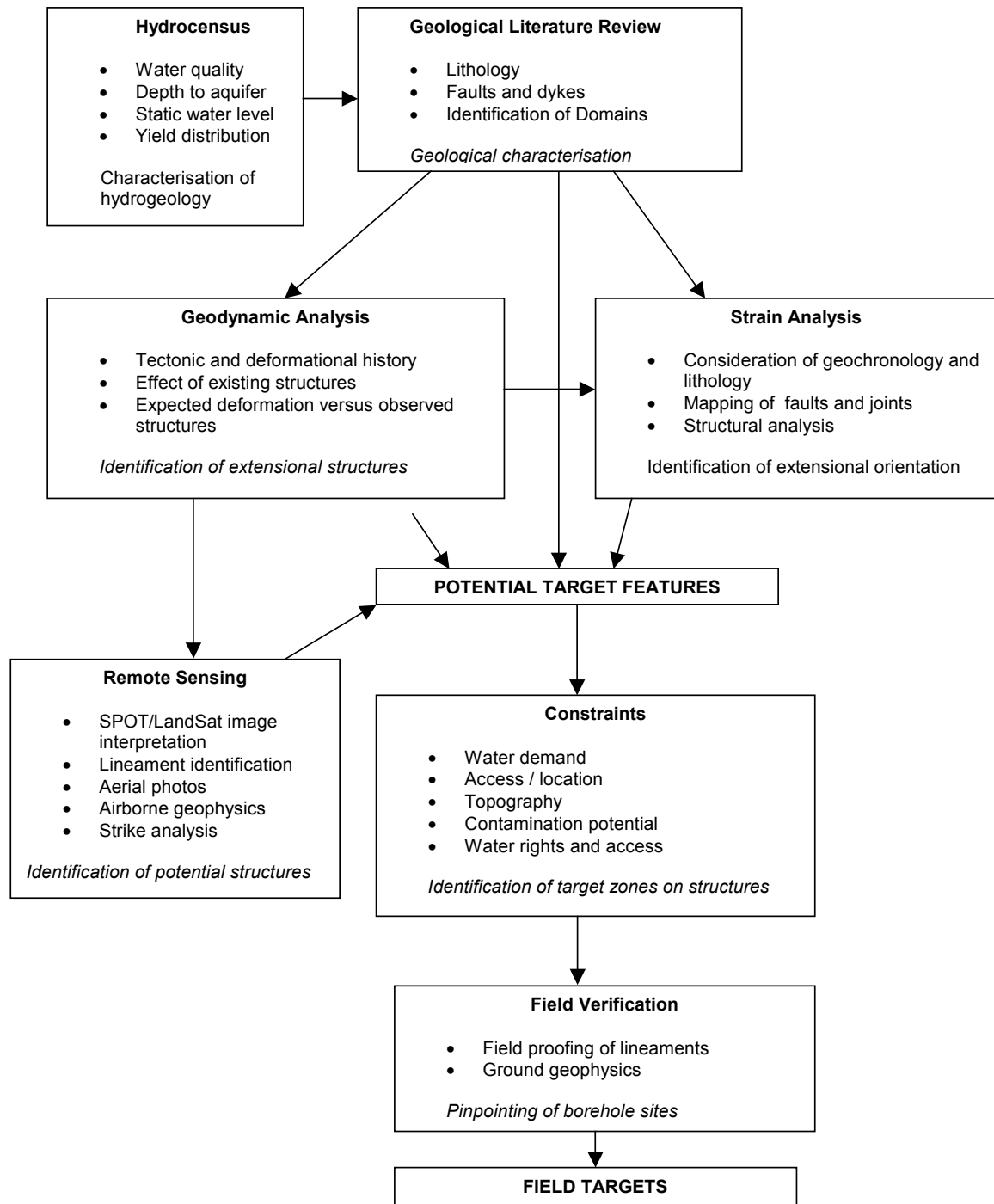


Figure 2.4. Flow chart of recommended groundwater exploration of Basement aquifers (Sami, 2009).

2.8. Groundwater recharge

Groundwater recharge in a catchment is an important parameter for a regional assessment of sustainable yields, but at the same time one of the most difficult to determine. The sustainability of a groundwater development is dependent, among other factors, on reliable recharge estimates, dominant recharge mechanisms and its spatio-temporal characteristics (Adams et al., 2004). It must however be emphasized that sustainable pumping rates of a single borehole depend more on the capture (i.e. increase of recharge and decrease of discharge due to pumping) and can be estimated without knowledge of (virgin) recharge rates (Devlin and Sophocleous, 2005). Estimating recharge in African Basement aquifers is not straightforward. Recharge is directly related to rainfall, although this relationship is not linear as shown in Figure 2.5 for southern Africa.

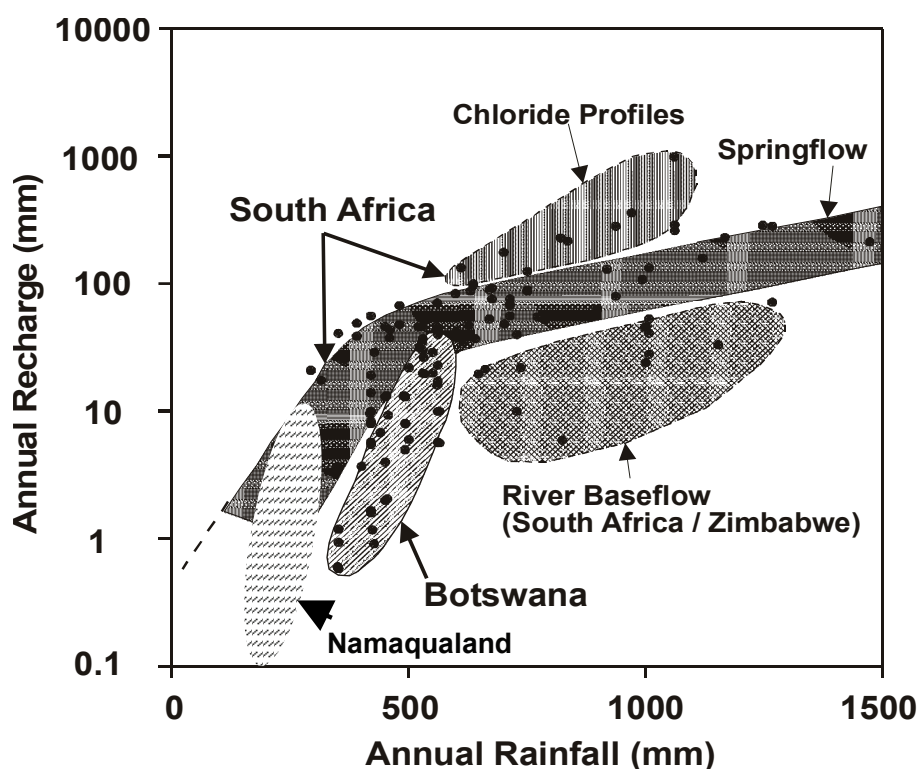


Figure 2.5. Recharge estimates for southern Africa (Gieske, 1992; Beekman et al., 1996; Beekman and Xu, 2003 and Adams et al., 2004).

Across much of southern Africa potential evaporation is higher than average annual rainfall, and recharge is likely to be episodic and often via preferred pathways rather than uniformly distributed. In many parts of southern Africa rainfall patterns are highly variable, both spatially and temporally, and it may be more useful to speak of longer wet and dry periods than annual averages, with corresponding effects on recharge.

There are as many methods available for quantifying groundwater recharge and each of the methods has its own limitations in terms of applicability and reliability (Table 2). The methods in Table 2 are grouped according to hydrologic zones, where methods referring to surface water and unsaturated zones estimate potential recharge whereas methods referring to the saturated zone estimate the actual recharge.

Table 2. Review of commonly used recharge methods for (semi-)arid southern Africa (Beekman and Xu, 2003).

Zone	Method	Limitations	Applicability ²			Rating ³		
			Flux (mm/yr)	Area (km ²)	Time (yrs)	Acc.	Ease	Cost
SW	HS	Ephemeral rivers	400-4000 (0.1-1000)	10 ⁻⁴ -1300 (10-1000)	0.3-50 (1-100)	2-3	1-2	1-2
	CWB	Inaccurate flow measurements	100-5000	10 ⁻³ -10	1d-1yr	2-3	2	3
	WM	Ephemeral rivers	1-400	10 ⁻¹ -5*10 ⁵	1d-10yr	2	2-3	3
Unsaturated ¹	Lysimeter	Surface runoff	1-500 (0-200)	0.1-30m ²	0.1-6	2	3	3
	UFM	Poorly known relationship hydraulic conductivity - moisture content	20-500	0.1-1m ²	0.1-400	3	2	2
	ZFP	Subsurface heterogeneity; periods of high infiltration	30-500	0.1-1m ²	0.1-6	3	2	2
	CMB	Long-term atmospheric deposition unknown	0.1-300 (0.6-300)	0.1-1m ²	5-10000	2	1	1
	Historical	Poorly known porosity; present ³ H levels almost undetectable	10-50 (10-80)	0.1-1m ²	1.5-50	2-3	2-3	3
Sat. - Unsat.	CRD	Deep (multi-layer) aquifer; sensitive to specific yield (S _y)	(0.1-1000)	(1-1000)	(0.1-20)	1-2	1-2	2
	EARTH	Poorly known S _y	(1-80)	(1-10m ²)	(1-5)	1-2	2	1
	WTF	In/outflow and S _y usually unknown	5-500	5*10 ⁻⁵ ->10 ⁻³	0.1-5	2	1	1
	CMB	Long-term atmospheric deposition unknown	0.1-500	2*10 ⁻⁶ ->10 ⁻²	5->10000	2	1	1
Saturated	GM	Time consuming; poorly known transmissivity; sensitive to boundary conditions	(0.1-1000)	(10 ⁻⁶ -10 ⁶)	(1d-20yr)	1-2	3	3
	SVF	Flow-through region; multi-layered aquifers	(0.1-1000)	(1-1000)	(0.1-20)	1-2	1-2	2
	EV-SF	Confined aquifer	(0.1-1000)	(1-100)	(1-100)	1-2	1-2	1-2
	GD	¹⁴ C, ³ H/ ³ He, CFC: poorly known porosity / correction for dead carbon contribution	¹⁴ C: 1-100 ³ H/ ³ He, CFC: 30-1000	¹⁴ C, ³ H/ ³ He, CFC: 2*10 ⁻⁶ ->10 ⁻³	¹⁴ C: 200-200000 ³ H/ ³ He, CFC: 2-40	3	2-3	3

HS: Hydrograph Separation – Baseflow	EARTH: Extended model for Aquifer Recharge and Moisture Transport through Unsaturated Hardrock
CWB: Channel Water Budget	WTF: Water Table Fluctuation
WM: Watershed Modelling	GM: Groundwater modelling
UFM: Unsaturated Flow Modelling	SVF: Saturated Volume Fluctuation
ZFP: Zero Flux Plane	EV-SF: Equal Volume - Spring Flow
CMB: Chloride Mass Balance	GD: Groundwater Dating
CRD: Cumulative Rainfall Departure	

¹ All methods for estimating fluxes through the unsaturated zone assume diffuse vertical flow whereas in reality flow along preferred pathways is the rule rather than the exception. These methods therefore tend to overestimate the diffuse flux.

² Data in brackets are estimates from Southern Africa; Rainfall may be up to 2000 mm/ in a year; other data represent global values and are taken from Scanlon et al. (2002).

³ Ratings for methods applied to semi-arid Southern Africa.

The evaluation of methods can be considered a follow up of the early work of Bredenkamp et al. (1995). Data for the applicability of methods are adopted from Scanlon et al. (2002) and accuracy rating from Kinzelbach et al. (2002): Class 1: difference from true value within a factor of 2, Class 2: within a factor of 5 and Class 3: within a factor of 10 or more. Ease of application is related to data requirements and data availability and is rated from 1: easy to use to 3: difficult to use. Cost is rated from 1: inexpensive to 3: expensive.

Methods excluded from the overview and review due to either an overly qualitative nature, high inaccuracy or an over-complicated method of application in the (semi-)arid environment are the rainfall-recharge relationships, soil-moisture / water budgets (Schulze, 1995), seepage meter, applied and heat tracers as well as (semi-) quantitative methods which involve ^2H , ^{18}O (Beekman et al., 1996) and ^4He (Selaolo, 1998).

In their review, Beekman and Xu (2003) recommended the CMB, CRD, EARTH, WTF, GM or SVF methods for arid and semi-arid southern Africa. Three of these methods (CMB, CRD and GM) are widely applied and represent an increasing complexity in their use and data requirements. Adams et al. (2004; 2009) developed a decision support framework for the selection of the appropriate recharge estimation method(s) in semi-arid Basement aquifers based on the availability and type of data.

3. Developing and managing groundwater in Basement aquifers

3.1. Drilling methods and borehole design

Given that nominal borehole success rates (often defined as a borehole being able to support a hand pump, a yield of roughly 0.1-0.5 L/s) are now higher than 90% in many Basement areas where proper geophysical surveys are carried out, it is considered that the constraint on exploiting the resource may be the choice of technology for abstracting groundwater (Lovell, 2007). The relative importance of the regolith and underlying fractured bedrock components of Basement aquifers depend on the particular Basement geology, tectonic history, climate and relief. Water point design (e.g. boreholes) is thus a case of ‘horses for courses’. It is site-specific and should be decided based on the depth and permeability of saturated weathering found. Lovell (2009) identified seven water point designs to cope with the highly variable ground conditions typical of Basement aquifers (Figure 3.1).

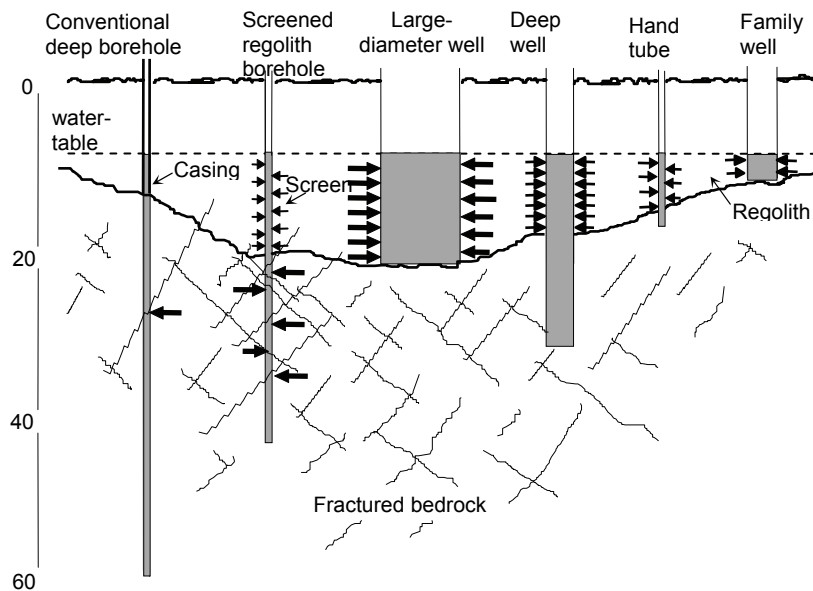


Figure 3.1. Typical water point designs for Basement aquifers (Lovell, 2009).

In South Africa conventional deep and screened regolith boreholes are the most common groundwater abstraction points used in rural water supply projects (Photo 1).



Photo 1. Borehole drilled 72 mbs and 120 mbs in the Hout River and Goudplaats Gneiss in the Limpopo Province respectively.

However, large diameter wells for water supply (operational and defunct) exist in the Basement aquifers of the Limpopo Province (Photo 2).



Photo 2. Large diameter collector wells in the Alluvium and Gneisses of the Limpopo Province.

Various drilling methods are used to construct water boreholes. By far the most common drilling technique used in South African is the air rotary percussion and down the hole (DTH) hammer (Vegter, 2000).

A borehole should be designed and constructed to fulfil the following conditions:

- Borehole efficiency is maximized
- Sand inflow to the borehole is kept to a minimum
- Materials are sufficient to last at least 25 years
- Any contaminated sources or aquifers, or zones of undesirable water quality should be sealed off from the borehole.

Although a borehole design is usually site-specific, general design criteria can be applied to Basement aquifers. Fundamental to all designs is that the soft shallow weathered zone is sealed off from the rest of the borehole. A sanitary seal consisting of cement grout followed by a few meters of solid casing is usually the simplest and most effective way of preventing contamination from shallow groundwater (e.g. pit latrines). A typical borehole design in a well-developed regolith and fractured Basement rock is illustrated in Figure 3.2.

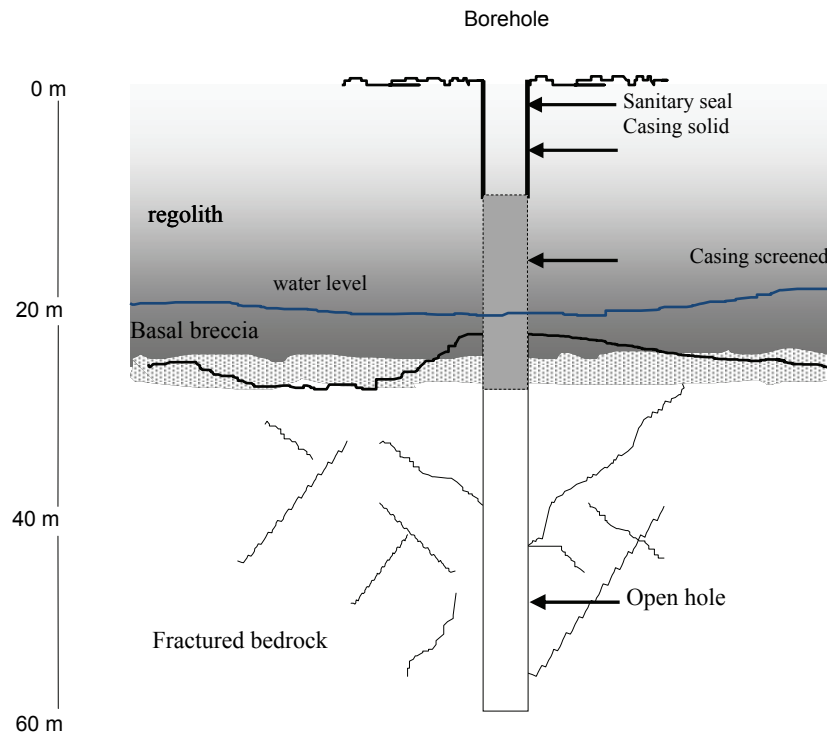


Figure 3.2. Borehole design in a typical Basement aquifer system.

3.2. Borehole development

A borehole must be developed before assessing whether it's successful or not. During the borehole development various methods (e.g. surge pumping, jetting, blowing etc.) are applied to remove drill fluids and debris (e.g. crushed rock, mud, sand, filter cake, drilling fluid etc.). This process will enhance the porosity and hydraulic conductivity around the borehole, which will improve the performance. In Basement aquifers hydro-fracturing as a development technique can be used to induce fractures and increase the well yield. Hydro-fracturing involves the injection of chlorinated water under high pressure into a short section of the open borehole isolated by packers. This method has been successfully applied to hard rock aquifers in North America, Scandinavia and Africa (Misstear et al., 2006).

3.3. Assessing the yield of a borehole

Pumping tests involve measuring the response of water-levels in an aquifer (i.e. draw-down) to controlled abstractions. The type and duration of a pumping test depends on the planned usage of the borehole, but typical tests in South African Basement aquifers include a multiple discharge test (step test), a constant discharge test and a recovery test. From the test results the aquifer (e.g. transmissivity, flow boundaries or flow regimes) and borehole (performance and efficiency) characteristics as well as an initial estimation of the sustainable or rather safe yield can be deduced. Van Tonder et al. (1998) developed the Flow Characteristic Method (FC Method, see also chapter 6.1.1) for the latter, and although it is widely accepted and used, it is often misinterpreted and its limitations are not taken into account by the user:

- The effect of boundaries can only be seen at very late times of the pumping test. This is especially important as African Basement aquifers may be better thought of as localised “pockets” (with limited spatial extent) rather than as a more uniform regional aquifer.
- The determined “sustainable” yield estimate is based on a probability of not exceeding the available drawdown, typically defined by the position of the main water strike in the borehole (known or derived from the test itself). Exceeding this position may cause a drastic decrease in yield and the borehole may dry up (Van Tonder et al., 1998). Such an approach does not follow the original sustainability concept (Brudtland, 1987), which takes environmental and social issues as well as the long-term protection of resource into account.
- The determined yield might be non-unique and dependent on the abstraction rate during the constant rate test and the extrapolation of the measured drawdown.

In crystalline aquifers short-term pumping tests (e.g. 24 hrs) may be adequate to predict the sustainability of an abstraction if the abstraction rate is small and the aquifer relatively uniform. However, the sustainability at higher abstraction rates can generally not be reliably assessed using short-term tests. The heterogeneous and discontinuous nature of Basement aquifers requires generally long term testing (e.g. 1 to 10 days) preferably with a comprehensive monitoring network to determine whether groundwater levels will stabilize during abstraction. Unfortunately most pumping tests in South Africa are single borehole tests with no observation boreholes, which raise concerns regarding the validity of recommended yields. The British Standards Institution (2003) recommends at least four observation boreholes spaced at geometrically increasing intervals along two perpendicular lines from the pumping well (Misstear et al., 2006). However, one or two strategically sited (e.g. along and perpendicular to a fracture zone) observation boreholes are economically more realistic and will suffice in most cases.

3.4. Groundwater Monitoring

Groundwater monitoring informs groundwater management on a local borehole scale (to e.g. avoid over-abstraction, see also Minimum Standards and Guidelines for Groundwater Resource Development for the Community Water Supply and Sanitation Programme, 1997) as well on a regional scale (to e.g. assess the quantity of water resources and the compliance with resource quality objectives according to the National Water Act, 1998). Despite this, monitoring of water resources and sources is often insufficient or absent due to a lack of financial resources, technical capacity or clear institutional responsibilities. However, several national DWA guidelines as well as international guidelines (e.g. ASTM standards, UNESCO, IAHS, etc.) for the development of groundwater monitoring plans are available and can be easily adapted to South African Basement terrains.

Due to the high intrinsic vulnerability of Basement rocks and potentially poor groundwater quality, monitoring of groundwater quality should be an essential component of any water supply borehole. The main objectives of groundwater quality monitoring are to document compliance with national standards or guidelines (e.g. SANS 241, 2006) and to provide both

long- and short-term data necessary to assess and predict the response of the resource quality to natural climatic variations and human-induced sources of pollution.

Groundwater level monitoring is recommended to verify if the recommended pumping rate is “sustainable” or whether the resource is being depleted. Combined water level and rainfall monitoring allows the response of an aquifer to recharge or drought episodes to be assessed.

3.5. Management of Basement aquifers

Groundwater Management issues

The Department of Water Affairs (DWA) proposed sustainability as a concept to resolve water-use issues, and it is along with equitable access to water one of the main principles of the National Water Act of 1998. In order to achieve sustainable groundwater use, the management of groundwater resources needs to balance economical, environmental and social considerations. The identified (MacDonald and Davies, 2000; Pietersen, 2004) management issues for Basement aquifers are:

- Sustainability of water sources, particularly during extended drought periods.
- Low rainfall and high evaporation rates affect recharge to Basement aquifers, resulting in slow circulation of groundwater and associated quality and quantity problems.
- The poor natural water quality of those Basement aquifers associated with low rainfall areas (high salinity), having a health impact on the affected communities.
- The vulnerability of shallow aquifers to pollution, particularly with the rapid growth in on-site sanitation and the intensification of agriculture.
- The lack of suitable institutional arrangements at the local and catchment scale hinders proper resource management.
- The relative performances and operational costs of boreholes, wells, family wells and collector wells.

Technical challenges

Groundwater in Basement rocks is particularly difficult to quantify and classify, since it does not occur in a uniform fashion (Wright, 1992). The aquifers respond discontinuously to abstraction, water levels may follow cycles related to rainfall that are considerably longer than a year, water quality and levels can vary over small areas, and borehole siting methods need to be fine-tuned for each particular location. Although Basement aquifers are typically considered low yielding, there is an increased interest in higher yielding boreholes, which will inevitably require a considerably greater understanding of the aquifer if they are to be utilised sustainably.

Recharge to Basement rocks is not easy to quantify, yet will need to be better understood in the context of climate change. Water points should be sited with prime regard for long periods of reduced recharge – experience in Zimbabwe has shown that expertly sited Basement water points can be “immune” to the harshest drought (Lovell, 2007). South African legislation now provides for the basic water needs of the environment as part of the Reserve, and more research needs to be done to determine how much water needs to be allocated for this need.

At the root of many of the technical problems of management lies the issue of data. The more complex the aquifer system, the more data and the denser the data networks need to be to

compensate. Knowledge is needed to mitigate risk, and if greater economic potential is to be realised from Basement water resources (e.g. irrigation or industrial use) the requirement to reduce risk grows.

Social and institutional challenges

In a sense, siting boreholes in Basement rocks that yield good water is the easy part. Much more difficult is keeping them operating, and this is by no means only a technical issue. Involving the end users of water points in the groundwater development plan and taking into account the preferences and real needs of communities is regarded as key for sustainable rural water supply programmes. However, without training and awareness of groundwater resources at local scale and with limited capacity within District Municipalities authorised as Water Services Authorities (WSA), this approach is bound to fail. Provision of water services is no simple task and to expect the community (village) to take responsibility for their water supplies in contrast to urban areas, which are serviced by bulk water suppliers, remains questionable. Rural councils or village water committees often need considerable assistance with water supply or management responsibilities.

Groundwater management approaches

Management strategies are required to address the unique characteristics and functions of groundwater in Basement aquifers, without neglecting socio-economic developmental targets. The need for an integrated approach to the management of Basement aquifers has been shown by various authors (e.g. Moriarty, 2000; UNEP, 2003; Pietersen, 2004) and the objectives should be to:

- Determine the sustainable yield of the aquifer systems and to develop policy and strategies for groundwater management at community and catchment scale.
- To protect the aquifer from possible pollution risks such as improper location of pit latrines and indiscriminate disposal of waste.
- To protect the communities from poor quality groundwater.
- To establish mechanisms for communities to participate in a meaningful way – they need to be well informed as regards the functioning of their water resources systems and likely consequences of their decisions.
- Develop appropriate monitoring and evaluation systems for resource sustainability as well as delivery and proper operation and maintenance of installed systems.

Framework for the management of Basement aquifers

Groundwater resource management has to deal with balancing the exploitation of a complex resource (in terms of quantity and quality) with the increasing demands of water and land users (who can pose a threat to the resource availability and quality). The proposed groundwater management framework of Basement aquifers is presented in Figure 3.3.

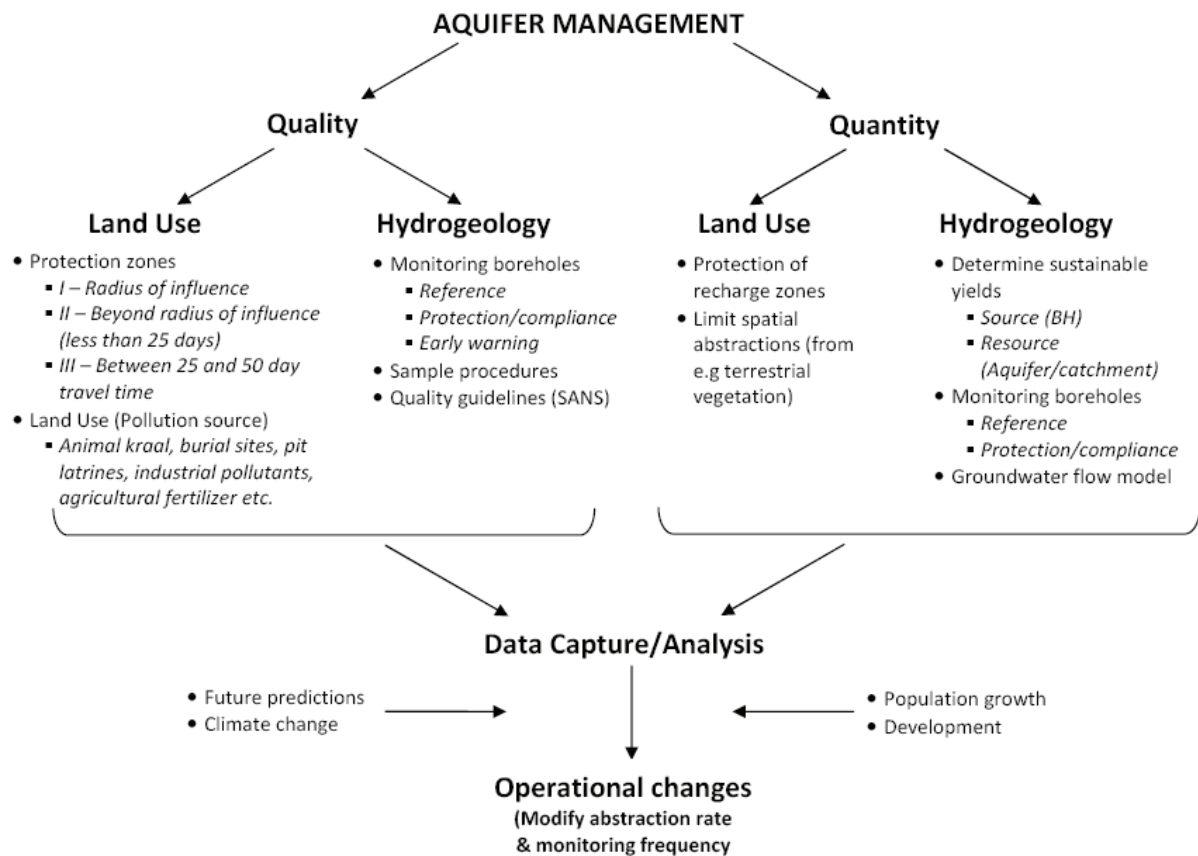


Figure 3.3. Groundwater Management for Basement rock aquifers.

4. The economic value of groundwater to rural households and agriculture

4.1. Introduction

South Africa is a dry, water scarce country and it seems probable that water shortages will redirect economic development (Nieuwoudt et al., 2004). Water scarcity has its roots in water shortage, and it is in the arid and semiarid regions affected by droughts and wide climate variability combined with population growth and economic development (like South Africa), that the problems of water scarcity are most acute (FAO, 2008). According to the United Nations Development Programme (UNDP, 2006), the roots of the crisis in water can be traced to poverty, inequality and unequal power relationships, as well as flawed water management policies that exacerbate scarcity.

Groundwater is usually considered as a good that is impossible to value or as a “free” good (Young, 2005). Market prices upon which to base groundwater-related resource allocation decisions are seldom available (Young, 1996). The resulting under-valuation of groundwater fosters misallocation in two ways: firstly the groundwater resource is not efficiently allocated relative to alternative current and future uses; and secondly authorities responsible for resource management and protection devote inadequate attention and funding to maintaining groundwater resources. The economic valuation of groundwater is needed to prompt water authorities to devote adequate attention and funding to the maintenance of groundwater quality and quantity.

The presented study investigates some of the typically irrigated field crops in Limpopo. It is in groundwater intensive sectors like agriculture where a relatively small change in policy is expected to have a significant impact on usage. Irrigation is the biggest consumer of groundwater in the study area, accounting for almost 75% of the total groundwater use. The study also investigated the value of existing and potential groundwater usage in rural households. According to DWAF (2008b) there are an estimated 251 806 households with access to water supply that is below the Reconstruction and Development Programme (RDP) service level and an estimated 665 769 households with access to sanitation levels below the RDP target in Limpopo Province alone. The current estimated number of households with no access to any form of formal water infrastructure in Limpopo is 65 129.

4.2. Research methods

4.2.1. Households

Following the approach taken by Thomas and Syme (1988), an interview survey and a statistical analysis of the results of the survey was undertaken for this study. Scoping field trips to the study area revealed that groundwater was the dominant water source in the following focus areas: In WMA1 there was the rural area between Dendron and Gilead and in WMA2 there was the rural area between Mooketsi and Elim. In WMA1, four villages were identified for more intensive surveying, namely Gaphago, Leokaneng, Kanana and Mohlajeng. In WMA2 three villages were selected, namely Lemondokop, Sereni and Hamashamba. Household surveys were conducted using a systematic random sampling

approach. The Contingent Valuation (CV) method was used to determine the willingness-to-pay (WTP) for assured water supply and sanitation (WSS) and the responsiveness of household groundwater use to tariff changes. Open ended questions were used. The WTP value represents the utility value (value in use) of groundwater to rural households.

4.2.2. Agriculture

Table 3 shows the horticultural area planted and volumes of production in Limpopo in the early 2000s. The centre of table potato production is Polokwane (Table 3), while the centre for tomato production is Mooketsi (Letaba in Table 3). The table potato hectrage and yield of Polokwane was 2 550 hectares and 71 893 metric tons respectively. The tomato hectrage and yield of Mooketsi was 3 259 hectares and 155 355 metric tons respectively. A total of three group discussions with farmers were conducted in July 2008 to develop data for a typical table potato and tomato farm. A questionnaire focussed on farm inputs and costs was used to assist during the group discussions.

Table 3. Horticulture area planted and volume of production in Limpopo (Statistics South Africa, 2002).

District	Crop			
	Table potatoes		Tomatoes	
	Planted (hectares)	Production (metric tons)	Planted (hectares)	Production (metric tons)
Dzanani	0	0	0	0
Ellisras	65	926	22	1260
Giyani	0	0	162	2335
Letaba	128	5100	3259	155355
Messina	278	6501	859	45847
Mhala	0	0	14	420
Mutale	0	0	41	591
Phalaborwa	0	0	46	942
Polokwane	2550	71893	115	4319
Potgietersberg	575	10299	128	2416
Soutpansberg	865	27418	180	5997
Thabazimbi	4	76	27	572
Warmbad	444	12210	36	2050
Waterberg	270	4746	81	2531
Limpopo Total	5179	139169	4970	224635

The group discussions provided the following typical farm data: farm size and structure, cropping composition and pattern, capital investment, borrowed capital outlay, gross production values, costs and crop water requirements and borehole data. This information was used to develop a linear programming (LP) model that was used to run parametric LP simulations. Optimal solutions were obtained using variable yield and producer price parameters.

4.2.3. Groundwater valuation

Effective groundwater management is contingent upon sound economic valuation of groundwater resources. To transform the concept of welfare into a single metric, the suggested measuring rod is that of money (Rhoads, 1985). A person's welfare change from

some promised improvement is measured as the maximum amount of money a person would be willing to forego to obtain the improvement. Established market prices are weak in capturing such hidden values. Economic valuation relies on a range of non-market economic valuation techniques such as an estimation of the degree to which people are willing to pay for benefits (Young, 1996). Economic value is different from price. Price does not in general measure economic value, and items with no market price can still have a positive economic value. This was first pointed out by Dupuit (1844) and Marshall (1879), but it took until the 1970s for this to become well accepted within modern economics (Hanemann, 2005).

This gives a distinction between economic value (value in use) and price (value in exchange). In most policy-related applications of economic valuations involving water, the relevant quantity that needs to be known is the marginal value rather than the average or total value of water. Precisely because water is a necessity of life, most people have some access to some water, and most policy interventions therefore involve changing the quantity and/or quality of access rather than transforming the situation from no access to some access. The point is that, *ceteris paribus*, there is likely to be some degree of diminishing marginal utility for consumers, and diminishing returns for producers, which imply that there can be a substantial difference between the marginal value of an increase in water supply and its average value. This needs to be emphasized because researchers have often incorrectly chosen to use an estimate of the average value of water to measure the benefits of a policy intervention (Hanemann, 2005).

The contingent value (CV) method has been elected as the approach to be used in determining willingness to pay (WTP) in the case of direct users of water such as households. The WTP concept generally refers to the economic value of a good to a person (or a household) under given conditions. Net economic benefits of improved water supply and sanitation (WSS) services, in simple terms, are estimated as the difference between the consumers' maximum WTP for better services and what is actually paid, which may or may not be different from the cost of the service (Gunatilake et al., 2007). Contingent value elicitation questions can be of two basic forms: open-ended or closed-ended. In an open-end question, the respondent is asked to state the maximum amount that he or she is willing to pay for the good that is being valued. With a closed-ended CV question (also referred to as a "dichotomous choice" or "referendum" question), the respondent is asked whether he or she is willing to pay a specified amount presented as the value of the improved service. The respondent is expected to answer "yes" or "no." Closed-ended questions have been the preferred form of elicitation question since it was introduced by Bishop and Heberlein (1979). On the other hand, open-ended questions provide more information than closed-ended questions; and do not require econometric modelling to analyze, as the mean WTP values of respondents can be readily estimated by simple arithmetic. However, answering an open-ended question on a new commodity requires a higher level of cognitive demand on the part of respondents, because individuals are typically not accustomed to performing such tasks in daily life decision-making (Gunatilake et al., 2007).

Typical farm crop budgets can be used in a process to estimate the maximum net revenue share of the water input, thus bypassing the need for a physical productivity measure. The

total crop revenue less non-water input costs (explicit and implicit) is a residual, the maximum amount the farmer could pay for water and still cover costs of production. It thus represents the on-site value of water. If water procurement costs are further subtracted, the net value for irrigation is then comparable to in-stream water values (Gibbons, 1986). Linear programming (LP) analysis was done on data from typical farms to determine irrigation water values. For the calculation of irrigation water values, the LP objective is to maximize net returns for a typical farm of specified acreage, subject to constraints which may be economic, institutional or physical, such as acreage limitations for each crop, input costs per unit, available technology, constant water requirements set for each crop, crop prices, and so forth. LP analysis is useful to estimate marginal values for irrigation water on a representative farm. Instead of water costs, water supply is varied and an LP solution is found for each quantity of water available to the farm, all other constraints remaining constant (Gibbons, 1986). Groundwater valuation is key in determining tariffs that send a clear and simple signal to consumers to encourage them to rationalize their demand for water. A low price gives the impression that there is an inexhaustible availability of water and reduces the economic justification for efforts to contain consumption. This leads to misallocation and misuse of the resource. At the same time, a price that is too high departs from the Pareto optimum because it unduly limits the consumption of an available resource, reduces user satisfaction and penalises the poor segments of society (Baroudy et al., 2005). As such, groundwater management policies need to strike a balance between economic efficiency and social equity goals within the environmental limits set by the availability of the resource.

4.3. Results and discussion

4.3.1. Households

According to Statistics SA (2004), the number of households in the Limpopo Province was 1 283 000 and approximately 85% of these were rural based. A total of 106 sampled households in the seven selected villages represented a small percentage of all rural households. The study results are therefore not representative for the entire province and can only be used as indications of value based on a site-specific analysis. Table 4 gives a definition of the terms that were used to describe household groundwater use characteristics.

Table 4. Free basic water data definitions (DWAF, 2008a)

No infrastructure	No access to any infrastructure.
Below RDP	Access to infrastructure below RDP standard e.g. pipe > 200 m from dwelling.
At RDP	Infrastructure necessary to supply 25 litres of potable water per person per day.
Above RDP	Households have access to in-house or in-yard water supply connections.

Households in the study area were observed to range between the ‘No infrastructure’ and the ‘At RDP’ levels of WSS service. Only communal standpipes were observed in the survey, and in limited cases the standpipe fell ‘in-yard’, but the reticulation pattern was that of communal taps. No ‘in-doors taps’ were observed. The communal standpipes were all DWAF installations and all households enjoyed a free basic supply at no charge. In some cases only a minimal charge was paid for repair and maintenance of the system. Although DWAF’s basic

water was free of charge, supply was chronically short in most villages because the pumping infrastructure could not satisfy water demand and as such water rationing was the norm. This caused the existence of an informal local water market that desperate water seekers would rely on in times of need. Residents with tanks and/or own boreholes were observed to collect water for speculation purposes, and these agents served as the water suppliers on informal local water markets.

There is a clear correlation between education levels and being aware of the potential threats from groundwater abuse. A higher education level was also found to be correlated with valuing groundwater services like dish washing and laundry, probably because the more educated were more health conscious. Larger household units tended to value household water services more than the single and smaller units respectively. Higher income households valued water for car washing more than the poor. They also consumed more water per capita per month, and they prioritised preservation of groundwater less than poorer households.

The more water stressed villages were found to value groundwater services more than the villages which were better endowed with groundwater resources. The former villages were also observed to travel greater distances on average to access water, and they were found to pay for their water, while those that got water nearer generally enjoyed free water. Borehole owners were found to travel shorter distances to get water than non-borehole owners. Borehole ownership was found to guarantee water availability, and owners generally did not buy water, except in instances of borehole breakdowns. Borehole owners also consumed more water per capita per month, which shows that they had access to more water per capita than non-borehole owners.

Table 5 shows the average per capita monthly water consumption by village. The highest per capita monthly water consumption was 922 litres per person per month in Gaphago village (which reported much better water availability), while the lowest per capita monthly water consumption was 546 litres per person per month in Lemondokop village (which reported a worsening of water availability). The overall mean per capita monthly water consumption for the selected villages was 761 litres per person per month or 25 litres per person per day.

Table 5. Per capita water consumption by village.

Village	Mean per capita monthly water consumption (litres)	Mean per capita daily water consumption (litres)
Gaphago	922.00	30.20
Loekaneng	840.00	27.50
Mohlajeng	810.00	26.60
Kanana	805.00	26.4
Mashamba	728.00	23.9
Sereni	675.00	22.10
Lemondokop	546.00	17.90
Total	761.00	25.001

Note: The infrastructure necessary to supply 25 litres of potable water per person per day indicated service level 'At RDP' level by DWAF standards.

Households prioritise groundwater for drinking, cooking, bathing, dish washing, hand laundry, washing floors, gardening, and for livestock watering in descending importance respectively (Table 6).

Water for outside cleaning and car washing was found to be of very limited importance. Water for toilet flushing, machine laundry, and showering was not important at all in the study area. The importance of groundwater was measured on a scale from one to ten, where one represented “not important at all” and ten “extremely important”.

Table 6. Importance and priority of groundwater uses.

Groundwater use	Importance mean weight	Weight description	Rank
Drinking	9.99	Extremely important	1
Cooking	9.99	Extremely important	1
Bathing	9.50	Extremely important	3
Dish washing	8.50	Quite important	4
Hand laundry	8.40	Quite important	5
Washing floors	6.80	Important	6
Garden watering	2.67	Limited importance	7
Livestock watering	2.25	Limited importance	8
Outside cleaning	1.40	Very limited importance	9
Car washing	1.40	Very limited importance	9
Machine laundry	1.00	Not important at all	11
Toilet flushing	1.00	Not important at all	11
Showering	1.00	Not important at all	11

70% of sampled households were found not only to be currently paying for water, but paying for it at exorbitant rates because of the informal water market (on average R40.00 per kl of groundwater), while only 30% were getting water for free. Lemondokop reported the highest average tariff (R83.33 per kl), while Leokaneng enjoyed the average lowest tariff (R8.00 per kl).

An important finding is that households are indeed willing-to-pay for assured groundwater delivery (Table 7). The highest observed WTP was R3.46 per kl of water in Kanana village (which reported much worse water availability over five years). The lowest observed WTP was R1.77 per kl of water in Gaphago village (where no water availability problem was reported). The overall mean WTP for assured household groundwater supply and sanitation for the study area was R2.28 per kl of groundwater. The difference in households’ WTP for water was not found to be statistically significant. Villages were also observed to be significantly different in how their households responded to change in water tariffs. Despite there being a statistically significant difference in responsiveness between village households, all the villages were observed to be overall unresponsive to tariff change because all the observations were nearly perfectly inelastic (elasticity was approximately zero).

Table 7. Household Willingness to Pay (WTP) for water by village.

Village	WTP (ZAR/kl)		
	Mean	Std. Dev.	Std. Error
Mashamba	2.32	1.65	0.30
Sereni	1.84	1.47	0.38
Lemondokop	2.67	1.72	0.44
Kanana	3.46	1.36	0.43
Mohlajeng	2.20	0.95	0.30
Gaphago	1.77	1.75	0.55
Loekaneng	1.84	1.47	0.38
Total	2.28	1.57	0.15

It should be noted that DWAF tap water was not levied and all villagers enjoyed free basic water from the DWAF standpipes. It was only in the case of water shortages that villagers were observed to buy water on the informal market as a last resort. Hence, naturally villagers were unwilling to pay tariffs that were much above zero (free water) for the DWAF tap water. This explains why the WTP tariffs for the DWAF service delivery were comparably lower than the exorbitant informal tariffs.

The DWAF survey of Limpopo recorded a minimum tariff of ZAR1.55/kl to a maximum of ZAR6.16/kl for the first tariff block (after free basic water) (DWAF, 2007). The average WTP value of groundwater falls within the range of Limpopo tariffs for the first tariff block.

4.3.2. Agriculture

A matrix for parametric LP is the same as for LP with the only difference that one or more parameters in the matrix are allowed to vary (Barnard and Nix, 1979). Crop yield level and unit producer price were the respective variable parameters in tomato and table potato production. The shadow value of irrigation groundwater was observed to rise with rising producer prices and rising yields per hectare. The detail given in Table 8 presents the results of the LP model found in this study. The ‘variable’ column represents the parametric element of the LP, where prices and yields were varied for tomato and table potato production, respectively.

The MVP of irrigation water represents the “true” economic value of an additional unit of irrigation water to a farmer. It represents the “economic value in use” to the farmer and in economic terms. The willingness to pay for an additional unit of irrigation water can be inferred from the imputed shadow value (MVP) of the water to the farmer. Generally speaking, this additional unit of water would in turn produce additional agricultural output, whose value is dependent upon the type of crop grown and the producer price that is specific to the region (Jabeen et al., 2006).

According to Table 8 in typical tomato production, the MVP of irrigation groundwater ranged from R0.58 to R10.38 per m³/a for producer price changes from R1.60/kg to R2.89/kg, and from R2.89 to R10.38 per m³/a for yield changes from 20 000kg/ha to 70 000kg/ha. In typical table potato production, the MVP of irrigation groundwater ranged from R0.42 to R8.50 per m³/a for producer price changes from R1.45/kg to R2.42/kg, and from R2.11 to R5.92 per m³/a for yield changes from 25 000kg/ha to 50 000kg/ha. A literature review on MVP in South Africa revealed that quite a number of the studies obtained MVP results for surface water that were less than R1.00/m³/a. Notable exceptions are presented in Williams et al. (2008), Louw (2002), and Backeberg (1996) whom all reported economic values of water in agriculture higher than R1.00/m³/a. When compared to the existing literature, the results in this study on the shadow value for groundwater are on the higher side and might reveal a tendency towards higher values of water in agricultural production.

Table 8. Linear programming shadow values of groundwater in typical tomato and table potato farms in Mooketsi and Polokwane areas respectively (2008).

Crop	Variable	Constant	MVP (ZAR/m ³ /a)	Reward to groundwater (ZAR/a)
Tomato	R2.89/kg	70 000kg/ha	10.38	689 746.50
	R2.50/kg	70 000kg/ha	5.83	-948 253.50
	R2.40/kg	70 000kg/ha	4.67	-1 368 257.00
	R2.00/kg	70 000kg/ha	3.50	-1 788 254.00
	R1.80/kg	70 000kg/ha	2.33	-2 208 254.00
	R1.70/kg	70 000kg/ha	1.16	-2 628 254.00
	R1.60/kg	70 000kg/ha	0.58	-2 838 254.00
	70 000kg/ha	R2.89/kg	10.38	689 746.50
	60 000kg/ha	R2.89/kg	8.90	155 746.50
	50 000kg/ha	R2.89/kg	7.42	-378 253.50
	40 000kg/ha	R2.89/kg	5.93	-912 253.50
	30 000kg/ha	R2.89/kg	4.45	-1 446 254.00
	20 000kg/ha	R2.89/kg	2.89	-1 980 254.00
Table potato	R2.42/kg	50 000kg/ha	8.50	628 932.20
	R2.11/kg	50 000kg/ha	5.92	-146 067.70
	R1.80/kg	50 000kg/ha	3.33	-921 067.80
	R1.70/kg	50 000kg/ha	2.50	-1 171 068.00
	R1.60/kg	50 000kg/ha	1.67	-1 421 068.00
	R1.50/kg	50 000kg/ha	0.83	-1 671 068.00
	R1.45/kg	50 000kg/ha	0.42	-1 796 068.00
	50 000kg/ha	R2.11/kg	5.92	-146 067.70
	45 000kg/ha	R2.11/kg	5.33	-323 567.70
	40 000kg/ha	R2.11/kg	4.73	-501 067.70
	35 000kg/ha	R2.11/kg	4.14	-678 567.80
	30 000kg/ha	R2.11/kg	3.55	-856 067.80
	25 000kg/ha	R2.11/kg	2.11	-1 033 568.00

The last column of Table 8 represents the optimal solutions for the selected crops, it is the total gross margin above specified costs (TGMASC). When TGMASC is negative, it reflects that the typical producer may produce at that constraint level in the short-run, but he may not be able to produce in the long-run. The farmer can cover the TVC, but may not be able to cover the total costs of production. A positive objective function value shows that the farmer is able to cover his total costs at that level of production.

The shadow values determined in this study could be used as a guide for the value of groundwater during tariff determination because of the limited role played by market forces in the allocation of groundwater.

4.4. Conclusions

Groundwater is an economically valuable resource to both rural households and to commercial agriculture in the Limpopo Province. Poor, rural households themselves attach significant economic value to role of groundwater in the assured provision of water supply and sanitation services. The erratic supply of free water services by government in rural villages has sparked an informal market in water at exorbitant prices. This reaffirms the statement that some of the world's poorest people are paying some of the world's highest prices for water. Poor, rural households in Limpopo are willing to pay for water at levels that are in the range of DWAF's own water tariffs.

For irrigated agriculture, the shadow value of groundwater for tomatoes and potatoes range between R0.42 to R10.38 per m³/a depending on yields and prices. This is on the higher side of most comparable studies on the economic value of water used for irrigation in South Africa. The large range in shadow economic values for irrigation water suggests possible gains from improved water allocation to highest productive uses, but more research on specific agricultural production systems and the possibility to trade in groundwater is required, both temporally and spatially. It is recommended to do further sensitivity analysis when determining irrigation shadow values for particular regions, types of crops and times of production. A model that incorporates parametric changes will yield better groundwater management inputs than those relying only on static recommendations only.

Water authorities have an important role to play in facilitating the allocation of groundwater to its most economically productive and socially desirable uses within the biophysical limits of the groundwater resource itself. It is important to establish people's own willingness to pay for improved groundwater provision and shadow values of groundwater use for irrigation as an input in this decision making process. It is expected that the tangible economic values for groundwater reported in this study will support the argument to develop more sustainable groundwater management systems to the socio-economic benefit of rural households and agricultural users in the Limpopo Province.

5. Basement aquifers of the Limpopo Province

5.1. Physiography

The Basement aquifers of the Limpopo Province underlie parts of the Limpopo (WMA 1) and the Luvuvhu and Letaba (WMA 2) Water Management Areas (Figure 5.1). The Limpopo basin is shared between South Africa, Botswana, Zimbabwe and Mozambique, and occurs in the northernmost portion of the country. It is bounded by the Limpopo River (running through the catchment) to the north, as well as the Luvuvhu and Letaba, Olifants, and Crocodile (West) and Marico WMAs (DWAF, 2003a). The Mokolo, Lephhalala, Mogalakwena, Sand and Nzhelele Rivers are major rivers in the Limpopo catchment. Two main perennial rivers flow through the Limpopo WMA project area: the Mogalakwena River which flows through the western side of the study area, and Sand River which flows through the eastern side of the study area (Du Toit, 2003). A number of smaller tributaries are also present. All of these rivers flow towards the Limpopo River in the north. The Limpopo River flows eastwards and eventually reaches the Indian Ocean in Mozambique (DWAF, 2003a).

The Luvuvhu and Letaba WMA is in the north-eastern corner of South Africa within the Limpopo Province, bordering on Zimbabwe in the north and Mozambique in the east. It also falls within the Limpopo River Basin shared by South Africa, Botswana, Zimbabwe and Mozambique. Approximately a third of the land area of the WMA falls within the Kruger National Park. The two main perennial rivers in the Luvuvhu/Letaba WMA project area are the Groot Letaba River and Klein Letaba River. Both of these rivers flow through the central part of study area. A number of non-perennial rivers flow through both the Limpopo and Luvuvhu/Letaba WMAs project areas.

The Limpopo WMA is characterised by subtropical temperatures. Seasonal summer rainfall is characteristic of the area with mean annual rainfall of less than 300 mm per annum in the Lowveld region to 1 000 mm per annum along the western escarpment (DWAF, 2003b).

The landscape of the Limpopo WMA is predominantly flat to rolling. The two major topographic features are the Waterberg in the southern portion and the Soutpansberg in the northeast portion (DWAF, 2003a). The topography, north of Polokwane, is relatively flat lying apart from the Blouberg and Soutpansberg areas in the northern part of the study area. The average elevation in the central part of the Limpopo WMA project area is between 400 and 800 metres above sea level and between 1200 and 1600 metres above sea level at Blouberg and Soutpansberg areas (Alberts, 1985).

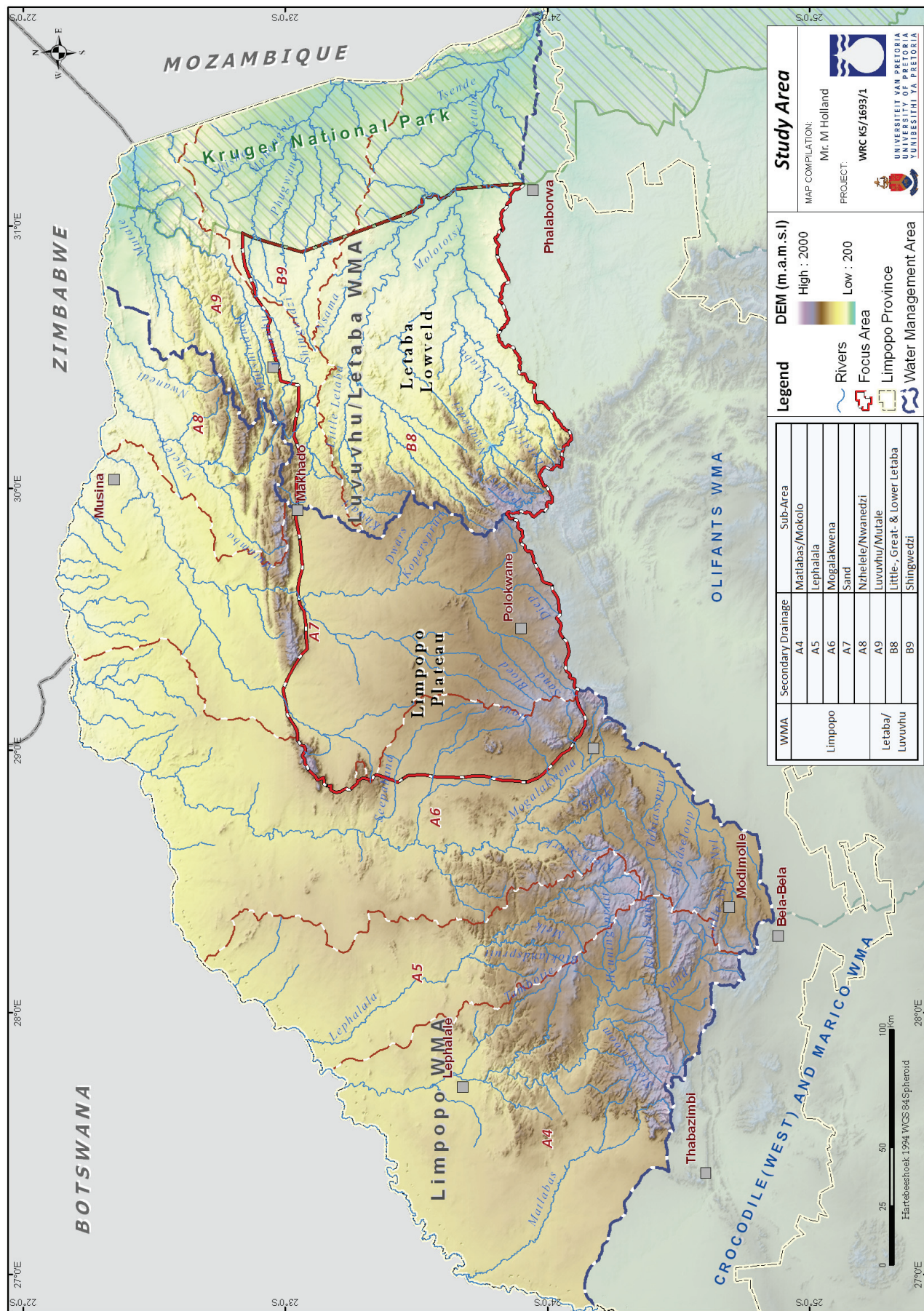


Figure 5.1. Study Area.

The Levuvhu-Letaba WMA has the Drakensberg range and eastern Soutpansberg in the western parts of the catchment with the Lowveld east of the escarpment (DWAF, 2003b). The topography between Tzaneen and Louis Trichardt in the central, north- and south-eastern parts is low-lying with an average elevation of between 200 and 400 metres above sea level. In the western part of the Luvuvhu/Letaba WMA project area the elevation is between 400 and 800 metres above sea level. To the south, near Tzaneen, the elevation increases up to 1600 at Magoebaskloof and Duiwelskloof (Du Toit, 2003b). Large portions of the WMA fall within conservation areas, including the Kruger National Park. Intrusions are observed in both WMAs and form pronounced dome-shaped koppies (inselbergs). Vegetation is mainly grassland (savannah), bushveld shrubbery and trees (DWAF, 2003b).

5.2. Recharge

Groundwater recharge in the Limpopo WMA is approximately 702 million m³/a (assuming recharge being 2% of mean annual precipitation (MAP) and 376 million m³/a in the Luvuvhu/Letaba WMA (2% to 3% of MAP). The distribution of recharge based on the GRA II dataset is presented in Figure 5.2. The GRAII dataset is based on the chloride method and adjusted to account for:

- Depth to groundwater table
- Soil drainage rate
- Rainfall season
- Geology / Landcover
- Topography as represented by slope
- Coefficient of variation of annual precipitation

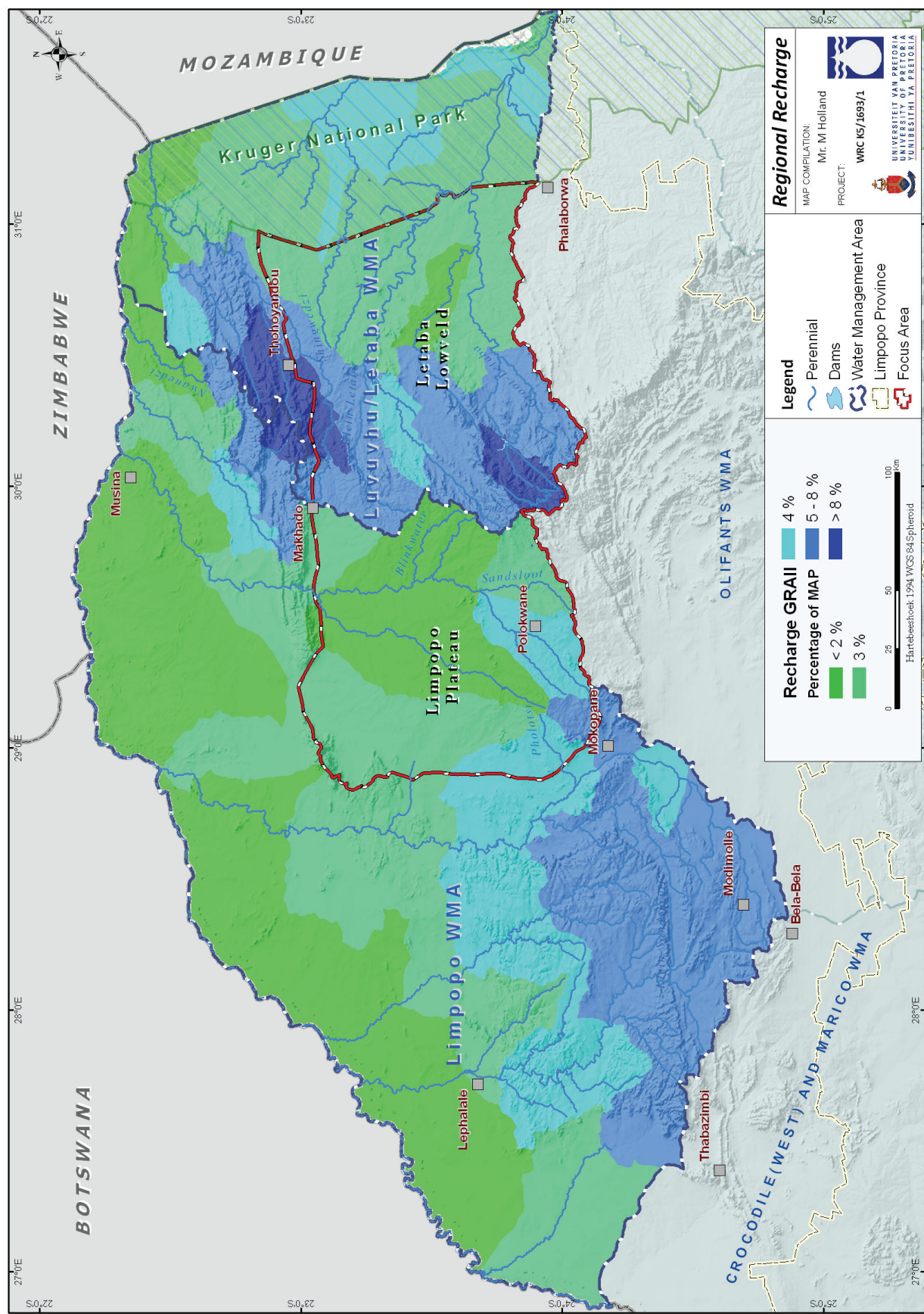


Figure 5.2. Regional recharge map for the Limpopo Province.

5.3. Geomorphology

Although the age of a land surface by itself is not an indication of the water bearing properties of the weathered zone, the factors controlling the nature and thickness of the weathered zone are partly determined by its geomorphologic history. The subcontinent has been subdivided into a number of denudational land surfaces of differing age. Tectonic movements and sea level changes initiated the onset of each erosion cycle due to a new set of base levels (Partridge and Maud, 1987). King (1975) recognised the following geomorphic cycles and their approximate inception ages: Gondwana (190 Ma), Post-Gondwana (135 Ma), African (100 Ma), Post-African (20 Ma), Pliocene and Quaternary (2 Ma). The erosion surfaces of southern Africa investigated by Partridge (1998) are presented in Figure 5.3

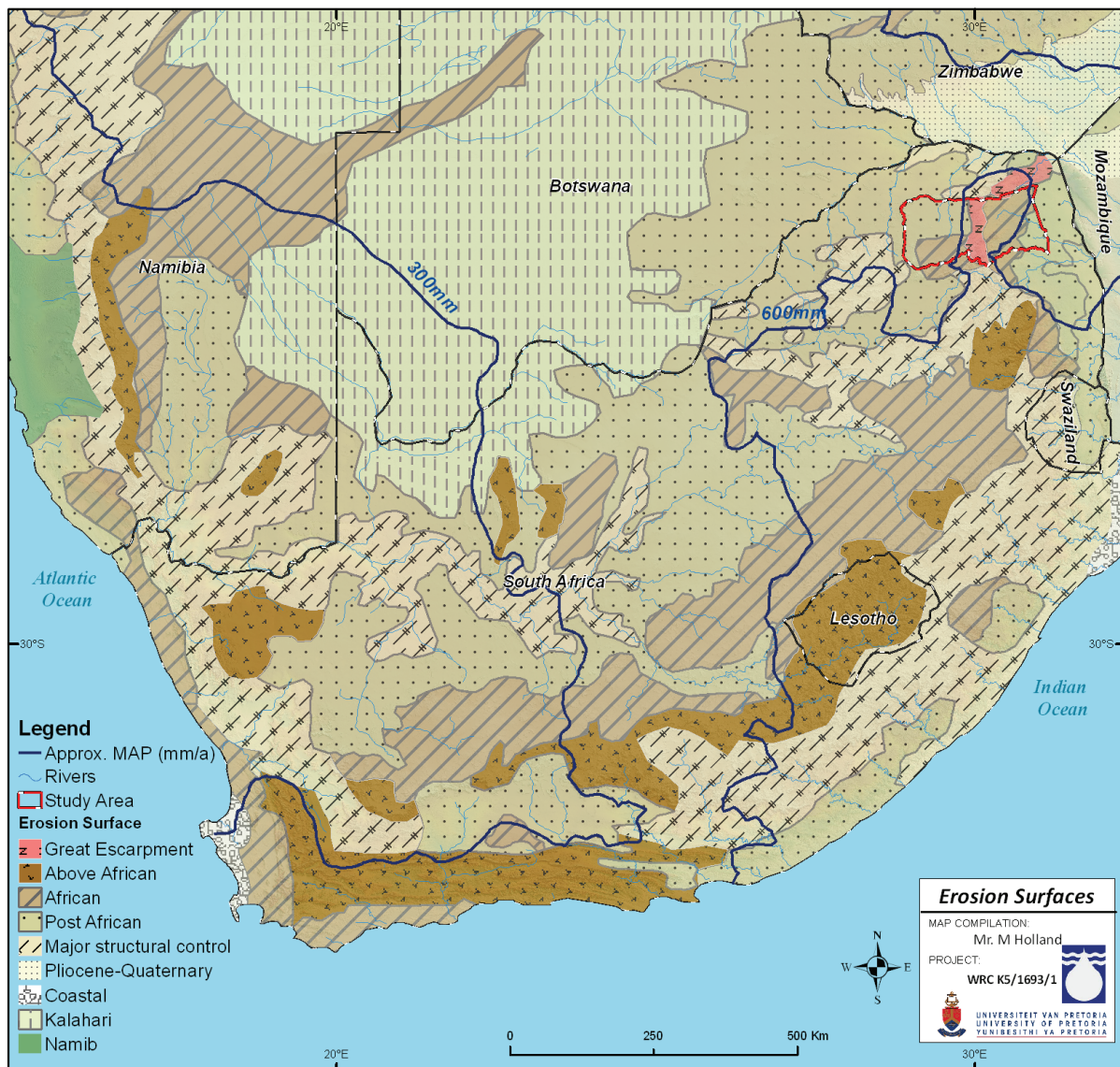


Figure 5.3. The distribution of erosion surfaces in southern Africa (adapted from Partridge, 1998; Taylor and Howard, 1999).

The geomorphic development of the subcontinent resulted in the Karoo cover being stripped and the subsequent superimposing of drainage systems onto the underlying geological

formations. The study area is largely situated on the African surface in the east and the Post African surface in the west (Figure 5.3). These surfaces represent long periods of weathering and erosion. The weathering fronts associated with the different erosion surfaces would have influenced the regional groundwater levels as well as the creation of groundwater flow paths. Groundwater investigations undertaken in the 1980s and 1990s alluded to a contention that the regolith was likely to be better developed beneath the older erosion surfaces than the younger ones, resulting in higher borehole yields (Jones, 1985; McFarlane et al., 1992). However, it is difficult to prove that the older erosion surfaces do indeed offer a more productive aquifer, due to the complexity and interplay of factors controlling the degree and thickness of weathering.

Geomorphic features observed in the study area are plains, hills, inselbergs, low mountains, lowlands, foothills and valleys. The area can be divided into a number of terrain morphology units (Kruger, 1983). These geomorphic zones together with a W-E topographic profile are shown in Figure 5.4.

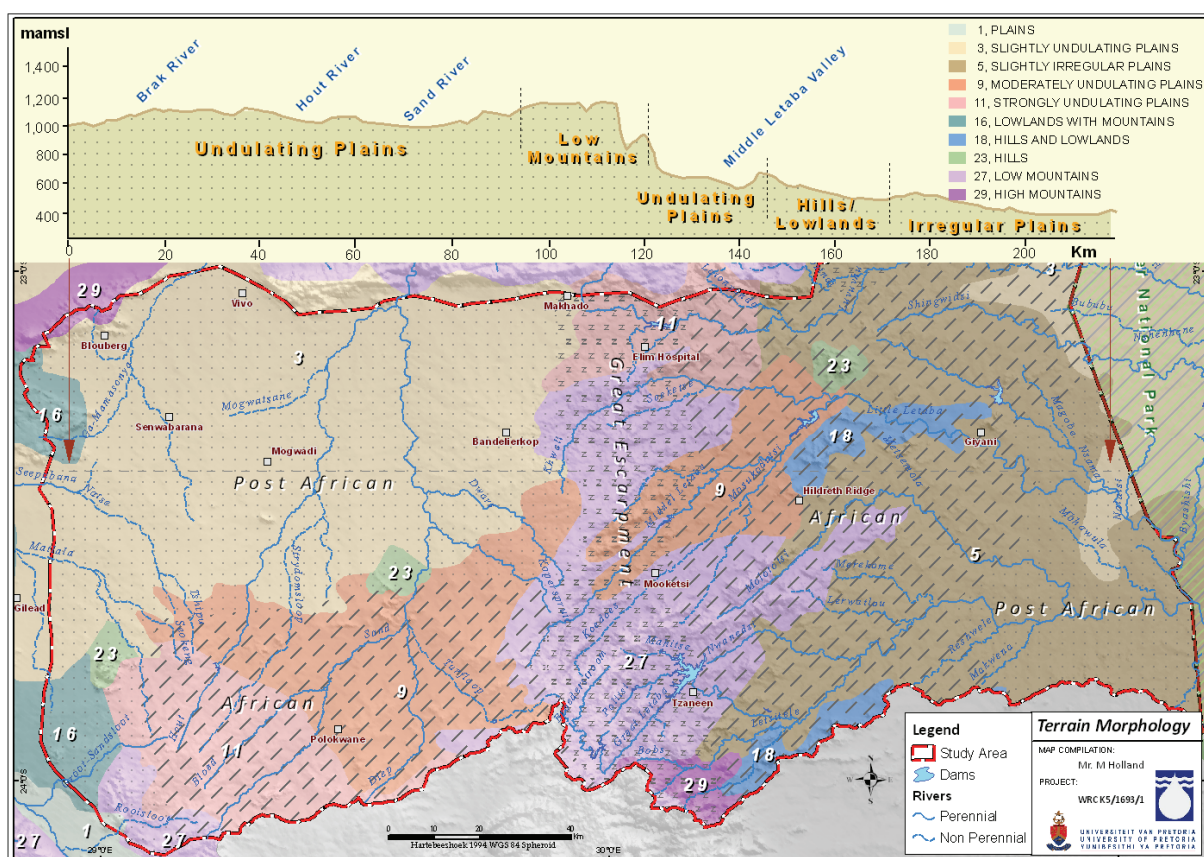


Figure 5.4. Terrain morphological zones of the focus area.

The Plateau to the west of the escarpment can be described as an extremely old erosion surface underlain by primitive Basement rocks into which several mature rivers have incised themselves. The escarpment contains a series of north-easterly trending mountain spurs, containing the upper reaches of rivers such as the Middle Letaba. Towards the east of the escarpment the ground surface drops eastwards to form a plain known as the Lowveld region.

5.4. Geological Setting

The focus area of this study is located on the north-eastern part of the Kaapvaal craton and the southern marginal shear zone (SMZ) of the Limpopo Mobile Belt (LMB) (Figure 5.5). Some authors (e.g. Roering et al., 1992; Windley, 1993) have suggested that the LMB in the northern part of South Africa is the world's earliest example of a Himalayan-type continent-continent collisional orogeny between two large Cratons (Kaapvaal- and Zimbabwe Cratons respectively). However, according to Kramers et al. (2006) no consensus regarding the geological process, setting or timing of the LMB has been reached.

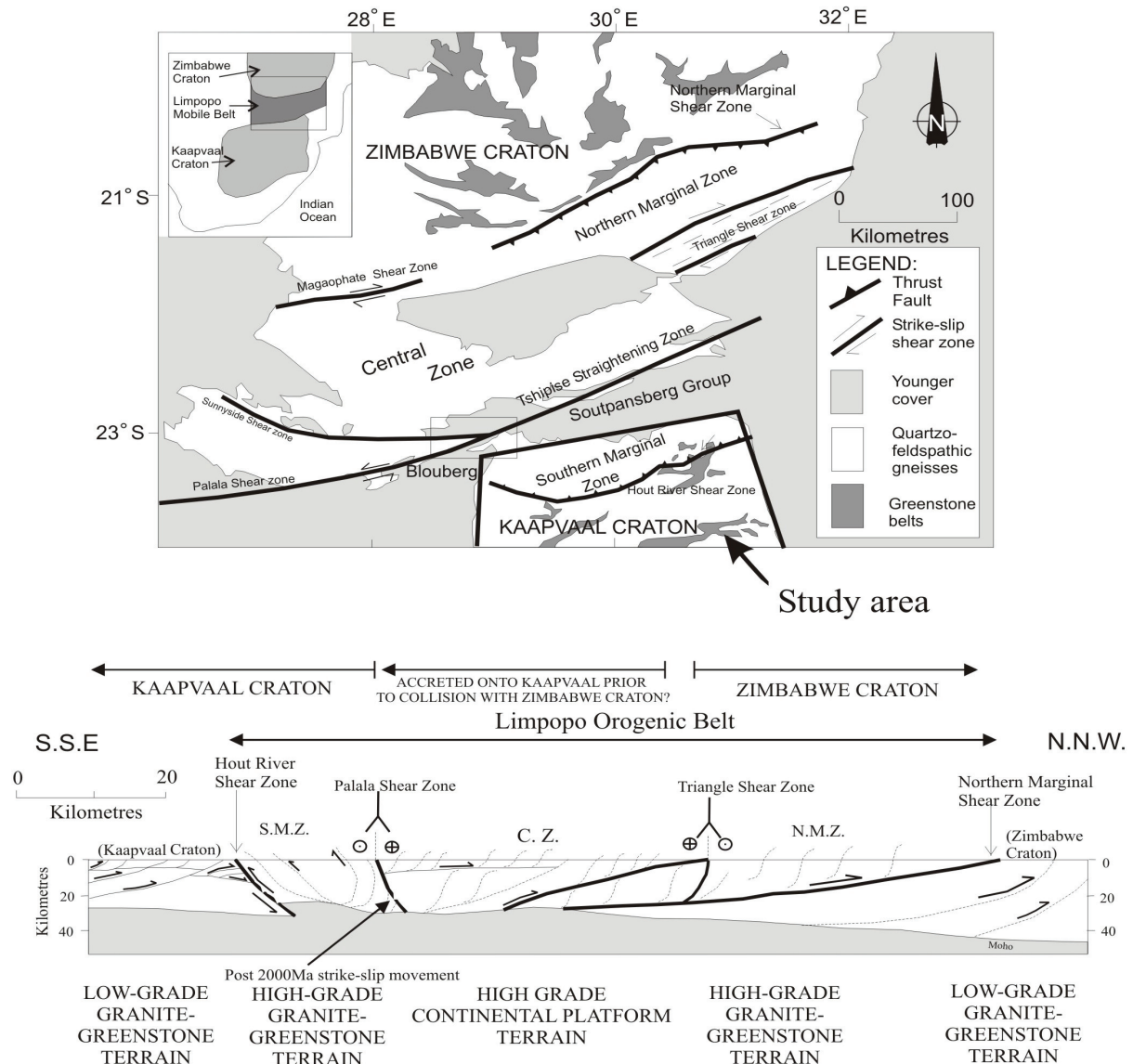


Figure 5.5. Generalised map of the Limpopo Mobile Belt showing the main features and subdivisions (Bumby and van der Merwe, 2004). Arrow indicates the location of the study area.

The resulting LMB consists of three main crustal zones, namely the Northern Marginal Zone (NMZ), the Central Zone (CZ) and the Southern Marginal Zone (SMZ), which lie parallel to one another in an ENE direction.

Hout River Shear Zone

The Hout River Shear Zone (HRSZ) is located on the southern side of the LMB and forms the boundary between the low grade Basement lithologies of the Kaapvaal Craton and the higher grade rocks of the SMZ (Figure 5.5). In general the HRSZ comprises EW striking, steeply northward-dipping thrusts and reverse faults, as well as several NE-SW striking strike-slip faults (Smit et al., 1992). The strike-slip faulting on the eastern part of the HRSZ changes to a system of frontal and lateral ramps towards the west. Geothermobarometric studies have shown that the vertical displacement of the HRSZ was of the order of 15 km (Miyano et al., 1992). According to Kreissig et al. (2001), the geochronology of the HRSZ stretches over ~90 Ma (c. 2690 until 2600 Ma.) of episodic shearing. The HRSZ can be readily recognised by the presence of several ultramafic bodies which are absent in the Kaapvaal Craton lithologies in the footwall. The metapelites of the Bandelierkop Complex are only found in the SMZ, north of the HRSZ. Furthermore, the distribution of swarms of dolerite dykes also seem to be influenced by the HRSZ, as these are more densely populated south of the HRSZ, in low-grade rocks of the Kaapvaal Craton and are less common within the SMZ.

5.4.1. Description of local geology

The geology of project area is dominated by Archaean Basement lithologies (granite, gneiss and greenstone) which outcrop in an approximately rectangular area bordered:

- to the south by younger overlying sedimentary strata and the major surface water divide,
- to the north by the Soutpansberg Group (volcanic rocks),
- to the west by the Northern limb of the Bushveld Complex,
- and to the east by the Drakensberg basalts of the Lebombo mountains.

A geological distribution map with the main shear zones and major lineaments is shown in Figure 5.6.

Archaean Gneisses

The area is characterised by the widespread occurrence of the Goudplaats-Hout River Gneiss suite, which comprises a wide spectrum of granitoid gneisses of various types and compositions. These gneissic bodies range from homogenous to strongly layered, from leucocratic to dark grey, and from fine grained to pegmatoidal varieties (Anhaeusser, 1992). According to Robb et al. (2006) the previous subdivision of the strongly migmatised Hout River Gneiss and less well-migmatised Goudplaats Gneiss is no longer regarded as tenable. However, all granitoid gneisses occurring between the Murchison (Gavelotte Group) and the Pietersburg-Giyani greenstone belts have been grouped together under the term Groot-Letaba Gneiss (Brandl and Kröner, 1993) (Figure 5.6). These rocks were previously regarded as part of the widespread Goudplaats Gneiss. The Groot-Letaba Gneiss consists of a variety of gneisses, including fine to medium grained tonalite and coarse grained trondhjemite (Robb et al., 2006). These rocks are bounded in the southeast by the Letaba Shear Zone (Figure 5.6).

Archaean Greenstone Belts

The Rhenosterkoppies (Zandrivierspoort Formation), Pietersburg (Pietersburg Group), Giyani (Giyani Group) and northern part of the Murchison (Gravelotte Group) Greenstone Belts

occur in the focus area. They are composed largely of extrusive mafic and, to lesser extents, ultramafic and felsic, rock. These Greenstone Belts are infolded mainly into grey granitic gneisses which dominate the early Archaean terranes (Brandl et al., 2006). The NE-trending Pietersburg and Giyani Greenstone Belts extend parallel up to the southern part of the SMZ of the Limpopo Belt. The Murchison Greenstone Belt exists along a major ENE-WSW crustal lineament known as the “Thabazimbi-Murchison Lineament (TML)”. The TML was an important control on the spatial emplacement of later successions like the Bushveld Igneous Complex, the Wolkberg Group, Transvaal Supergroup, and the Waterberg Group. Because of the orientation of the TML, the Greenstone Belts and the LMB, many of the geological structures recorded in the study area are parallel to this NE-SW trend.

Neoarchaeon Intrusions

A number of massive, unfoliated granite intrusions occur as batholiths, plutons and stocks in the focus area. These granitic intrusions form prominent topographical features that can be seen north of Polokwane. The most distinct of these plutons are the Matlala Granite, the Moletsi Granite, the Mashashane Suite (Granites) and the Matok Granite. The Matok Granite was emplaced just north of the HRSZ. The Duivelskloof leucogranite and the Turfloop Granite, which form elongated northeast-trending batholiths, are the most voluminous granite bodies in the study area. However, the contacts with the surrounding granitoid gneisses of these large batholiths are not well defined. Various other granite intrusives occur throughout the study area (e.g. Shamiri- and Hugomond Granite) including the Schiel Complex located immediately north of the northeast-orientated Kudus River Lineament (Figure 5.6). The quartz syenite complex is intruded into the high-grade granitic and migmatitic Goudplaats-Hout River Gneiss in which fragments of the metapelitic gneiss of the Bandelierkop Complex occur.

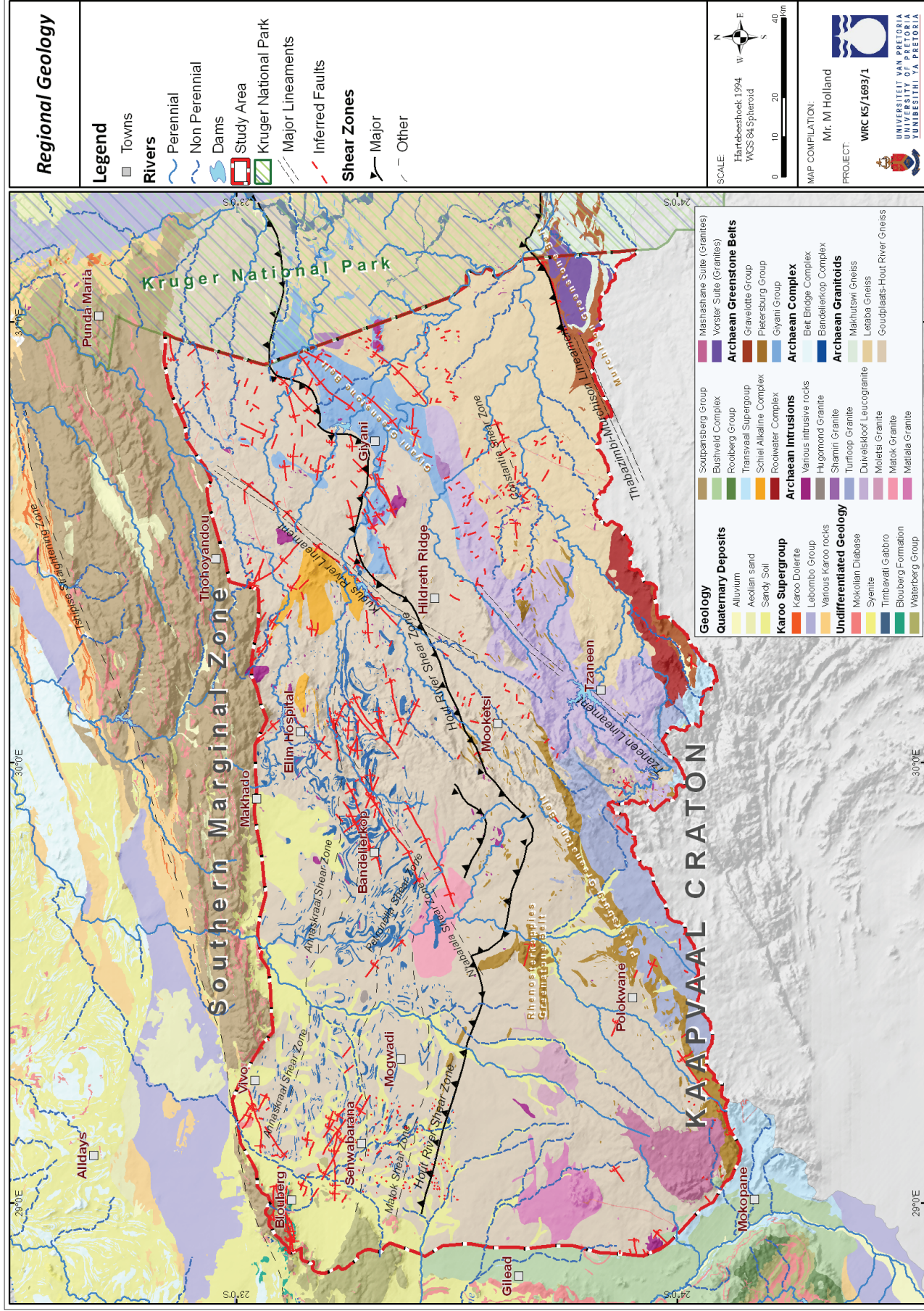


Figure 5.6. Regional geology of the focus area.

Younger rocks of significance

The Soutpansberg Group emerges as a large east-west trending mountain range (escarpment) from the Kruger National Park in the east to Vivo in the west, and forms the northern border of the present study area. Outliers of the volcano-sedimentary Soutpansberg rocks also outcrop further to the west (Figure). The Waterberg Group (arenites and rudites) similarly outcrops along the north-western margin of the study area and rests unconformably on the rocks of the Bushveld Complex and the Archaean gneisses. The western edge of the study area is bound by the northern limb of the Bushveld Complex. This is a large economically important layered intrusive complex, comprising the lower Rustenburg Layered Suite and Lebowa Granites Suite above, which intruded into the Archaean Basement. The northern edge of the northern limb of the Bushveld Complex appears to butt against the Hout River Shear Zone, and the extent of intrusion may thus, in part, be controlled by such pre-existing structures. The eastern margin of the study area is marked by the eastern edge of the Kaapvaal craton. This area is underlain by rocks of the Drakensberg Group (Karoo Supergroup) which comprise flood basalts and pyroclastic deposits.

The presence of quaternary cover of soil, calcrete and ferricrete is common. These covers are generally not very thick but widespread towards the northeast of the area. Water bearing alluvial deposits is found mostly along major rivers (e.g. Sand River, Hout River) in the west. In the east alluvium is present along the lower reaches of the major tributaries. Their potential as high recharge and storage zones suggests that high borehole yields could be obtained in their sites of occurrence, but is presumably limited in extent. Alluvial deposits are indicated on the 1:250 000 geological map sheets and are presented in Figure 5.6.

5.4.2. Geological timeline of local occurrences

The summary of crystallisation/emplacement age for granitoid intrusions and other younger rocks pertaining to the focus area is based on Robb et al. (2006) and Kramers et al. (2006):

- 3 600-3 200 Ma Palaeoarchaean intrusions (Goudplaats-Hout River Gneiss)
- $\pm$ 3 200 Ma Greenstone Belts (Giyani, Pietersburg, Murchison)
- 3 200-2 800 Ma Mesoarchaean intrusions (Groot Letaba Gneiss; Voster Suite)
- 2 800-2 500 Ma Neoarchaean intrusions (Batholiths) (e.g. Matok- Matlala granites; Duivelskloof leucogranite)
- 3 100 Ma Central Kaapvaal Craton is stable
- 2 700 Ma Limpopo Belt (First event)
- 2 700 Ma Ventersdorp-related mafic dykes.
- 2 060 Ma Intrusion of the Bushveld Complex
- 2 000 Ma Palala Shear Zone Reactivation (Second Limpopo event)
- >1 850 Ma Deposition of Waterberg Group
- 1 850 Ma Deposition of Soutpansberg Group
- 180 Ma Extrusion of Drakensberg Flood Basalts

5.5. Structural Setting

Fracture zones are primarily structurally controlled; consequently, an understanding of the deformation events due to tectonic history forming lineaments, joints, faults, folds, synclines, anticlines or graben structures is essential to their characterisation

5.5.1. Neotectonics

Figure 5.7 shows the orientation of the maximum stress axes (σ_1) currently measured within southern Africa (Zoback, 1992), which suggests that the southern continent is presently subjected to NW-SE directed shortening, and NE-SW directed extension. According to Bird et al. (2005) the dominant NE-SW extensional regime in the study area results from the unbroken lithosphere's resistance to relative rotation between the Somalia- and African Plates.

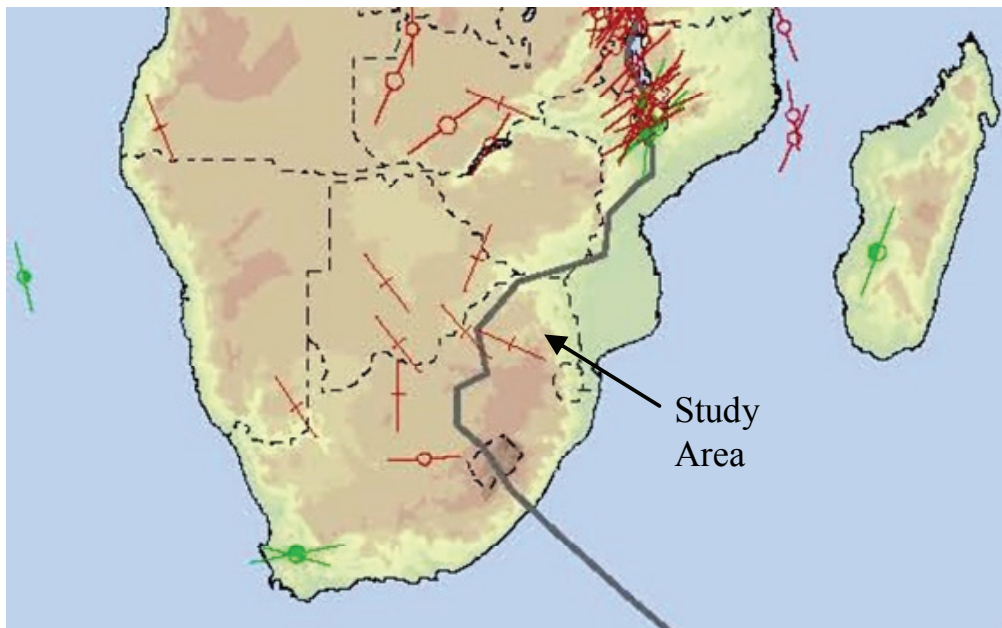


Figure 5.7. Neotectonic stress map of southern Africa (Zoback, 1992). Long axes indicate the orientation of crustal shortening.

Any pre-existing secondary structures or discontinuities within rocks will similarly be affected by this regional stress field, and their properties as groundwater conduits may be controlled by their orientation relative to this stress field. Planar structures which strike perpendicular to the neotectonic maximum stress direction (i.e. those which strike NE-SW) are likely to have restricted flow, as the fault/joint surface is likely to be closed by the perpendicular compression. In contrast, planes which strike parallel to the maximum stress direction are perpendicular to the extension direction, leading to dilation along the surface, and enhanced groundwater flow along them. However, the impact of neotectonic activity on groundwater in the Limpopo Basement rocks is as yet unknown and has rarely been studied.

5.5.2. Dyke swarms (Crustal domains)

Perhaps one of the most differentiating structural features of the study area is the high frequency and orientation of dyke swarms. The magnetic nature of the dykes makes aeromagnetic data ideal for mapping these features and most magnetic lineaments identified on aeromagnetic maps are therefore associated with dyke swarms (not necessarily reflected on the published geological maps) (Figure 5.8). The age and orientation of the north-east trending dyke swarms and associated aeromagnetic lineaments coincide with the 2 700 Ma Ventersdorp rift structures (Uken and Watkeys, 1997). It is clear that during this period the northeastern Kaapvaal Craton underwent NW-SE extension, in contrast to the current NE-SW extensional regime. The magnetic lineaments thus show an orientation dictated by an inherent fracture pattern in each particular domain of the crust. Stettler et al. (1989) subdivided parts of the Kaapvaal Craton and the Limpopo Belt according to the prevailing aeromagnetic lineament pattern into five domains (Figure 5.8).

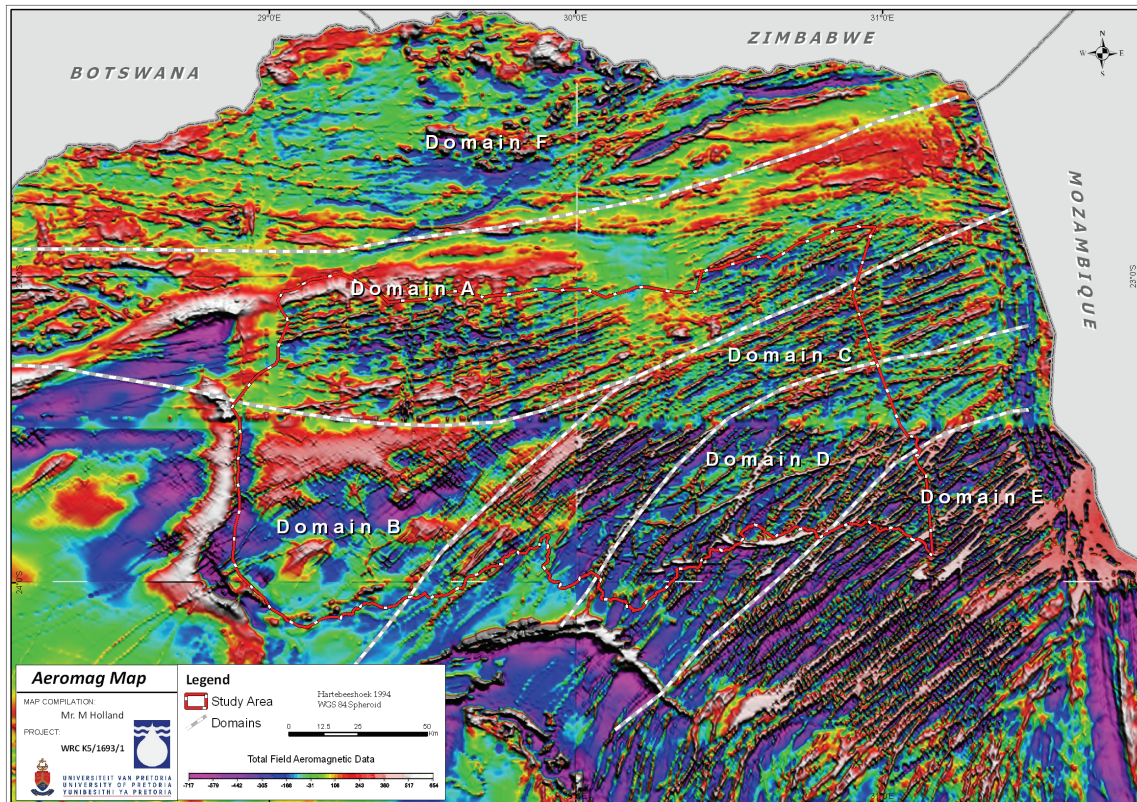


Figure 5.8. Aeromagnetic map showing tectonic domains (Adapted from Stettler et al., 1989). Data source: Council for Geoscience (SA).

To describe the structural influence on groundwater occurrence in the Limpopo Basement rocks, the regional aeromagnetic data and related interpretation conducted by the Council for Geosciences was used to delineate structural regions (Figure 5.9). Recognition of these regions therefore provides a tectonic and morpho-structural framework to describe hydraulic parameters on a regional scale.

The inferred dykes were used to construct rose diagrams to illustrate the dominant orientation of the chosen regions within the focus area (Figure 5.9). Although the boundary between

Region A and Region C is based on the major surface water divide (escarpment) the mean strike direction of the inferred dykes are N85°E and N63°E respectively. The two southern Regions correspond closely with the regions identified by Stettler et al. (1989) with prominent strike directions of N51°E in Region B compared to N47°E in Region D for inferred dykes. Towards the western edge of Region B the lineation frequency is low, and shows less of an orientation preference; however towards the east the lineament has a high degree of lineament orientation (similar to Region D). Therefore the mean strike direction of the dykes is biased towards these lineament orientations. The Hout River Shear Zone was regarded as the margin between the northern and southern regions.

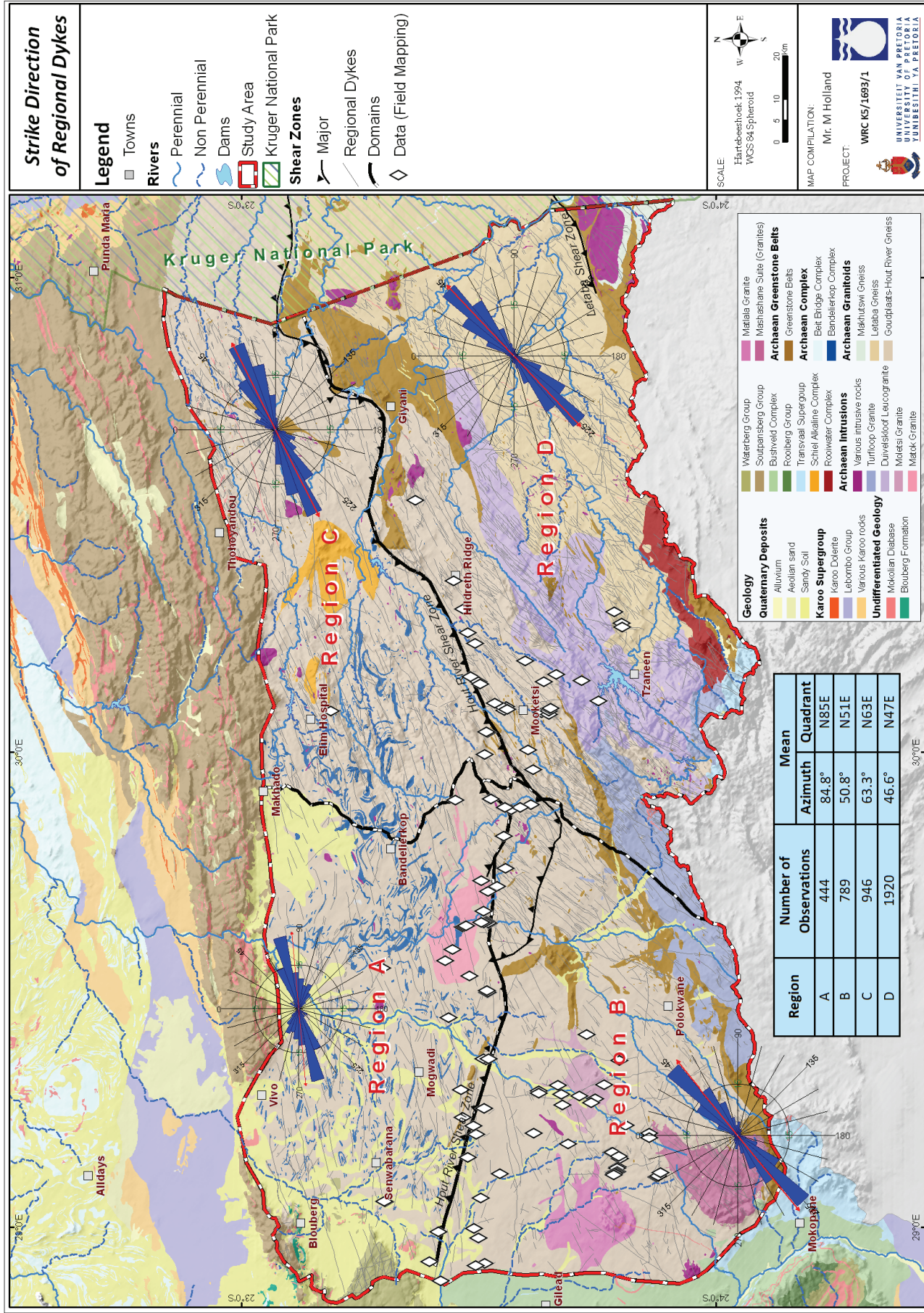


Figure 5.9. Identified structural domains based on the orientation of regional dykes (Aeromagnetic and published dykes).

5.5.3. Structural analysis

The geological field study of the Basement aquifer research project included an analysis of dominant structure types such as joints, faults/shears, foliation, folds and dykes (Petzer, 2009). The distribution of field measurements is shown in Figure 5.9.

Joints

The measured joint directions were statistically evaluated using rose diagrams and density distribution of joint planes in stereographic projections (Figure 5.10). Sub-vertical lineations dominate the density distribution (Petzer, 2009), but the rose diagram indicates an overall fairly random distribution of joint strike directions (Figure 5.10). The mean joint strike direction of N13°W suggests a slightly dominant northwest trend for the field observations. To detect variations of the joint directions across the study area, rose diagrams were constructed for each of the four delineated structural domains (Figure 5.11).

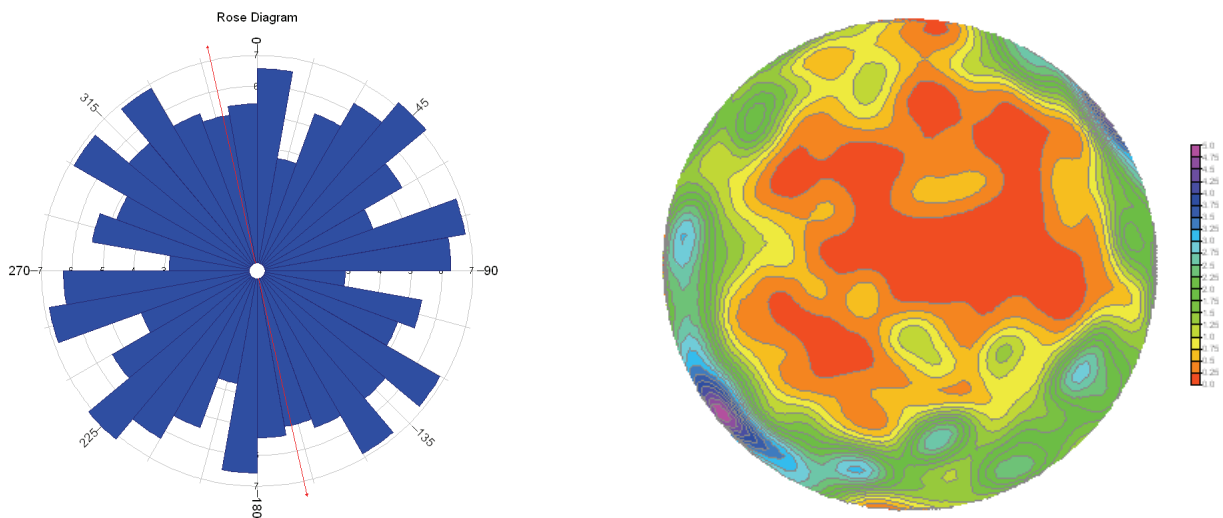


Figure 5.10. Rose diagram (left) derived from the strikes of all joint planes and density distribution (right) of all poles to joint planes (350 observations).

Joints in Region A show a predominant NNE-SSW strike direction, whereas the limited number of field observations for Region C shows a distinct E-W trend. Region B to the south of the HRSZ shows no clearly preferred orientation of joints, similar to the observed dyke orientations in the western parts of Region B. The more complex joint pattern suggests NW-SE, NE-SW and N-S striking joints. In Region D joints strike predominantly in a NW-SE direction, perpendicular to most of the other structures observed in the area such as dolerite dykes (Figure 5.9). Under the current neotectonic stress in the area, NW-SW compression (NE-SW extension) may close-up NE-SW trending lineaments and open-up those trending NW-SE. If the assumption holds true, the NW-SE trending joints are likely to be favourable conduits for groundwater. On the other hand, it is believed that many of these joints are tectonically induced, suggesting that the study area was at one stage subjected to NW-SE extension (NE-SW compression) as displayed by the dolerite dykes in the area. Such a regime would favour the formation of open discontinuous conduits in the NE-SW direction, but at the same time closing many brittle structures that might have been favourable groundwater conduits in the geological past.

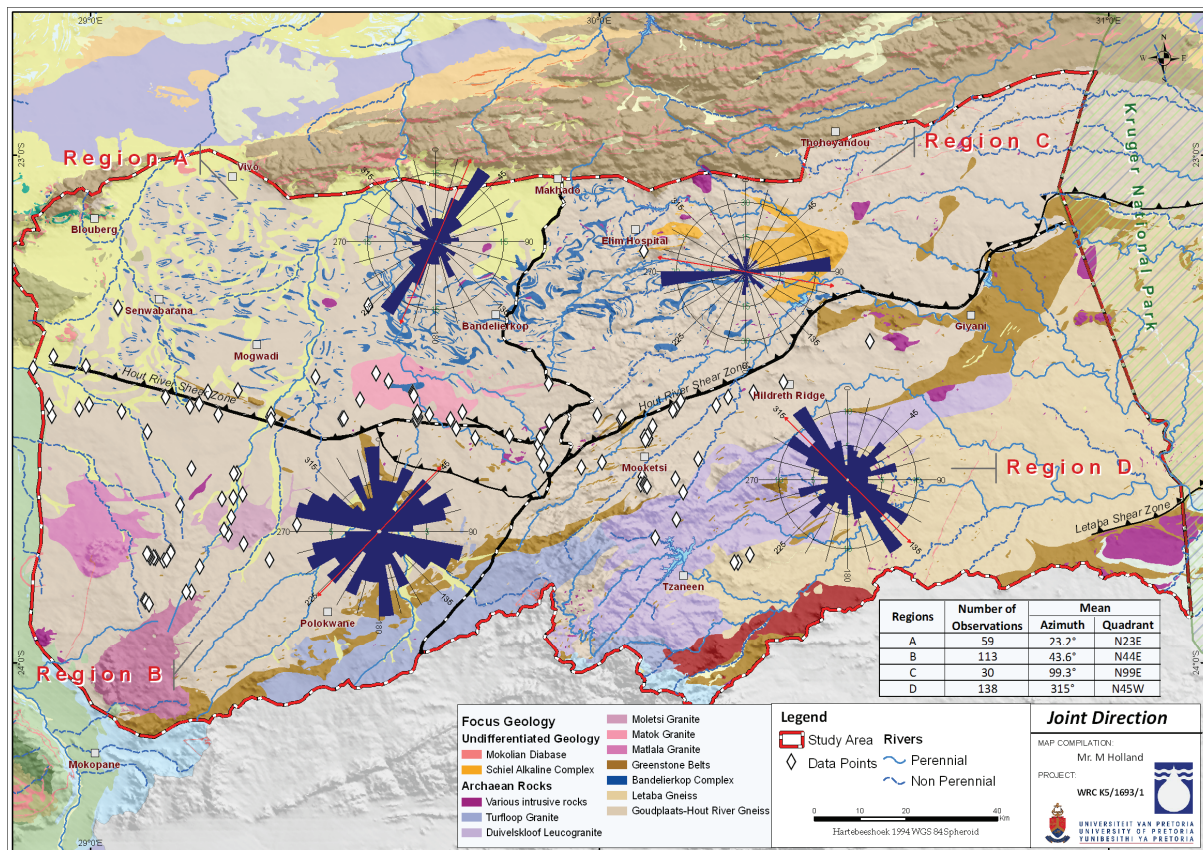


Figure 5.11. Rose diagrams of joint strike directions and distribution of field observation points.

Faults

Although not quite as common as joints, the few faults observed in the field suggest E-W and NNW-SSE strike direction. For a more regional assessment of the fault trends the following datasets were used:

- Inferred faults from the regional and high resolution aeromagnetic interpretation conducted by the Council for Geosciences (with displacement of dykes and other features as an indication of faulting).
- Inferred faults from ASTER image interpretations conducted by a remote sensing consultant on behalf of the Department of Water Affairs Limpopo regional office.
- Published faults from the 1:250 000 geological map sheet.

The combination of these datasets results in rather random faults strike directions, though the NNW-SSE trend is evident (Figure 5.12).

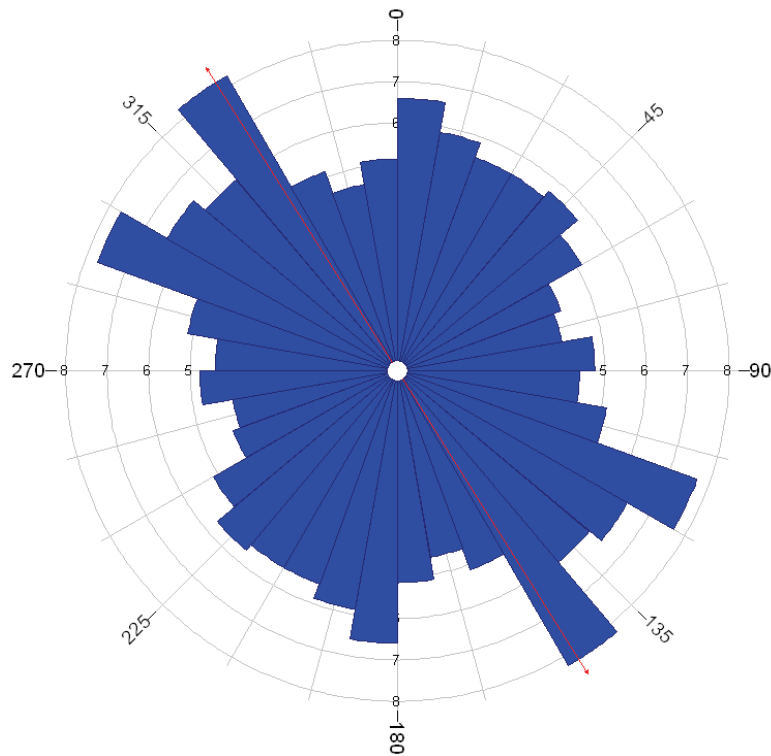


Figure 5.12. Rose diagram derived from the strikes of inferred faults observed in the focus area.

5.6. General Description of Groundwater Occurrence

Fresh unweathered Basement rocks in the Limpopo Province have a very low primary porosity, permeability and storage capacity. The possible occurrence of groundwater is thus related to secondary hydrogeological properties developed from the processes of weathering, faulting, fracturing and/or the influences of intrusives (e.g. batholiths and dykes). In turn, a number of factors do affect the ways in which rocks fracture and weather e.g.:

- Weathering depends on the mineralogy, texture and granularity of the crystalline Basement rock in addition to physical factors such as zones of tectonic disturbance, hydraulic gradients and the presence or absence of any primary or secondary permeability. Since water is identified as the main weathering agent through hydrolysis and dissolution (Jones, 1985) there are obviously strong climatic controls on the development of the weathering profile. Furthermore, the dissolution of minerals and leaching tend to increase the permeability but the decomposition of secondary clay minerals could reduce the productivity of the regolith as an important part of the aquifer.
- Fracturing and fissuring may occur at or near lithological contacts, for instance between the major intruded plutons, along contact zones of dykes or sills and in fault and shear zones. Fracture systems may be formed due to surface decompression, or by tension or compression depending on the regional stress field. The permeability of fracture systems is dependent on apertures of the single fractures as well as their interconnectivity and frequency.

2. Deeper fractured aquifers; composed mainly of crystalline material (i.e. igneous and metamorphic rocks) characterised by an intact and relatively unweathered matrix with a complex arrangement of interconnected fracture systems.
3. Alluvial aquifers; alluvial material overlies or replaces the weathered overburden and creates a distinct intergranular aquifer type. These elongated aquifers follow rivers (so called valley trains), sand rivers or drainage lines with limited width and depth, which typically vary according to the topography and climate.

A conceptual illustration of the aquifer systems typically found in the focus area is provided in Figure 5.14.

Limpopo Plateau

The thickness of the regolith in the Limpopo Plateau generally extends to between 15 and 50 meters below surface. Below the weathered zone is a zone of fracturing, which according to geohydrological studies done by Dziembowski (1976) and Jolly (1986) in the Dendron/Mogwadi area may extend to depths greater than 120 m. Towards the south west of Louis Trichardt/Makhado, electrical resistivity depth soundings collected by Timmerman et al. (1983) indicate weathering depths of between 20 and 40 m. Borehole siting, drilling and pumping tests around Polokwane by Du Toit (1986) showed weathering depths of between 9 and 36 m. Du Toit (1986) concluded that although there is some correlation between yield and weathering depth, higher yields (> 3 L/s) are more often associated with the fractured fissure layer irrespective of the thickness of the overlying weathered layer. The only substantial deposits of alluvium occur along the major surface drainage courses (e.g. Sand- and Hout Rivers). Orpen (1986) estimated the thickness of alluvium deposits along the Sand River to be not more than 8 to 15 m. Nel (2000) suggested that in the absence of a continuous impermeable clay (collimation) layer, the alluvial and regolith/fractured aquifers are in hydraulic continuity. The alluvial deposits typically consist of red or sandy clay (calcified in places) which overlies sand, gravel and pebbles.

A survey conducted by Vegter (2003a) on the Polokwane/Pietersburg Plateau groundwater region found that 52% of boreholes drilled were successful (yield > 0.1 L/s).

Letaba Lowveld

The western part of the Letaba Lowveld is characterised by mountainous terrain, incised valleys, high rainfall and dense vegetation. A number of perennial springs occur in the area. Although it is expected that a thicker regolith will form due to a more tropical climate, the region is regarded as semi-arid with the majority made up of relatively impermeable bedrock with shallow weathering. According to Bush (1988) the gneisses in the Mooketsi area are well weathered, but weathering depths rarely exceed 36 m. De Villiers (1967) noted similar weathering depths in the greater Letaba area. The higher-lying areas including the footwalls east of the escarpment are poorly weathered (e.g. the Tzaneen, Duiwelskloof and Modjadji areas). It is expected that the weathering depth in the younger granites (e.g. Duiwelskool Granites) is lower than in the surrounding Goudplaats-Hout River Gneiss. Alluvial deposits occur along the major drainage courses (e.g. Molototsi-, Groot Letaba- and Klein Letaba Rivers). Vegter (2003b) gave a success rate of boreholes yielding more than 0.1 L/s in the Lowveld groundwater region of 49%.

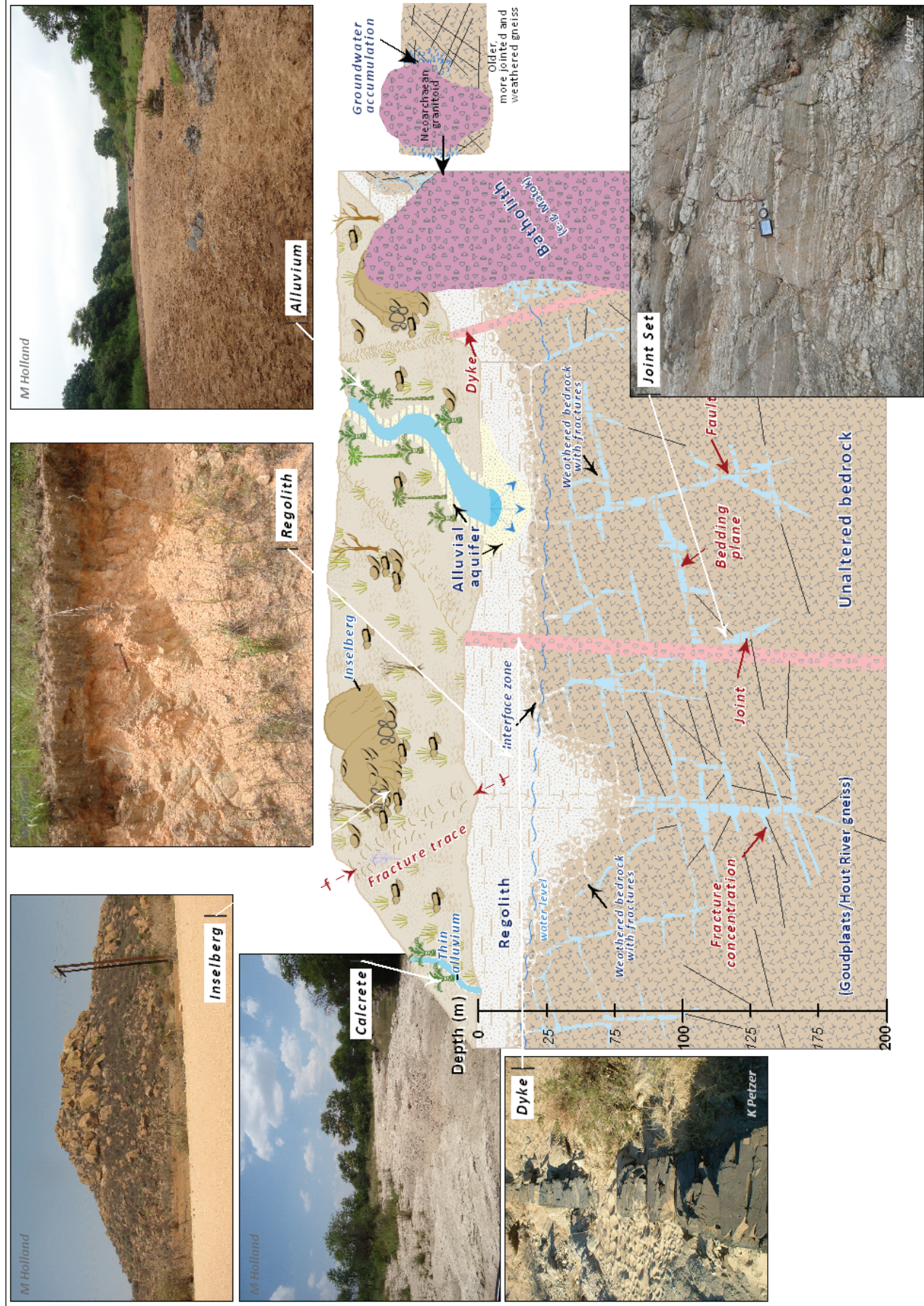


Figure 5.14. Generalised section of the aquifer systems found in the Limpopo Province and photo's of observed geological features.

5.8. Analysis of borehole data

The dataset compiled for the Limpopo Province consisted of over 8 000 boreholes contained in the GRIP Limpopo database. The lithology has been recorded and updated on 1 206 holes and approximately 3 000 boreholes have been tested. The majority of the pumping tests were single-well tests, primarily to recommend “sustainable” abstraction rates for rural water supply boreholes. Although the determination of aquifer parameters was not a priority, over 2000 boreholes within the area were analysed using the Flow Characteristic Method (Van Tonder et al., 1998). It should be noted that different consultants and contractors were used in the GRIP project to conduct and analyse the pumping tests over a number of years. The data is therefore not only influenced by subjective analysis of results, but also potentially influenced by long-term climatic fluctuations, seasonal rainfall and changes in groundwater extraction regimes by farmers, communities and/or mines. Nevertheless, the recorded 2 322 transmissivity values and 3 019 recommended abstraction rates provide two parameters to measure the productivity of boreholes in the Limpopo province. Other parameters included in the compiled database are borehole depths, groundwater levels, water strikes, airlift yields, and constant discharge rates including observed draw-downs.

5.8.1. Data distribution

The distributions of transmissivities and borehole yields for the Limpopo Plateau and the Letaba Lowveld, illustrated in Figure 4.15, are positively skewed and follow lognormal distributions.

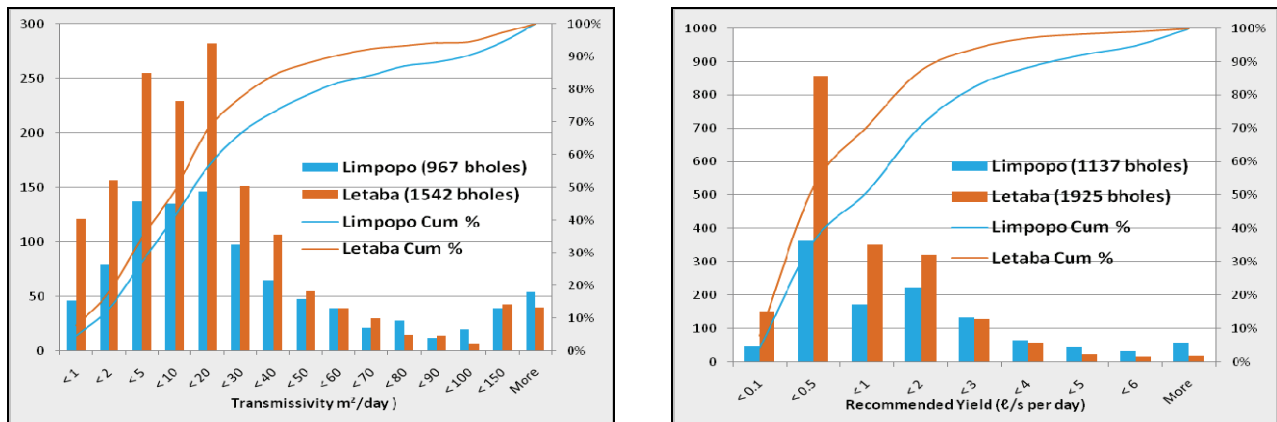


Figure 5.15. Cumulative distribution of transmissivities [m^2/day] and recommended yield (l/s per day) for the Limpopo Plateau and the Letaba Lowveld.

Lognormal distributions are frequently reported in regional studies of fractured rock aquifers (e.g. Hoeksema and Kitanidis, 1985; Razack and Lasm, 2006). Seventy percent of derived transmissivities lie between $4 \text{ m}^2/\text{d}$ and $40 \text{ m}^2/\text{d}$; however, several boreholes with significantly higher transmissivities (outliers), especially in the Limpopo Plateau, “push” the arithmetic mean for this area to $38 \text{ m}^2/\text{d}$ (Table 9).

Table 9. Statistical summary of transmissivities and recommended yields.

Parameter	Transmissivity m ² /d			Rec. Yield L/s per day		
	<i>Focus Area</i>	<i>Limpopo Plateau</i>	<i>Letaba Lowveld</i>	<i>Focus Area</i>	<i>Limpopo Plateau</i>	<i>Letaba Lowveld</i>
Nr. Of BH's	2509	967	1542	3062	1137	1925
Arithmic Mean	29.67	37.98	24.46	1.04	1.46	0.80
Median	11.00	15.00	10.00	0.50	0.80	0.40
Harmonic Mean	3.01	2.88	3.11	0.19	0.17	0.20
Standard Error	1.13	2.18	1.20	0.02	0.05	0.02
Standard Deviation	56.43	67.90	47.14	1.38	1.76	1.06

5.8.2. Success rate and yields

The yield data obtained from the GRIP dataset were examined in terms of the drilling success rate achieved (Figure 5.16). The yield data are based on airlift and recommended sustainable yields (pumping tests) and any borehole equipped with a pump even if no yield data were recorded regarded as successful. In 30% of the cases no yield or equipment status were recorded and in 9% of the cases dry drills (boreholes) were noted. 61% of boreholes can be regarded as successful with yields greater than 0.1 L/s. This value is considerably higher than Vegter's (2003a; 2003b) success rate of 49 and 52% for the Letaba and Limpopo groundwater regions respectively, which was based on data obtained from the National Groundwater Database in 1998 before the Limpopo GRIP programme was implemented. The increased drilling success rate may be attributed to the more accurate GRIP dataset and the success of the programme in terms of groundwater development for rural communities.

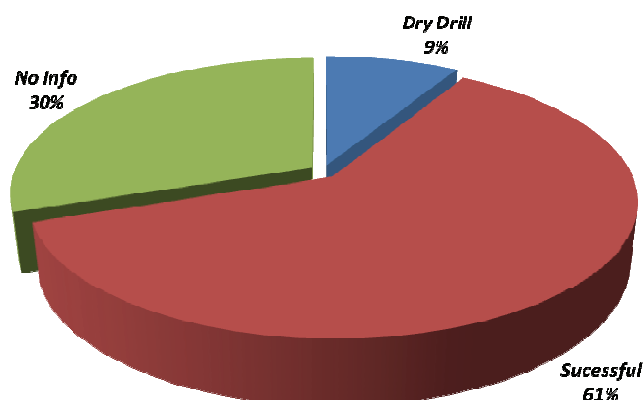


Figure 5.16. Success rate for boreholes contained the GRIP dataset for the study area.

The frequency distribution of airlift yields (for boreholes with airlift yield data) in the two focus areas (Figure 5.17) shows distinct differences between the regions. While the total number of dry boreholes is higher in the Letaba Lowveld than in the Limpopo Plateau, they constitute only 25% of all boreholes in comparison to 35% in the Limpopo Plateau. 30% of boreholes in the Limpopo Plateau and 39% of boreholes in the Letaba Lowveld had an airlift yield between 0.1 and 3 L/s, while 35% of boreholes drilled in the Limpopo Plateau and 36% in the Letaba Lowveld yielded more than 3 L/s.

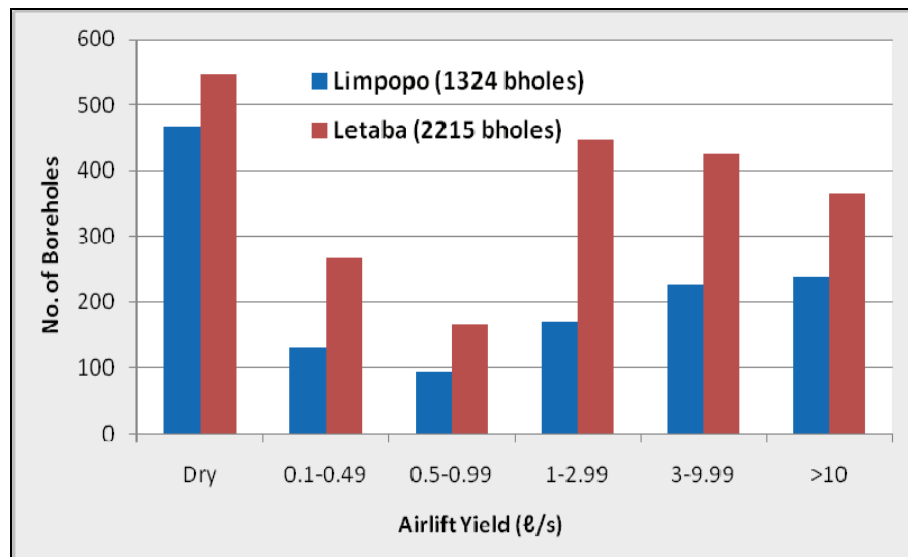


Figure 5.17. Distribution of borehole airlift yield in the Limpopo Plateau and Letaba Lowveld.

5.8.3. Water level-, borehole-, water strike-, and weathering/fracturing depth

A summary of the regional borehole characteristics for the Limpopo Plateau and the Letaba Lowveld region is given in Table 10. The depth of weathering and fracturing is based on driller's description of the formation where rock type is weathered and fractured (including jointing and broken rock). While the weathering depth represent in-situ weathered material.

Table 10. Summary of borehole characteristics in the focus area.

m.b.g.l*	Limpopo Plateau				Letaba Lowveld			
	Nr. of BH's	Min	Mean	Max	Nr. of BH's	Min	Mean	Max
BH Depth	<u>2066</u>	7.1	70.3	250.0	<u>2813</u>	7.7	62.9	182.0
Water Level	<u>1563</u>	0.6	16.9	82.6	<u>2177</u>	0.5	14.8	72.6
Water Strike	<u>202</u>	1.2	35.6	87.0	<u>646</u>	1.1	28.1	80.0
Weathering	<u>481</u>	1	21.6	63.0	<u>750</u>	3	18.4	82
Weathering/ Fracturing		5.0	62.5	150	<u>750</u>	4.0	58.6	149

*- meters below ground level.

The borehole depths follow a normal distribution (Figure 5.18) for both regions with sixty percent of boreholes drilled to depths between 50 and 80 m, indicating the tendency to drill to fixed depths regardless of the hydrogeological conditions encountered. However, boreholes drilled in the Limpopo Plateau are generally deeper than in the Letaba Lowveld (Table 10), with 42% of boreholes exceeding 60 m depth in the Limpopo Lowveld in comparison to 34% in the Letaba Lowveld.

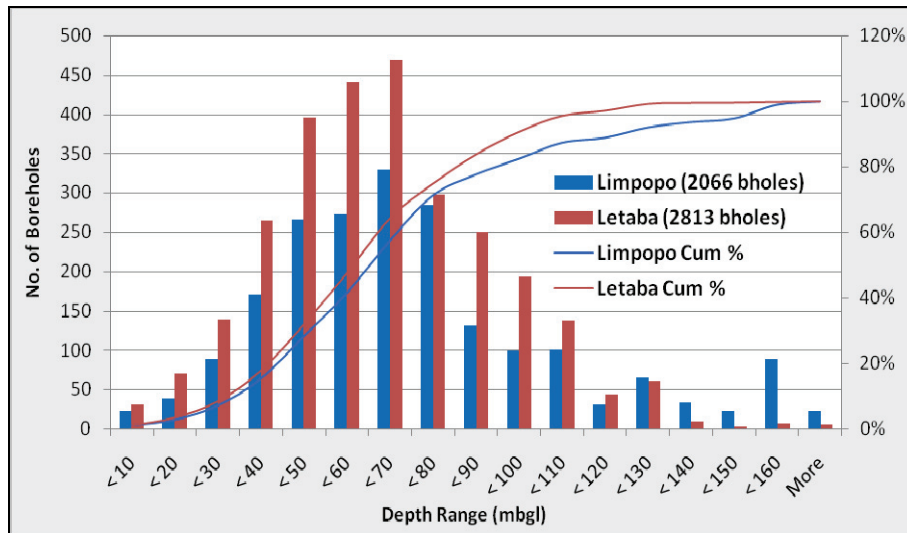


Figure 5.18. Distribution of borehole depths in the Limpopo Plateau and Letaba Lowveld.

Recorded groundwater depths follow approximately a log-normal distribution (Figure 5.19), with modes (highest frequency) between 5 and 10 mbgl for both focus areas and 90% of groundwater levels below 30 mbgl. The arithmetic mean depth to groundwater (Table 10) is slightly higher for the Limpopo Plateau (16.9 mbgl) in comparison to the Letaba Lowveld (14.8 mbgl).

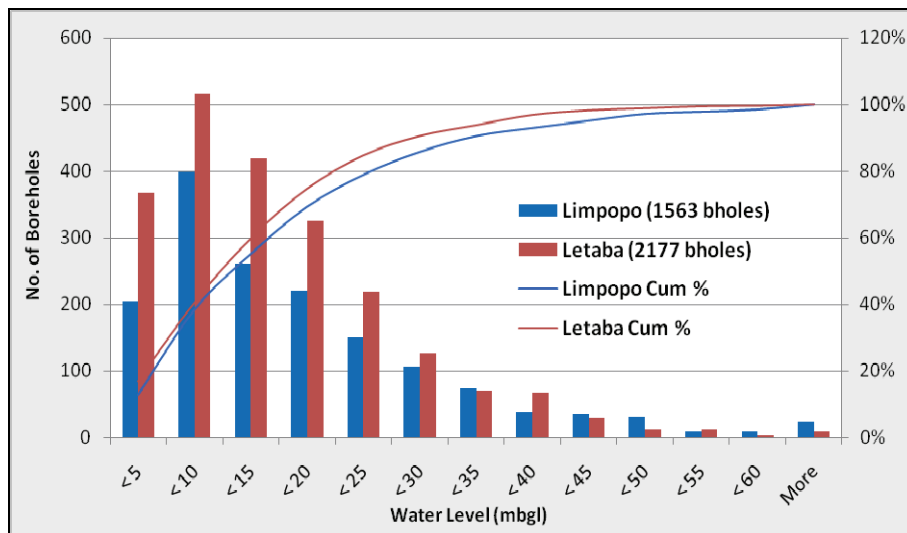


Figure 5.19. Distribution of groundwater levels in the Limpopo Plateau and Letaba Lowveld.

Fewer than 1 000 borehole database entries for both focus areas contain information on water strike depths, but their frequency distribution (Figure 5.20) is markedly similar to the borehole depth distribution (Figure 5.18), suggesting that drilling is stopped once a sufficient water strike is encountered. 60% of boreholes strike water before a depth of 40 m in the Limpopo Plateau and before 30 m in the Letaba Lowveld. This might explain the generally shallower drilling depths in the Letaba Lowveld, with a potentially higher risk of borehole failure during droughts. 25% of the 202 boreholes with water strike information in the Limpopo Plateau strike water beyond a depth of 50 m, compared to a mere 8% in the Letaba Lowveld region, suggesting a deeper base of weathering and fracturing in the Limpopo Plateau.

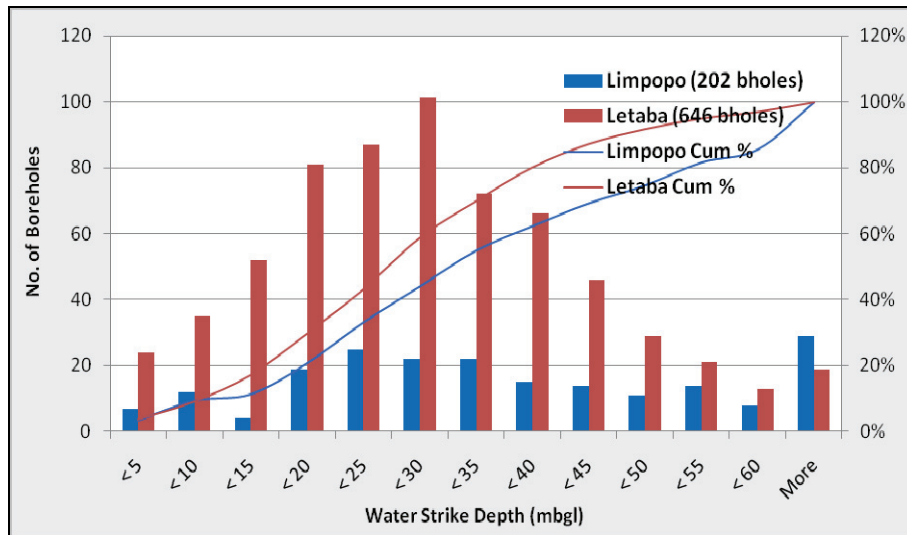


Figure 5.20. Distribution of depth of first water strikes in the Limpopo Plateau and Letaba Lowveld.

Figure 5.21 depicts the depth of weathering and/or fracturing based on just over 1 200 geological logs for the regions. In most cases it is difficult to distinguish the depths of weathering from fracturing from the geological logs. A combined dataset was therefore produced and can be regarded as a proxy for the depth to fresh bedrock.

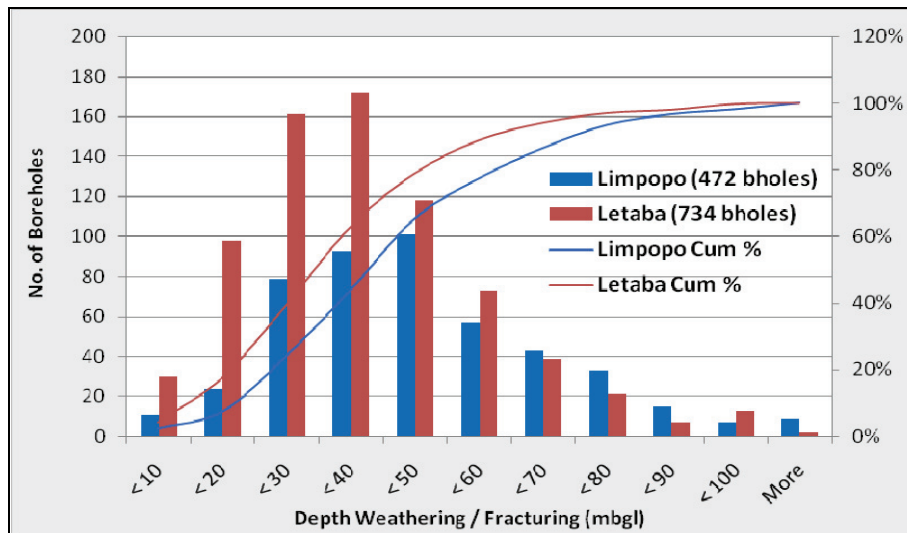


Figure 5.21. Distribution of depths of weathering plus fracturing in the Limpopo Plateau and Letaba Lowveld.

The arithmetic mean depth of weathering / fracturing is 44.7 m in the Limpopo Plateau compared to the shallower 36.2 m in the Letaba Lowveld (Table 10). The depth of weathering / fracturing exceeds 60 m for 23% of boreholes in the Limpopo Plateau and only for about 10% of boreholes in the Letaba Lowveld.

In summary, boreholes drilled in the Limpopo Plateau are generally deeper, show deeper-water strikes, water levels and depths of weathering compared to the Letaba Lowveld. The above description clearly illustrates the variability within the focus area and corroborates the appropriateness of the factors used for the delineation of the two regions.

An extremely poor correlation between water level and depth of weathering / fracturing in the Limpopo Plateau might be assumed, while essentially no correlation between water level and

depth of weathering / fracturing is found in the more rugged Letaba Lowveld area (Figure 5.22). The poor correlation between borehole depth and depth to weathering / fracturing (Figure 5.23) can be attributed to fixed drilling depths regardless of the hydrogeological conditions encountered. Many of the boreholes were logged as fractured over the entire (pre-defined) drilling depth, with numerous borehole logs erroneously showing a depth of weathering exceeding the borehole depth. While the accuracy of the geological logging is obviously questionable, the actual fresh bedrock might be found at depth below the drilled depth. The latter may well be the case in the northern region of the Limpopo Plateau, where fracturing zones extend to depths greater than 120 m (Jolly, 1986).

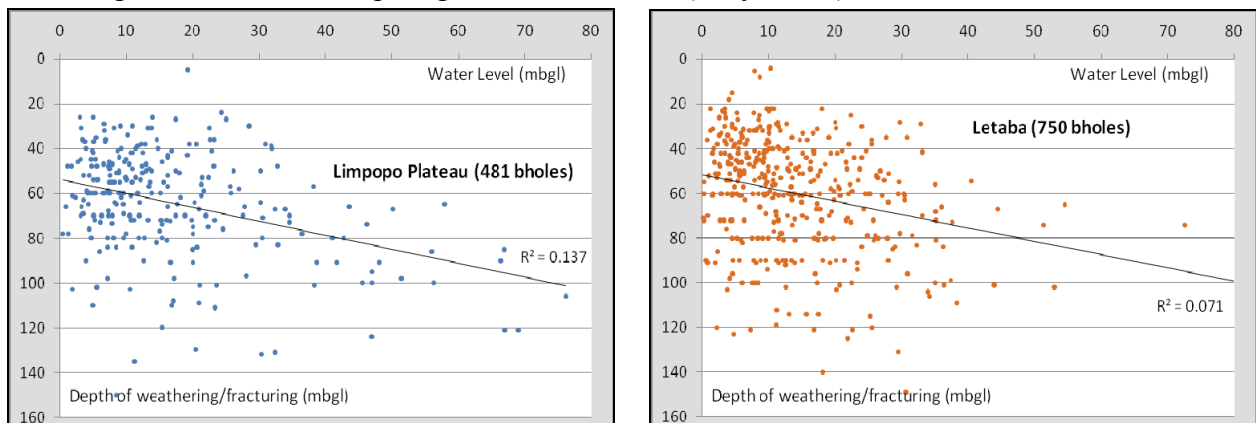


Figure 5.22. Relationship between water levels and depth of weathering / fracturing.

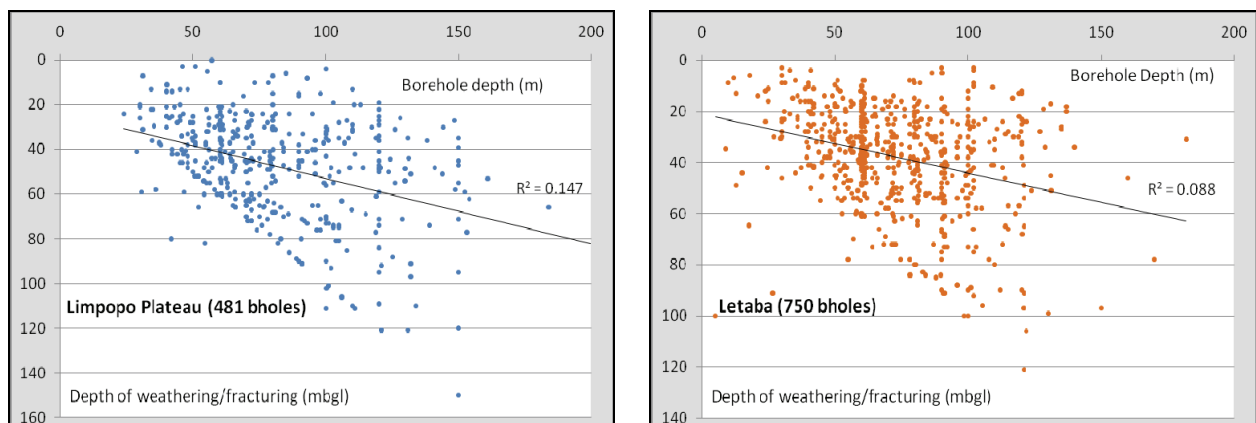


Figure 5.23. Relationship between borehole depth and depth of weathering / fracturing.

5.9. Water quality

The natural groundwater quality in the Basement aquifers of the Limpopo Province is generally suitable for human consumption, though elevated salinities or trace element (fluoride) concentrations render selected natural water qualities, especially in the Limpopo WMA, detrimental to human health. Nitrate, most probably related to anthropogenic influences, is a further parameter affecting the natural water quality.

The dominant water types in Limpopo WMA vary from a Na-Mg-HCO₃ to a Na-Mg-Cl groundwater facies, with the first being found in recharge areas (e.g. Blouberg and

Soutpansberg), and the latter a result of prolonged residence and fluid-rock interaction times in the subsurface in areas of discharge (e.g. alluvium along rivers) or low recharge (e.g. quaternary deposits in the northern part of the WMA).

Groundwater in the Luvuvhu and Letaba WMA is generally a fresher (in comparison to the Limpopo WMA) Mg-HCO₃ facies, with a recognizable pattern of elevated mineralization with reduced precipitation/recharge is.

5.9.1. Groundwater quality hazards

Regional nitrate concentrations in both WMAs are considerably elevated (Figure 5.24) with 31% of the 652 samples analysed for NO₃ in the Limpopo WMA falling into Class II (maximum allowable concentration 10-20 mg/l NO₃ as N) and 21% of the samples exceeding acceptable drinking water limits prescribed in SANS 241 (2006), leaving fewer than half of the samples within recommended limits (Table 11). The situation looks only marginally better for the Luvuvhu and Letaba WMA, with 18% of the samples (n=857) beyond acceptable NO₃ concentration limits, 16% within Class II ranges and only 66% within recommended limits for drinking water. The elevated nitrate levels can usually be related to poor agricultural practices and on-site sanitation.

Table 11. Relative distribution of SANS 241 (2006) water quality class for WMA1 and WMA2

SANS 241	EC	TDS	Ca	Mg	Na	K	Cl	SO ₄	NO ₃ as N	F
<i>Limpopo WMA focus area (n=760)</i>										
Class I	483	463	695	527	623	749	494	749	315	644
Class II	217	241	40	123	78	3	188	1	199	44
> Class II	51	47	16	101	50	2	69	1	138	63
<i>Luvuvhu and Letaba WMA focus area (n=857)</i>										
Class I	685	666	856	683	778	857	712	856	566	802
Class II	145	166	20	101	57	0	113	0	139	40
> Class II	27	25	8	73	22	0	32	1	152	14

Another disturbing, though natural parameter influencing the water quality is fluoride, which renders around 8% of the Limpopo and 2% of the Luvuvhu and Letaba WMA samples unsuitable for human consumption without prior treatment.

Beyond the obvious influence of nitrate and fluoride on the suitability of groundwater as a drinking water source, several samples show major ion concentrations and subsequently electric conductivities beyond acceptable limits. This can mostly be related to evaporative concentration of elements in discharge areas or due to low recharge values as well as long residence times for selected samples.

Beyond the inorganic constituents, the microbiological quality of groundwater may pose a major health hazard due to increased risks of waterborne diseases. Accordingly the project team engaged in a sampling campaign in selected focus areas to assess the overall microbiological water quality of the resource itself (i.e. borehole), and not at the point of water delivery (i.e. tap), where the water quality might be further jeopardized due to the state of the storage and distribution infrastructure.

Heterotrophic bacterial counts are used to indicate the general microbiological quality of water, i.e. the amount of bacteria present in the water. The total coliform bacteria count, which includes bacteria from the faecal group, is an indicator of the general sanitary quality of the groundwater, with many of these bacterial colonies originating potentially from an aquatic environment. The total faecal coliform bacteria count, which is related to human or animal faecal pollution, refers to probable faecal pollution of water. The presence of coliform bacteria implies the potential presence of waterborne pathogens (DWAF, 1996).

According to the Department of Water Affairs' water quality guidelines (DWAF 1996) for domestic use, the total heterotrophic bacterial plate count of all groundwater samples from both WMA focus areas indicates a slight or increased risk of bacterial infection and infectious disease transmission. Twelve groundwater samples show a significantly increased risk for infectious disease transmission according to the total coliform bacterial range and one sample (H17-0420) from Mojosi in the Luvuvhu and Letaba WMA indicates a significant risk for faecal coliform (Appendix A).

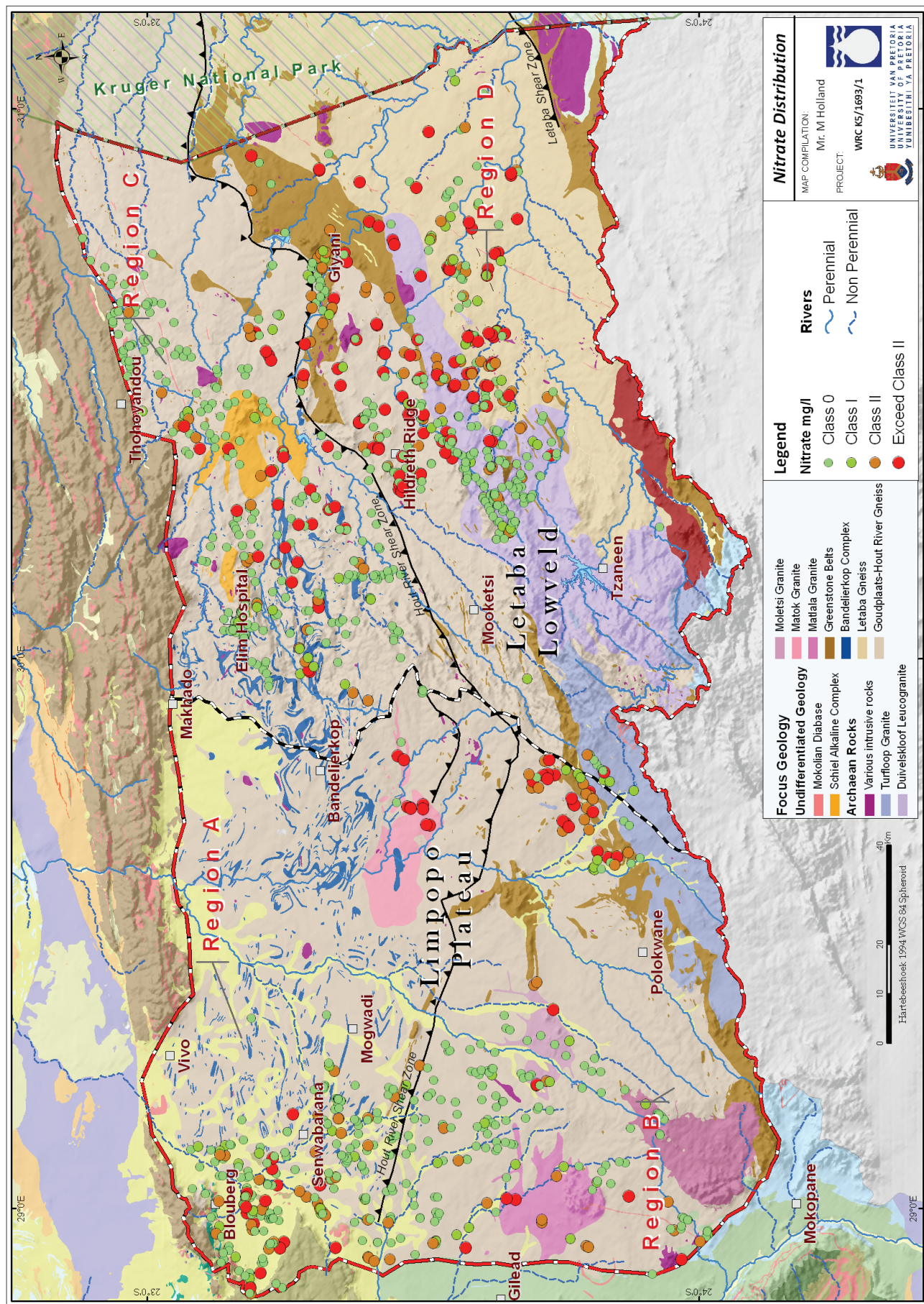


Figure 5.24. Nitrates distribution map, classes based on SANS (2006).

6. Investigation of pumping test techniques and sustainable pumping rates

6.1. The sustainable yield concept

The Department of Water Affairs and Forestry (DWA) proposed sustainability as a concept that will resolve water-use issues and is along with equitable access to water one of the main principles of the National Water Act of 1998. However, the meaning of the word 'sustainability' is often contested and is operationally and conceptually one of the most complex that modern science has faced (Cabezas and Fath, 2002). When applied to groundwater usage, 'sustainability' implies use that does not cause long-term deterioration of the overall resource, in terms of any measurable criteria like quality and quantity (Wright and Xu, 2000). Sustainable yield is often confused with 'safe yield', which assumes the attainment of a long-term balance between groundwater abstractions and annual recharge (Sophocleous, 1997). The safe yield concept implies natural replenishment as the sole limiting factor to pumping and may result in the depletion of surface water bodies and eventually the aquifer as a whole through surface-groundwater interaction (Sophocleous, 1997). Todd (1959) defined safe yield according to four determining factors, water supply (recharge to the basin or rate of movement of groundwater through the basin), economics (lowering of water levels until pumping is not economically viable), water quality (poorer water quality limits pumpage) and water rights (legal limits on safe yield). Several definitions of safe yield assume that recharge means 'natural recharge', and is equal to natural discharge. Definitions of 'sustainable yield' however, imply that 'recharge' includes also induced recharge as a result of groundwater abstractions, with induced recharge from stream depletion as the most important contribution (Kalf and Wooley, 1995). The interrelationship between sustainability and recharge depends also on aquifer storage. If the storage capacity of an aquifer is limited due to size or specific storativity, storage becomes the limiting factor for sustainability in times of droughts and not recharge. A similar case exists when an aquifer rejects parts of the potential recharge in the rain season. Such limited storage capacity is the case for about three quarters of the aquifers in South Africa (Seymour and Seward, 1996) and especially for Basement aquifers with a thin regolith.

Aquifers are in a state of natural long-term equilibrium prior to pumping, and in order to maintain this equilibrium, groundwater abstractions must be balanced by increased recharge (increase in the amount of water entering the system) or reduced discharge (reducing the amount of water leaving the system). Abstractions from storage indicate on the other hand non-equilibrium conditions. The increase in recharge and decrease in discharge is termed 'capture' and equilibrium is achieved when it balances pumping. Thus, it is only after pumping that the change in recharge will contribute to the determination of a sustainable yield (Seward et al., 2006). For sustainable yield, one would need to balance induced recharge or decrease in natural discharge with groundwater abstractions (Sophocleous, 1997). One method of assessing sustainable abstractions is therefore the analysis of seasonal variations in baseflow as an indicator of seasonal recharge and water demand fluctuations (Maimone, 2004).

When considering the spatial scale of an aquifer system, it is important to understand the associated scale of influence of a groundwater abstraction. Withdrawals from an aquifer might have a severe impact on individual ecosystems locally, but per square kilometre these withdrawals might be minor in terms of total recharge and discharge. Hence, a sustainable yield should account for small-scale local impacts and simultaneously consider the ability of an aquifer as a whole to recover from pumping stress (Maimone, 2004). Despite this, borehole and groundwater basin sustainability are often treated independently. The extent to which recharge is increased and through-flow is intercepted determines the sustainability of a borehole. Thus the position, spacing and depth of boreholes determine the possible sustainable borehole yield (Seward et al., 2006). For an aquifer system under natural conditions with no development, a balance or equilibrium between average inflow and outflow will develop in the long-term. With groundwater abstraction the outflow will decrease because of the capture. When considering a groundwater basin as whole, all the individual abstraction points where ‘capture’ is possible, permissible and sustainable, will together define the basin yield (Seward et al., 2006). It must be emphasized that the spatial distribution of these abstraction points strongly influences the total sustainable basin yield.

Beyond these components of a sustainable water budget for an aquifer system, several anthropogenic factors like waste water treatment and storm water collection, future increases along with location and time frame of regional water demand, associated costs and level of assurance of water supply have to be taken into account (Maimone, 2004). Tradeoffs between economy and ecology or demands of present and future generations present another challenge.

6.1.1. Sustainable pumping rates derived with the FC method

The recommended abstraction rates or “sustainable yields” in the GRIP dataset were determined using the FC Method. The sustainable yield is in this context defined as the discharge rate that will not cause the water level in the well to drop below a prescribed limit, identified from the nature and thickness of the aquifer (especially water strikes) and the depth of the well. The sustainable yield (Q_{sus}) is determined as (Van Tonder et al., 2002):

$$Q_{sus} = Q_{ob} \frac{S_p}{S_{ob}(t')}$$

where S_p is the drawdown of the well corresponding to the prescribed limit, $S_{ob}(t')$ is the observed drawdown at the time t' during a test with a constant discharge rate Q_{ob} and t' represents the minimum operation time in which the drawdown shall not exceed the prescribed limit. In order to estimate the sustainable yield, $S_{ob}(t')$ needs to be known over a long time period. $S_{ob}(t')$ is generally extrapolated using Theis’s well equation or a Taylor series expansion based on the extrapolation of drawdown measurements at late time, including drawdown derivatives. Such an approach is questionable in the calculation of the sustainable yields, especially if the aquifer system is heterogeneous or boundaries are not in close proximity to the tested well and pumping tests restricted to a few days. While van Tonder et al. (2002) recommend a very conservative approach for the estimation of sustainable yields (e.g. neglecting or assuming minimum recharge), the available drawdown

in the abstraction borehole as one of the most critical parameters for the yield estimations is often set to a specific water strike depth (known or derived from test itself) without any considerations of potential environmental impacts.

6.2. Managing sustainability

It is well accepted that aquifer systems are intricate and difficult to predict once human intervention has had an effect. Therefore, an adaptive management approach seems to be most appropriate for sustainable management of groundwater resources. Such approach deals with uncertainty associated with an imperfect knowledge base with regard to the regional status of groundwater resources due to shortcomings in regional monitoring of drainage basins, the limited knowledge of groundwater parameters as a result spatial and temporal parameter variability and uncertainties about the impacts of groundwater use on surface water or the ecology due to complex interdependencies (Seward et al., 2006). “Scenarios and goals are [therefore] regarded as hypotheses and estimates to be tested and challenged as the knowledge base grows” (Seward et al., 2006). From above-stated issues, it is clear that adaptive management is necessary in order to make sound predictions and recommendations as the knowledge base for groundwater expands with continuous monitoring.

6.3. Pumping test data

6.3.1. The GRIP data set

Pumping tests are commonly used to characterize aquifers and to evaluate aquifer responses to groundwater exploitation. In the area under investigation, single-well pumping tests were primarily conducted to recommend sustainable abstraction rates for rural water supply boreholes. Therefore determining aquifer parameters were not a priority. It must be noted that the determined ‘sustainable abstraction rates’ are based on the FC method (see chapter 6.1.1), i.e. they address only the long term assurance of water supply from a borehole based on available drawdown figures and abstraction rates and by no means the sustainable borehole or aquifer yield defined above (see chapter 6.1.1).

Most of the hydraulic tests in the framework of the GRIP project involved a step drawdown test (3 steps of up to 60 minutes each), followed by a constant-rate pumping test for 6 to 48 hours. Changes in water levels were typically only measured in the abstraction well during pumping and recovery. One of the shortcomings identified in the interpretation of the single well tests with the FC method was the insensitivity of transmissivity determinations to changes in storativity. In order to ensure consistency in the analysis of pumping tests within the Limpopo GRIP project, the various interpreters therefore assumed a constant storativity value of $1E-03$. In order to advance the conceptual understanding of Basement aquifers, results from GRIP pumping test dataset with monitoring boreholes were re-analysed considering the spatial drawdown behaviour or several pumping tests repeated if monitoring boreholes were newly drilled or previously not monitored.

6.3.2. Description of new Basement pumping tests

In order to determine sustainable yields of well fields in Basement aquifers of the Limpopo Province, a number of hydraulic tests of boreholes have been conducted between 2007 and 2010. Although every effort was made to conduct pumping tests based on pre-determined target areas such as geological zones, shear zones or lineaments, several targeted boreholes were blocked, closed or currently in use and could not be tested. Initial testing focused in the Letaba Lowveld on a relatively low yielding area towards the east of Elim. An additional three boreholes in the Lemondokop region were tested with the main objective of determining the hydraulic properties of the Hout River Shear Zone. Another five 48 hr tests were conducted at the Muyexe village to establish hydraulic parameters for the protection zone delineation which formed part of the groundwater management plan for the village (available from the authors on request).

The pumping test conducted in the Limpopo Plateau mainly focused on the high yielding area south of Senwabarana. Two potential well fields were also tested and will be discussed in detail in the subsequent section (see chapter 6.3.5). The locations of all pumping tests conducted within the project framework are given in Figure 6.1.

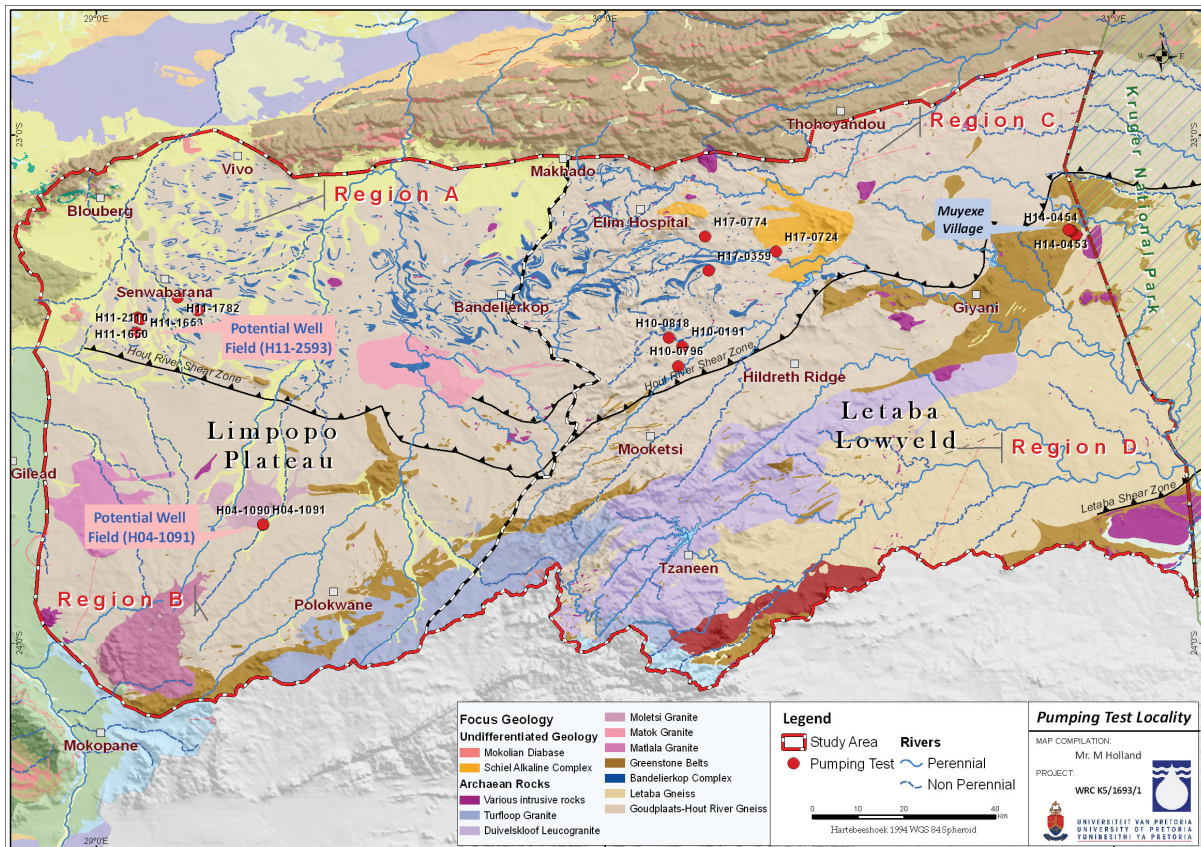


Figure 6.1. Location of pumping tests boreholes.

The pumping tests performed included step drawdown tests and constant discharge tests to estimate the transmissivity, storativity and long-term yield of the borehole. The details of the tested boreholes are given in Table 12. Although most pumping tests were conducted with an observation borehole nearby, not all observation boreholes responded to abstraction for various reasons (e.g. distance of observation boreholes). The pumping test data were generally analysed

with the software package AQTESOLV Pro version 4.5 using curve fitting of late-time data. In order to determine realistic aquifer characteristics from the pumping test data, the applied analytical solutions underlying conceptual models (e.g. confined, unconfined, leaky and fractured aquifers) must be representative of the characteristics of the real aquifer system.

Table 12. Details of tested boreholes.

Area	BH Nr.	Date	BH Depth (m.b.g.l)	Water Level (m.b.g.l)	Constant Yield (L/s)	Duration (hrs)	Drawdown	Observation BH's
Limpopo Plateau	H11-1650	Aug-08	64	21.44	31	72	5.6	H11-1651 (301 m), H11-1652 (255 m)
	H11-1653	Sep-08	79	22.23	33	24	4.6	H11-1651 (398 m), H11-1652 (441 m), H11-1654 (451 m)
	H11-2110	Sep-08	67	22.52	22	24	11.4	H11-2109 (211 m)
	H11-1782	Aug-08	101	36.38	11	24	16.0	H11-1781 (48 m)
	11-1763	May-08	150	34.64	1.4	24	11.0	H11-1764 (120 m)
Letaba Lowveld	H10-0818	May-08	51	12.48	2	24	7.3	H10-0823 (40 m)
	H10-0796	Apr-08	80	23.16	0.9	24	7.9	H10-0100 (40 m)
	H10-0191	Apr-08	83	30.09	5	24	19.0	H10-0816 (180 m)
	H14-0277	Aug-09	60	6.36	5.4	48	10.2	H14-0279 (220 m)
	H14-0279	Aug-09	85	7.61	6.3	48	20.9	H14-1288 (50 m), H14-1301 (250 m)
	H14-0453	Aug-09	47	7.86	7.5	48	18.0	H14-0277 (130 m), H14-0454 (290 m)
	H17-0359	Dec-07	113	24.80	1.2	24	18.0	-
	H17-0724	Dec-07	72	22.56	1.1	24	23.4	-
	H17-0774	Nov-07	52	12.53	1.2	24	8.0	-
	H14-0454	Aug-09	37	11.24	5	48	12.7	-
	H14-0275	Aug-09	59	28.55	5	48	11.9	-

Geological information on tested boreholes was used in conjunction with diagnostic plots to identify the aquifer system and prevailing flow regimes for a specific test (Kruseman and de Ridder, 2000). While a variety of solutions (Table 13) were tested for the modelling of the tests, leaky or fractured double porosity aquifer models proved to be the most suitable.

Table 13. Analytical solutions used for the interpretation of the pumping tests.

<i>Confined aquifer</i>	<i>Unconfined aquifer</i>	<i>Leaky aquifer</i>	<i>Fractured aquifers (Double porosity)</i>	
Theis (1935) Hantush (1961) Cooper-Jacob (1946) Moench-Prickett (1972) Papadopoulos-Cooper (1967) Dougherty-Babu (1984) Barker (1988)	Theis (1935) Cooper-Jacob (1946) Neuman (1974) Moench (1997) Tartakovsky-Neuman (2007)	Hantush-Jacob (1955) Hantush (1962) Hantush (1960) Neuman-Witherspoon (1969) Moench (1985)	Moench (1984) Barker (1988) with slab-shaped or spherical-shaped blocks	Gringarten-Witherspoon (1972) Gringarten <i>et al.</i> (1974) Gringarten-Ramey (1974)

6.3.3. Aquifer Response Classification

The heterogeneity of basement aquifers attributes to a diverse set of hydraulic properties that vary not only from site to site but even from borehole to borehole. The classification of the aquifer response to hydraulic testing remains problematic as similar drawdown behaviours can be observed for different types of aquifers. In some cases, the analysis was ambiguous and different analytical solutions could be applied, e.g. a leaky aquifer type (Hantush-Jacob method) or an unconfined porous aquifer with delayed yield behaviour (Neuman's solution) could hardly be distinguished from a double porosity behaviour (fractured model) based on the observed data.

From the pumping tests listed in Table 12 there are generally two categories of drawdown curves conceptualized, which represent different modes of aquifer response to abstractions. The first type shows an approximate sigmoidal drawdown curve on a semi-logarithmic plot, indicative of an unconfined porous aquifer with delayed yield, or a confined fractured double porosity aquifer. The observed time-drawdown curve (including its derivatives) does not allow for a differentiation between these models and both models can be conceptually justified. An example such behaviour is shown in Figure 6.2.

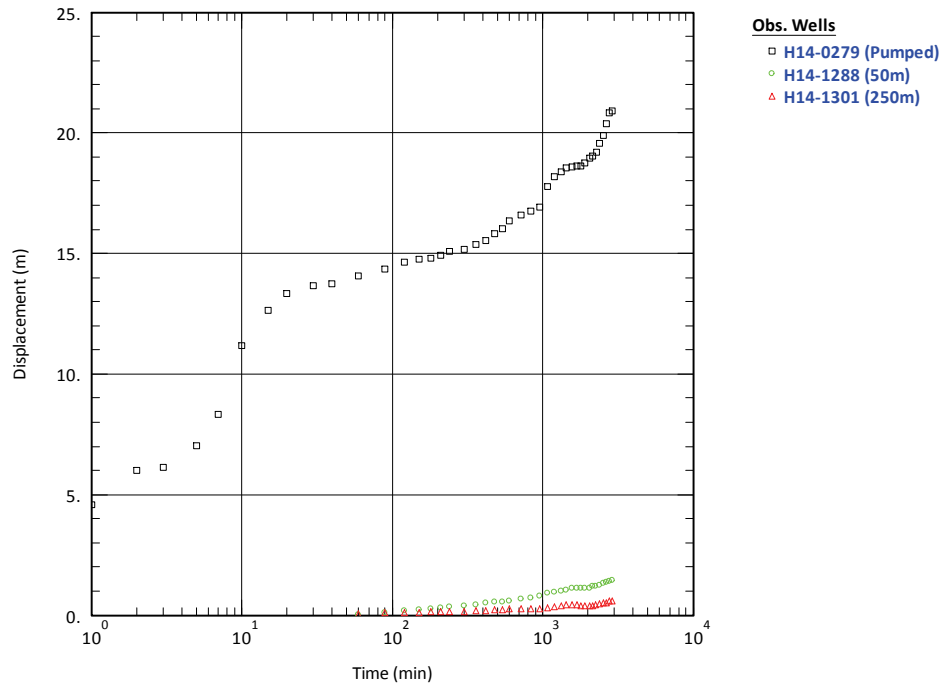


Figure 6.2. Semi logarithmic plot of borehole H14-0279 as an example the typical sigmoidal drawdown behaviour.

While the porous aquifer model explains the stabilised drawdown (flat segment) at intermediate times by (delayed) recharge from an overlying, less permeable aquifer; the fractured aquifer model assigns it to increased seepage from matrix blocks feeding into the fracture. The shape of the three dominant stages of the observed drawdown curves does not allow for a differentiation between these models and both can be conceptually justified, with water strikes at the bottom of the weathered zone (porous aquifer) versus deeper water strikes at fracture intersections (fractured aquifer). The latter is often substantiated by the distinct dips (fracture dewatering) during late times of the associated derivative data. In this model the

early flow towards the well is from fracture storage, supported at intermediate times by seepage from the rock matrix before water is derived from both systems at late times with dewatering of selected fracture systems. Once these fractures are dewatered, a marked increase in drawdown respectively decrease in transmissivity becomes apparent.

In the case of borehole H14-0279, no satisfactory simultaneous fit of the pumped and observed boreholes using a single solution could be achieved (Figure 6.3). The drawdown behaviour of the second observation borehole (H14-1301) may represent a different aquifer when compared to the pumping borehole and the first observation borehole (H14-1288).

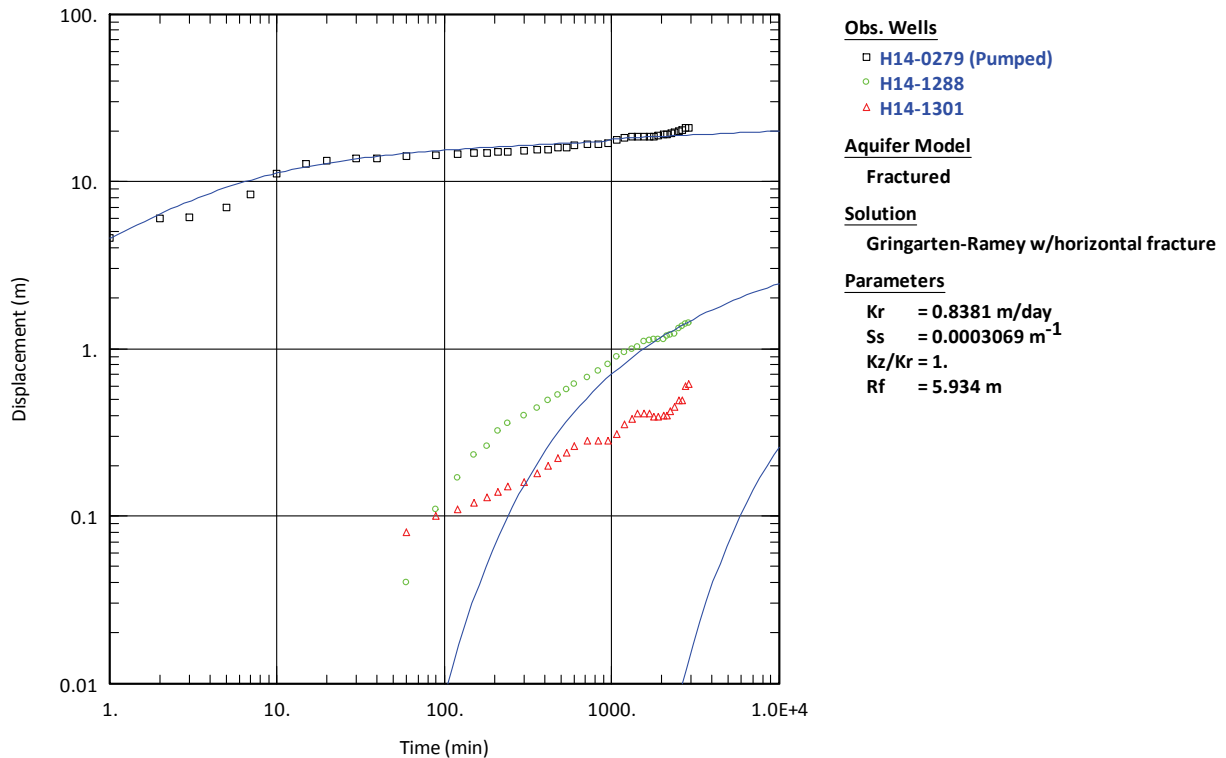


Figure 6.3. Logarithmic time-drawdown plot of borehole H14-0279 and associated observation boreholes.

The test was analysed using a range of solutions, considering different times of the data as well as boreholes.

- The single fracture model of Gringarten & Ramey (1974) provided realistic results for the pumping well and the 1st observation borehole ($K = 0.85$ m/day ($T \approx 51$ m²/day), $S = 3E-04$).
- Neuman's solution (1974) for an unconfined aquifer with delayed yield, fit of data for all boreholes ($T = 56$ m²/day, $S = 9E-03$, $S_y = 1E-03$),

The second type of observed time-drawdown behaviour can be conceptualized as flow to a pumping well from an aquifer with limited spatial extent (closed boundary). These typically low yielding boreholes have low transmissivities and limited significance in terms of water supply.

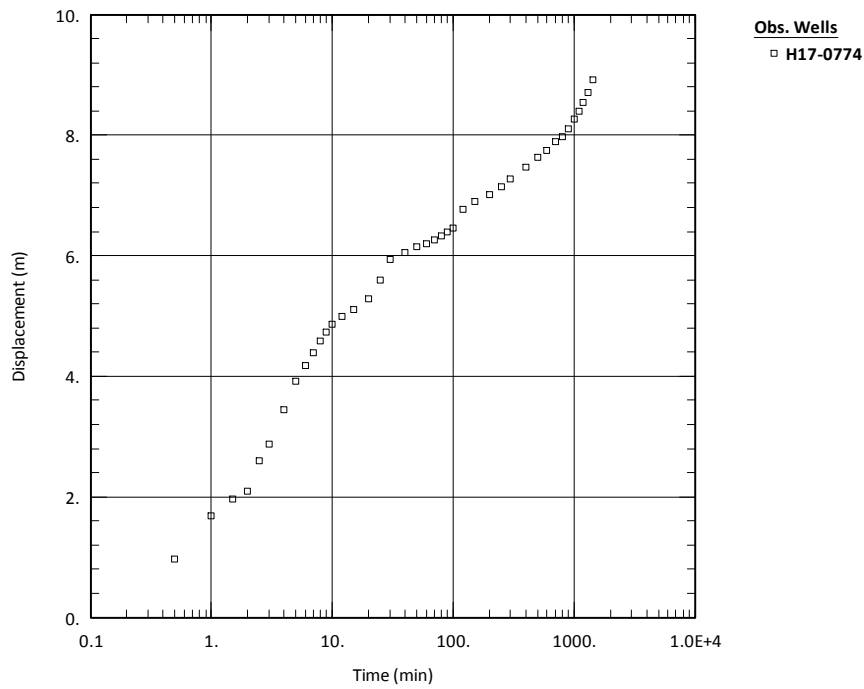


Figure 6.4. Semi logarithmic plot of borehole H14-0774 as an example the typical drawdown behaviour of pumping tests of boreholes that lead to failure.

The time-drawdown relationship indicates a linear flow regime at early times, which changes at intermediate times gradually towards a bi-liner and a spherical flow regime. The drawdown is briefly sustained by leakage and linear flow prevails again towards the end of the test, when the borehole starts to fail (no-flow boundaries).

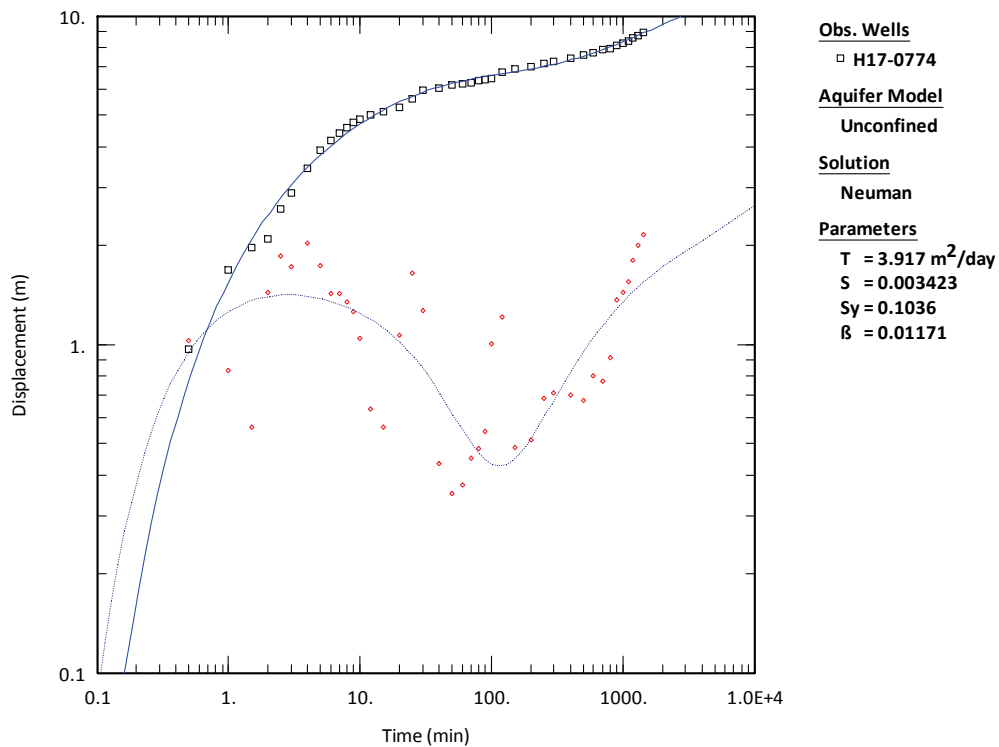


Figure 6.5. Logarithmic time-drawdown plot and automatic curve of borehole H14-0774.

In the case of borehole H17-0774, both the Barker's model for double porosity fractured aquifers ($K = 0.1$ m/day ($T \approx 6$ m²/day), $S = 1E-05$) as well as Neuman's solution for an unconfined aquifer with delayed yield ($T = 4$ m²/day, $S = 3E-03$) provided a realistic curve fit (e.g. Figure 6.5). However, the determined hydraulic conductivity of 0.1 m/d for the fractured aquifer solution is theoretically only applicable to a single intersected fracture and hardly comparable to the transmissivities determined with porous media aquifer. In addition a single boundary was incorporated into the curve of the Neuman solution which yielded an obvious good fit with realistic hydraulic parameters (Figure 6.5).

6.3.4. Summary of pumping test results

The hydraulic parameters obtained from the pumping test analysis and the analytical solutions applied for the curve matching procedure are summarised in Table 14. The representative values for T and S were obtained from the aquifer test analysis at both the pumped and the observation boreholes (if available).

Table 14. Summary of pumping tests and determined transmissivities T and storativities S .

Area	BH Nr.	Applied solution	Aquifer Type	T m ² /d	S	Alternative Solution	T m ² /d	S	Rec. Yield L/s per day
Limpopo Plateau	H11-1650 [#]	Neuman-Witherspoon	Leaky	330	2.E-01	Cooper-Jacob (Confined)	440	6.E-02	3.5
	H11-1653 [#]	Hantush-Jacob	Leaky	220	2.E-03	Cooper-Jacob (Confined)	210	6.E-04	4
	H11-2110*	Neuman-Witherspoon	Leaky	180	6.E-05	Cooper-Jacob (Confined)	330	9.E-04	3
	H11-1782*	Hantush-Jacob	Leaky	50	2.E-04	Cooper-Jacob (Confined)	40	2.E-04	2.5
	11-1763 [#]	Neuman-Witherspoon	Leaky	4	5.E-04	Cooper-Jacob (Confined)	8.5	3.E-04	0.3
Letaba Lowveld	H10-0818*	Hantush-Jacob	Leaky	47	9.E-04	Cooper-Jacob (Confined)	34	5.E-04	0.5
	H10-0796 [#]	Neuman	Unconf.	7	1.E-03	Hantush-Jacob (Leaky)	6		0.2
	H10-0191 [#]	Hantush	Leaky	1	3.E-03	Neuman (Unconfined)	4	3.E-03	0.1
	H14-0277*	Neuman	Unconf.	95	2.E-03	Hantush (Leaky)	75	4.E-04	1.8
	H14-0279*	Gringarten-Ramey	Fractured	51	3.E-04	Neuman (Unconfined)	56	1.E-03	1.6
	H14-0453*	Neuman	Unconf.	77	4.E-04	Hantush (Leaky)	48	2.E-03	1.1
	H17-0359 [?]	Neuman	Unconf.	4	1.E-03	Hantush-Jacob (Leaky)	5	7.E-04	0.2
	H17-0724 [?]	Neuman	Unconf.	1	9.E-03	Gringarten-Ramey (Fractured)	1.2	8.E-05	0.1
	H17-0774 [?]	Neuman	Unconf.	4	3.E-03	Barker (Fractured)	6	1.E-05	0.2
	H14-0454 [?]	Neuman	Unconf.	16	2.E-03	-		4.E-06	0.5
	H14-0275 [?]	Gringarten-Ramey	Fractured	43	5.E-02	Gringarten-Ramey (Fractured)	52	9.E-04	0.8

* - Observation hole monitored with drawdown.

- Observation borehole monitored with no-influence.

(?) – Low confidence in determined parameters.

It is clear from the pumping test results that the confidence level of the determined hydraulic parameters (T and S) generally increases if observation boreholes are present. A number of tests had to be interpreted based on their recovery data plots (Agarwal, 1980) due to inconsistent discharge rates with associated erratic water level responses during the abstraction test. Some tests were conducted with a too low abstraction rate, i.e. the aquifer was not stressed sufficiently to estimate parameters or sustainable yields accurately. Re-testing of selected boreholes at a higher discharge rate provided evidence of fracture dewatering and no-flow boundaries at late times.

The arithmetic average storativity value determined is 5.E-02 and 7.E-03 for the Limpopo Plateau and Letaba Lowveld respectively, coinciding closely with the constant storativity value of 1.E-03 used in the initial analysis of the GRIP dataset.

6.3.5. Testing of potential well fields

Moletsi well field

The Moletsi Granite, which intruded into the Hout River Gneiss, is located approximately 20 kilometres northwest of Pietersburg (Figure 6.1). The contact with the surrounding gneiss is mostly concealed except for a few exposures more noticeably in riverbeds. Numerous diabase dykes probably of Mokolian age also cut the granite. During the batholiths project conducted by du Toit (2001) numerous boreholes targeted this contact zone. A number of existing boreholes were augmented by a newly drilled observation borehole (H04-2449) perpendicular to the existing boreholes orientations (Figure 6.6).

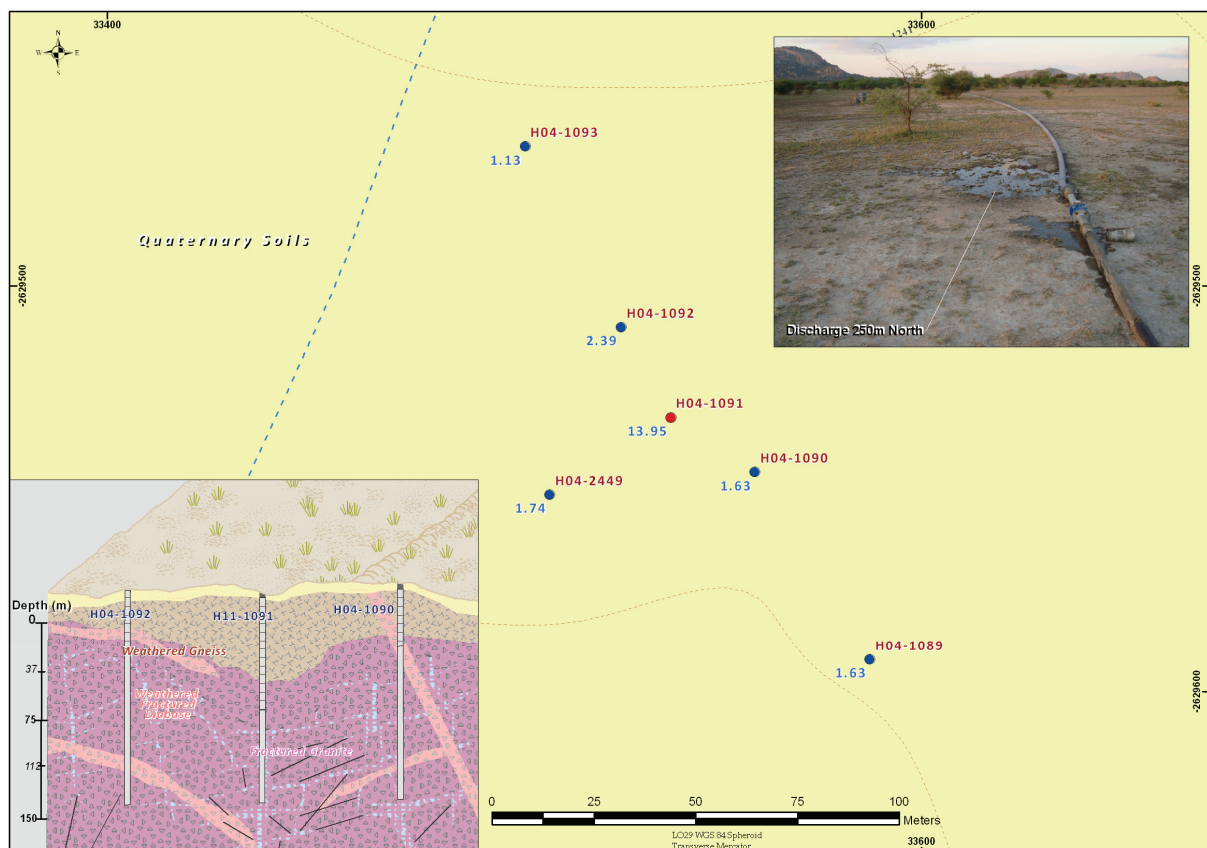


Figure 6.6. Borehole setting of pumping test conducted at the Moletsi Granites. (Drawdown achieved at the end of constant test is indicated on the map).

The constant discharge test was conducted at borehole (H04-1091) with a discharge rate of 10 L/s for a period of 72 hours. The observation boreholes and a summary of the drawdown and water level for each borehole are listed in Table 15.

Table 15. Summary of observation boreholes.

Bh ID	Distance from abstraction hole (m)	BH Depth (m)	Start WL (mbgl)	Drawdown (m)
H04-1091	0	150	9.76	13.9
H04-1089	76	150	9.78	1.6
H04-1090	25	150	9.71	1.6
H04-1092	26	150	9.71	2.4
H04-1093	76	150	9.14	1.1
H04-2449	42	52	9.74	1.7

The observation boreholes reacted in the same way as the abstraction borehole and are generally in good hydraulic contact. The estimation of the transmissivity based on methods from Neuman (1974) and Barker (1988) yields values between 60 and 80 m²/day and an average storage coefficient of $S = 3E-03$. The long term recommended yield not taking into account other abstraction influences is 2.5 L/s/day.

Brilliant farm well field

The Brilliant farm is approximately 35 km east of Mogwadi which is well known for its irrigation farming community. Irrigation farming took its toll in the early 1990s the Mogwadi (Dendron) district was declared as an underground water control area under the old water act of 1956. Towards the east of Mogwadi the area is characterised by typical rural communities. The villages have little or no infrastructure and basic water supply services are poor. During 2000/2001 the groundwater potential of the Hout River Gneiss with special reference to the area were investigated. Five out of the six exploration boreholes drilled on the farm had an airlift yield of above 20 L/s. During the current study two of these boreholes were re-tested at an average yield of 30 L/s for 24 and 72 hrs. In both cases minimal drawdown was obtained and strain on the testing equipment due to high discharge rates lead to fluctuating abstraction rates and erratic water level responses. A large diameter borehole (300 mm) was drilled to effectively increase discharge rates to up to 60 L/s. In addition, three observation boreholes were drilled at right angles to the large diameter pumping test hole (Figure 6.7).

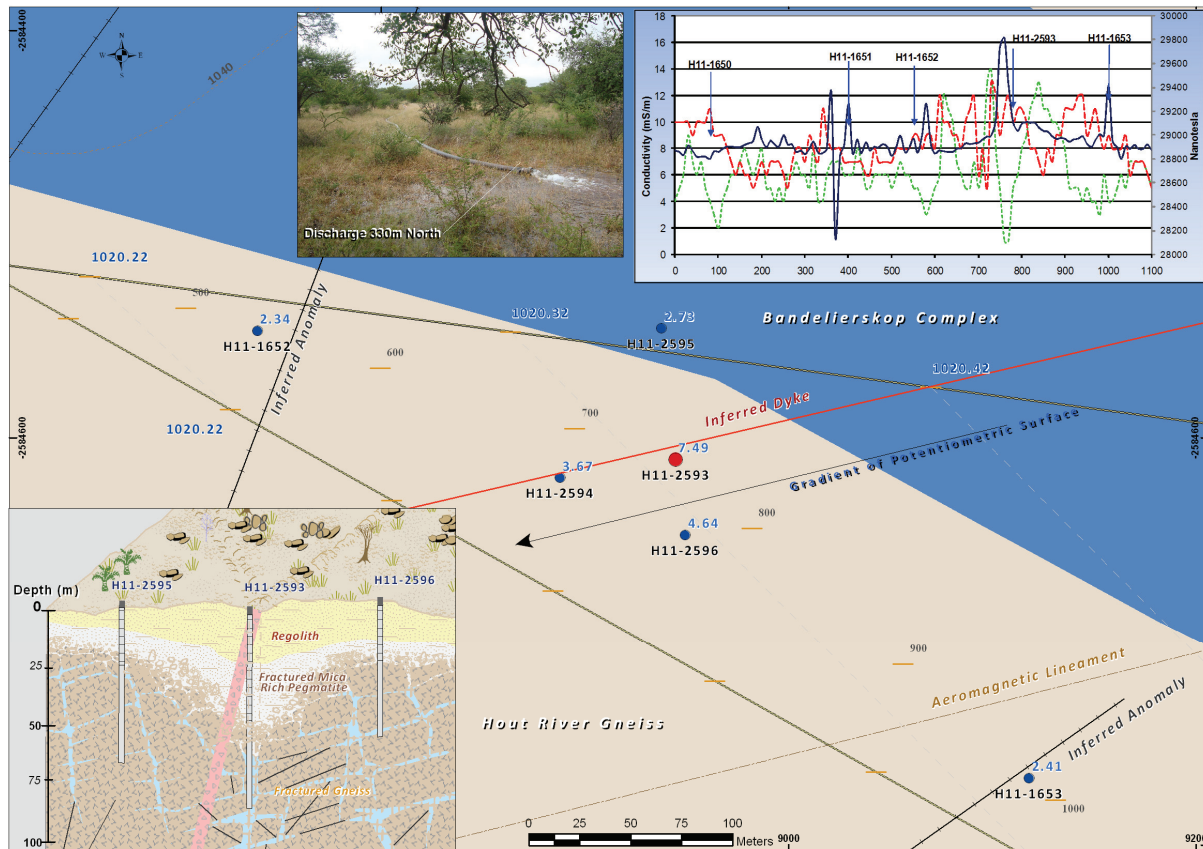


Figure 6.7. Borehole setting of pumping test conducted at the farm Brilliant. (Drawdown achieved at the end of constant test is indicated on the map).

The constant discharge test was conducted at borehole (H11-2593) with a discharge rate of 55 L/s for a period of just over 60 hours, possibly the largest documented discharge test conducted in the basement lithologies of the Limpopo Province to date. The observation boreholes including initial water levels and final drawdown values are listed in Table 16.

Table 16. Summary of observation boreholes.

Bh ID	Distance from abstraction hole (m)	BH Depth (m)	Start WL (mbgl)	Drawdown (m)
H11-2593	0	84	24.04	7.49
H11-1652	215	90	22.86	2.34
H11-1653	233	78	23.23	2.41
H11-2594	58	120	24.09	3.67
H11-2595	65	72	23.86	2.73
H11-2596	38	52	23.85	4.64

A slightly better hydraulic connection is observed between the boreholes east and south of the discharging well compared to the northern borehole (H11-2596). The estimation of the transmissivity based on Moench's (1984) double porosity fractured aquifers (slab-shaped blocks) yields a value of 1 200 m²/day and an average storage coefficient of $S = 1E-02$. Despite the recommended yield of 14 L/s/day derived from the FC-method, a yield of only 9 L/s per day is suggested until monitoring data have been collated to assess the impact of the abstraction on regional water levels.

6.3.6. Suitable pumping test

Proper planning and execution of a pumping test will yield reliable data and enable the user to estimate realistic parameter values along with sustainable yields. The most common factors influencing a proper analysis of a pumping test are inconsistent pumping rates during constant discharge pumping tests (especially at high yields) and insufficient drawdowns (i.e. too low rate or too short duration) that do not reach the main water strikes or encounter boundary conditions. Observation boreholes are often monitored haphazardly by contractors without understanding the importance of the observed results.

In order to estimate the long-term sustainable yield of a borehole, the following procedure is recommended:

- A step drawdown test (minimum 4 steps of 1 hour each) to locate the depth of the main water strike as well as to determine a suitable abstraction rate for the constant discharge test.
- The constant discharge rate should ideally reach 80-90% of the available drawdown after one or two days and maintain it for another day if the drawdown stabilises in order to stress the aquifer sufficiently. Otherwise the test should continue until failure of the borehole
- At least one observation borehole at a distance of 20 to 50 m from the abstraction borehole should be installed and monitored at regular intervals to determine the spatial extent of drawdown. The confidence of determined hydraulic parameters increases significantly as the monitoring borehole allows the direct determination of storativity values.
- A sound conceptual model for the aquifer including locations and distances to potential flow boundaries needs to be developed and applied for the interpretation of the test. The model will determine the choice of analytical solution employed for the interpretation of the test.

7. Revised Conceptual Model

7.1. Factors influencing borehole yields

In order to identify factors, which influence the hydrogeological parameter, the dataset was spatially sub-divided using available GIS layers. Selection criteria ranged from lithology, erosion surfaces, rivers, structures, lineaments and faults. The (arithmetic) mean values of the selected subsets are compared to the corresponding population mean and a one-sided Student t-test used to determine the level of confidence that the specific value is larger or smaller than the population mean. This approach ensured an objective unbiased assessment of a large number of influencing factors. It must be noted that the assessed boreholes were not drilled randomly, but after preliminary site-investigations. The dataset is in this regard biased towards anomalies and higher yields in comparison to random sampling of Basement aquifers are expected. However, the large number of successful as well as unsuccessful boreholes compensates partially for this statistical bias.

7.1.1. Spatial distribution of transmissivity

The spatial distribution of transmissivity and recommended yield values obtained from the GRIP dataset is presented in Figure 7.1 and Figure 7.2 respectively. The classification scheme of both variables is based on the geometric interval, i.e. by minimizing the square sum of elements per class. From the onset the difference of borehole productivity between the tectonic / morphostructural regions described in section 5.5.2 is obvious (e.g. between Region A and Region D). The cumulative frequency graphs in Figure 7.3 confirms that Region A is more productive followed by Region B, Region C and then Region D. It should be noted that a major part of Region D comprises the Tzaneen escarpment, which is underlain by the poorly weathered and fractured Duivelskloof Leucogranites. Immediately east of the Leucogranite outcrop higher yielding boreholes are evident (Figure 7.2)

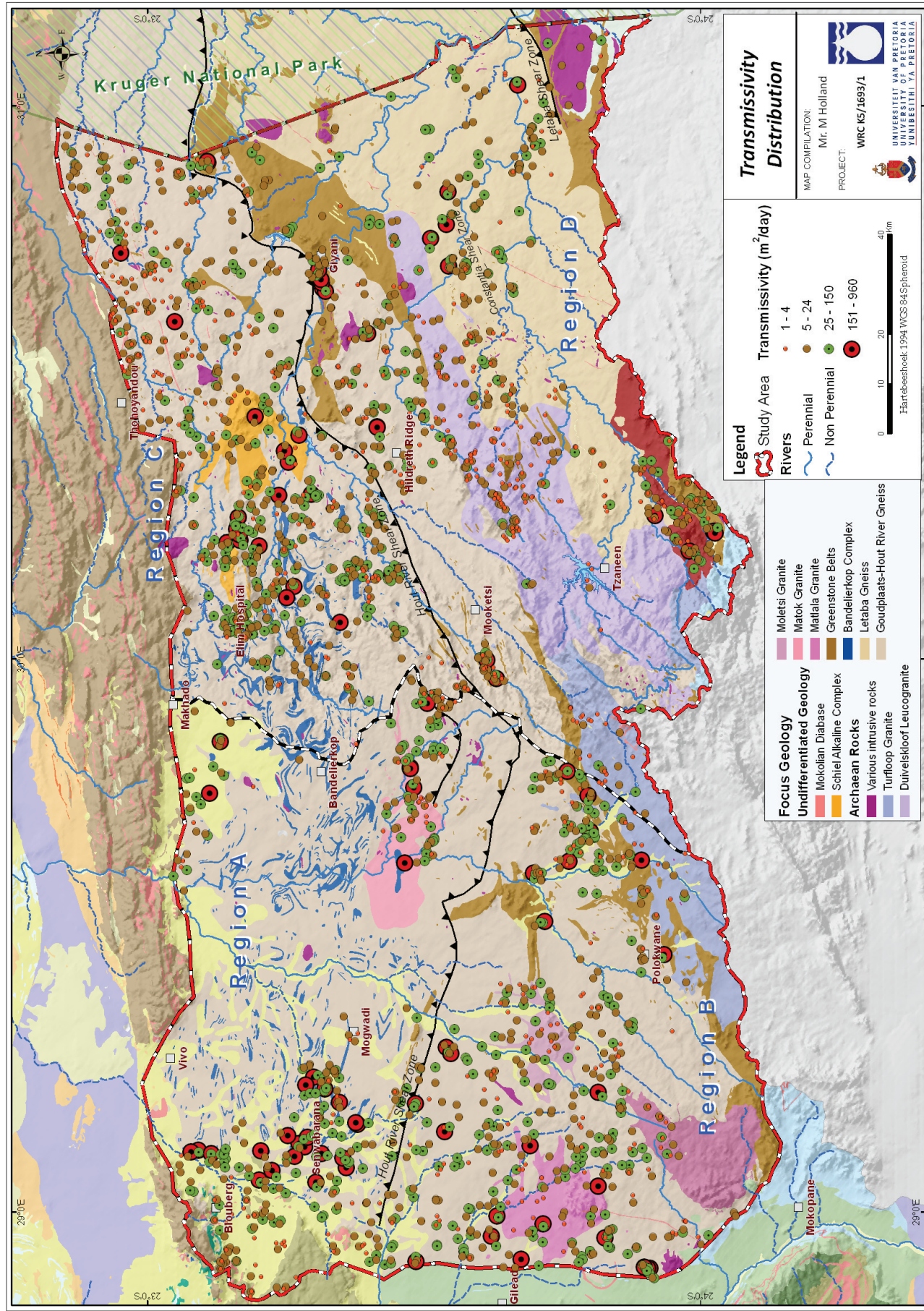


Figure 7.1. Spatial distribution of transmissivity values obtained from the GRIP dataset.

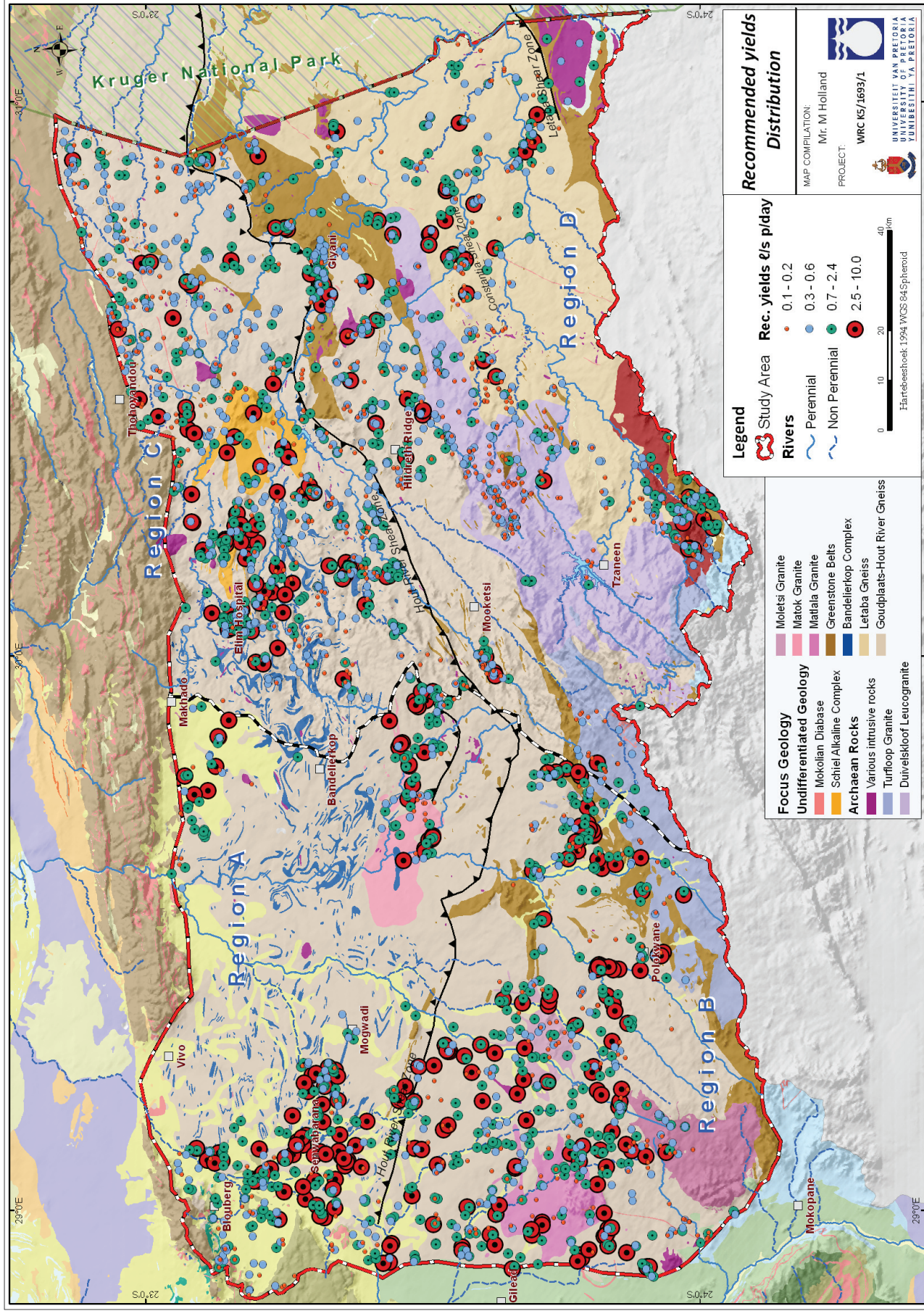


Figure 7.2. Spatial distribution of recommended yields obtained from the GRIP dataset.

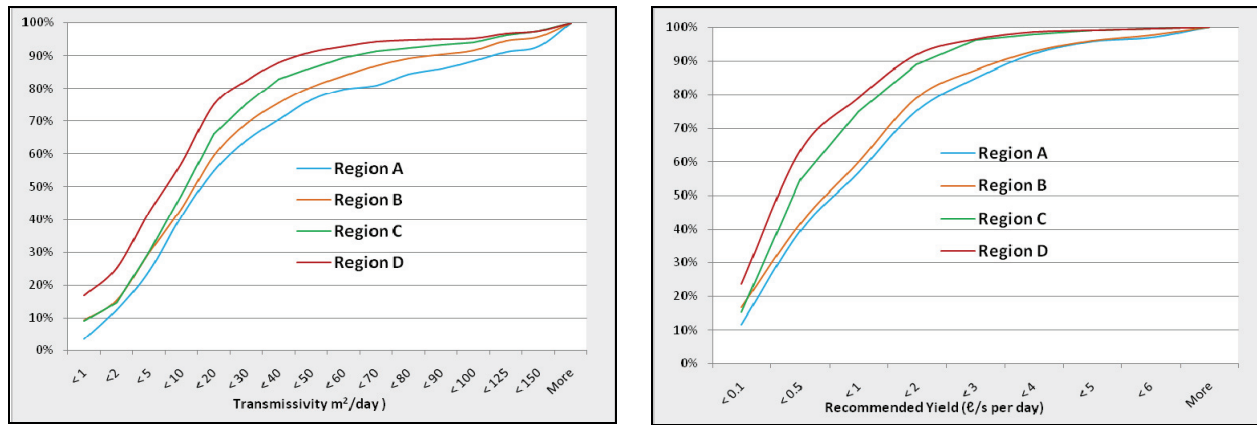


Figure 7.3. Cumulative frequency distributions of transmissivity and recommended yields from boreholes classified according to the structural region (delineated in section 5.5.2).

7.1.2. Rock Type

The first analysis is based on the lithological information (drillers geological note) captured in the GRIP dataset. Unfortunately 90 percent of the lithology captured pertains to the Letaba Lowveld rather than the Limpopo Plateau. Nevertheless the cumulative frequency graph of the major lithologies in the area clearly indicates the relative poor productivity of granites and diabase/dolerite associated with dykes in comparison to pegmatites (Figure 7.4).

The metamorphic rocks gneiss and schist have similar geological characteristics and expectedly similar transmissivity ranges.

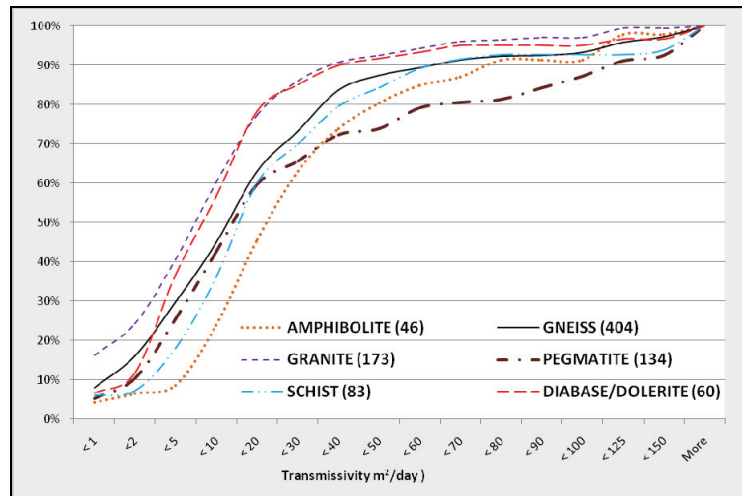


Figure 7.4. Cumulative frequency distributions showing the influence of lithology on borehole productivity.

Pegmatite is clearly more productive especially in the latter ranges of the frequency plot. Eighty percent of boreholes drilled in pegmatite attained transmissivities of 60 m²/d with a mean value of 44 m²/d (Table 17). The amphibolites can be associated with the structural events coupled with regional amphibolites-grade metamorphism that resulted from a continental collision between the Kaapvaal and Zimbabwe Cratons (Anhaeusser, 1992). These mylonitic rocks associated with crushing and intense shearing within the Hout River Shear Zone are more favourable groundwater targets than the adjacent granite and gneisses. Based on the results, rock type does play an important role in selection of productive drilling targets.

However, these rocks such as pegmatite often occurs as veins, forming features of restricted extent rather than a regional groundwater exploratory feature (Cook, 2003).

Table 17. Mean transmissivity and recommended yields for different lithologies obtained from drillers logs.

Lithology	Nr. of BH's	Transmissivity m ² /d	Rec. Yield L/s per day
<u>ALL</u>	827	29.6	0.85
AMPHIBOLITE	33	35	<u>1.29</u>
DIABASE/DOLERITE	36	20	0.82
GNEISS	426	31	0.97
GRANITE	140	21	0.74
PEGMATITE	117	<u>44</u>	1.13
SCHIST	75	29	0.94

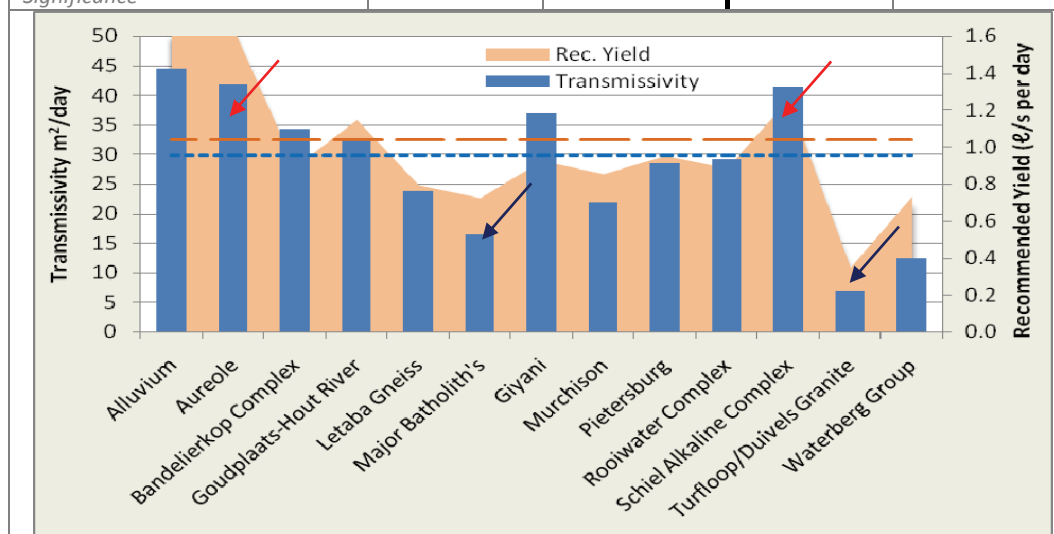
For the second analysis the geological information for each borehole was obtained from the published 1:250 000 geological maps. The identification of “alluvium” boreholes was based on the published maps as well as 100 m buffer zones along major river courses. To get a clearer overview on the significance of the granite intrusives a 500 m buffer (in- and outside of the mapped features) was used to present the metamorphic aureole of the batholith’s outcropping mostly in the Limpopo Plateau. The boreholes were grouped according to the geological or lithological setting and the corresponding mean values along were calculated and compared (one-sided Student t-test) to the total population (Table 18).

There is a distinct variability in the transmissivities between the lithologies and geological setting of the focus area. The highest transmissivities are – as expected – observed in the primary alluvial aquifers, while the contact zones of the younger granite batholiths provide the highest transmissivities of the basement rocks itself. Although most of the study area is located on crystalline rocks, the presence of quaternary covers of soil, calcrete and ferricrete or alluvial sediments along drainage channels are common. These covers are generally not very thick, but widespread towards the north-east of the area and their potential as high recharge and storage zones suggest that high yields could be obtained.

Intrusives such as batholiths can displace the host rocks during intrusion in order to create space for the ascending magma. A number of physical changes occur in the host rock e.g. tension jointing, peripheral cleavage and ductile deformation, enhancing the water bearing characteristics of the host rock within the aureole, as evident from the elevated transmissivities and yields. The younger, large elongated leucogranites together with the main batholiths bodies itself and the sedimentary rocks of the Waterberg group have the lowest transmissivities. While the geological analysis of the data set indicates the obvious, i.e. that the geology influences borehole productivity, the variability within each rock type (e.g. the gneisses of the Letaba and Goudplaats-Hout River formations) relate to other factors such as fracture density and susceptibility to weathering.

Table 18. Determined hydrogeological parameter based on the geological setting of boreholes.

Parameter	Transmissivity m ² /d		Rec. Yield L/s per day	
	Nr. of BH's	Values	Nr. of BH's	Values
<u>All data</u>	<u>2 484</u>	<u>30</u>	<u>3032</u>	<u>1.04</u>
Alluvium	200	44	245	1.63
Significance		100%		100%
Aureole	60	42	68	1.64
Significance		95%		99%
Bandelierkop Complex	47	34	51	0.89
Significance		69%		81%
Goudplaats-Hout River Gneiss	1 400	33	1650	1.14
Significance		96%		100%
Letaba Gneiss	195	24	281	0.79
Significance		97%		100%
Major Batholith's	84	16	102	0.72
Significance		100%		100%
Giyani	61	37	109	0.92
Significance		77%		89%
Murchison	24	22	26	0.85
Significance		93%		91%
Pietersburg	38	29	40	0.95
Significance		56%		65%
Rooiwater Complex	40	29	48	1
Significance		53%		83%
Schiel Alkaline Complex	50	42	41	1.26
Significance		90%		84%
Turfloop Duivelskloof Granite	230	7	299	0.35
Significance		100%		100%
Waterberg Group	55	12	72	0.73
Significance		100%		100%



7.1.3. Weathered layer (regolith)

To establish the influence of the weathered layer on the productivity of a borehole, the depth to bedrock (interpreted as fresh un-weathered / un-fractured bedrock from geological logs) were related to transmissivity and recommended yield. The spatial distribution of boreholes with detailed geological logs used in the analysis is illustrated in Figure 7.5. The scatter plots (Figure 7.6) show no correlation between transmissivity and weathering. Chilton and Foster (1995) highlighted the fact that very few authors if any could obtain significant correlations between regolith thickness and borehole yield from statistical approaches. The authors attributed these poor correlations to the subjectivity of the yield value itself and to the overriding local factors such as well construction or efficiency. The common viewpoint in basement hydrogeology is therefore that a deeper weathering profile would have a major controlling factor on the borehole productivity due to enhanced permeability and storage of this zone. However, the semi-arid area of investigation is characterised by a relatively thin regolith (with less important water strikes) that is generally present above the main water strike(s) (refer to Table 10). Historical groundwater exploration within the area targeted successfully structural features and contact zones at depth within the unweathered bedrock instead of the rather thin regolith. Regionally, the influence of the weathering layer on borehole productivity is therefore considered poor. However, an ideal borehole or well would still intercept long or interconnected fractures in the solid rock which are in contact with a large volume of overlying, low permeability material that provide a consistent source of water.

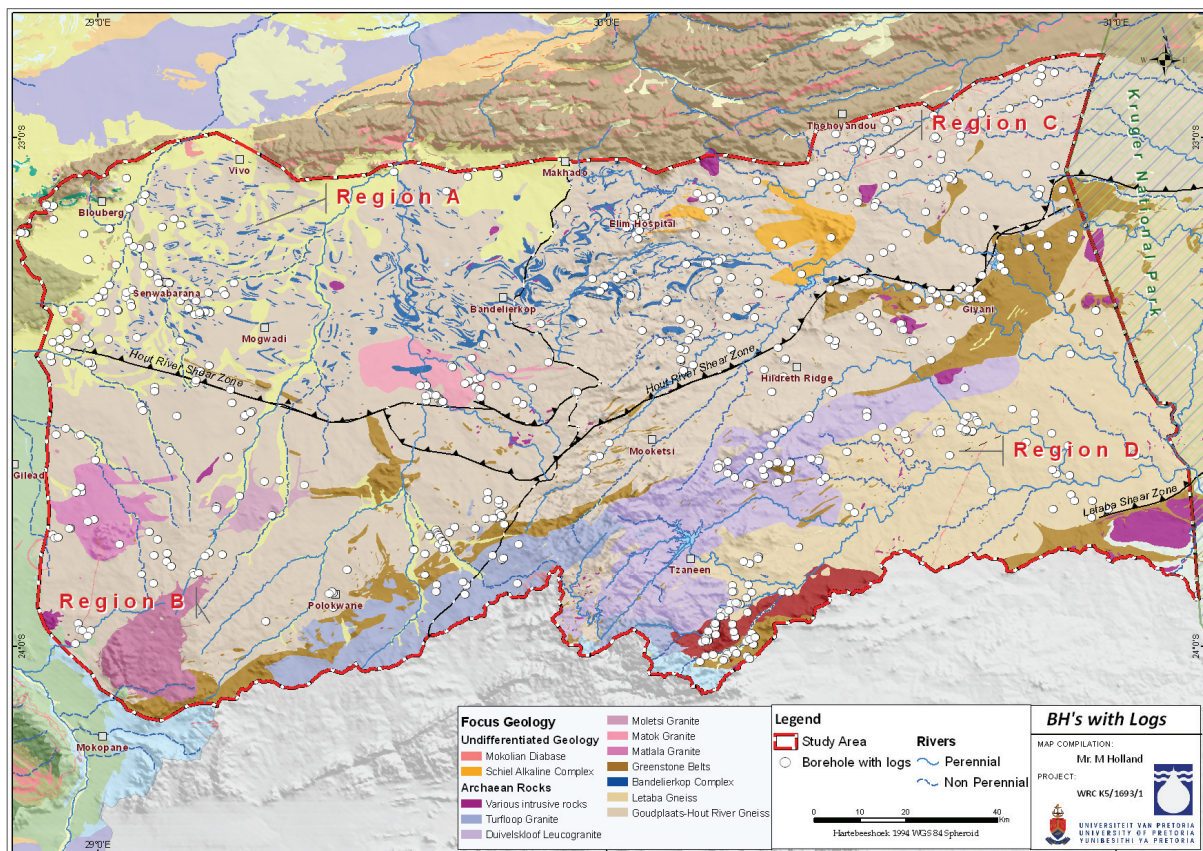


Figure 7.5. Distribution of boreholes with detailed geological logs.

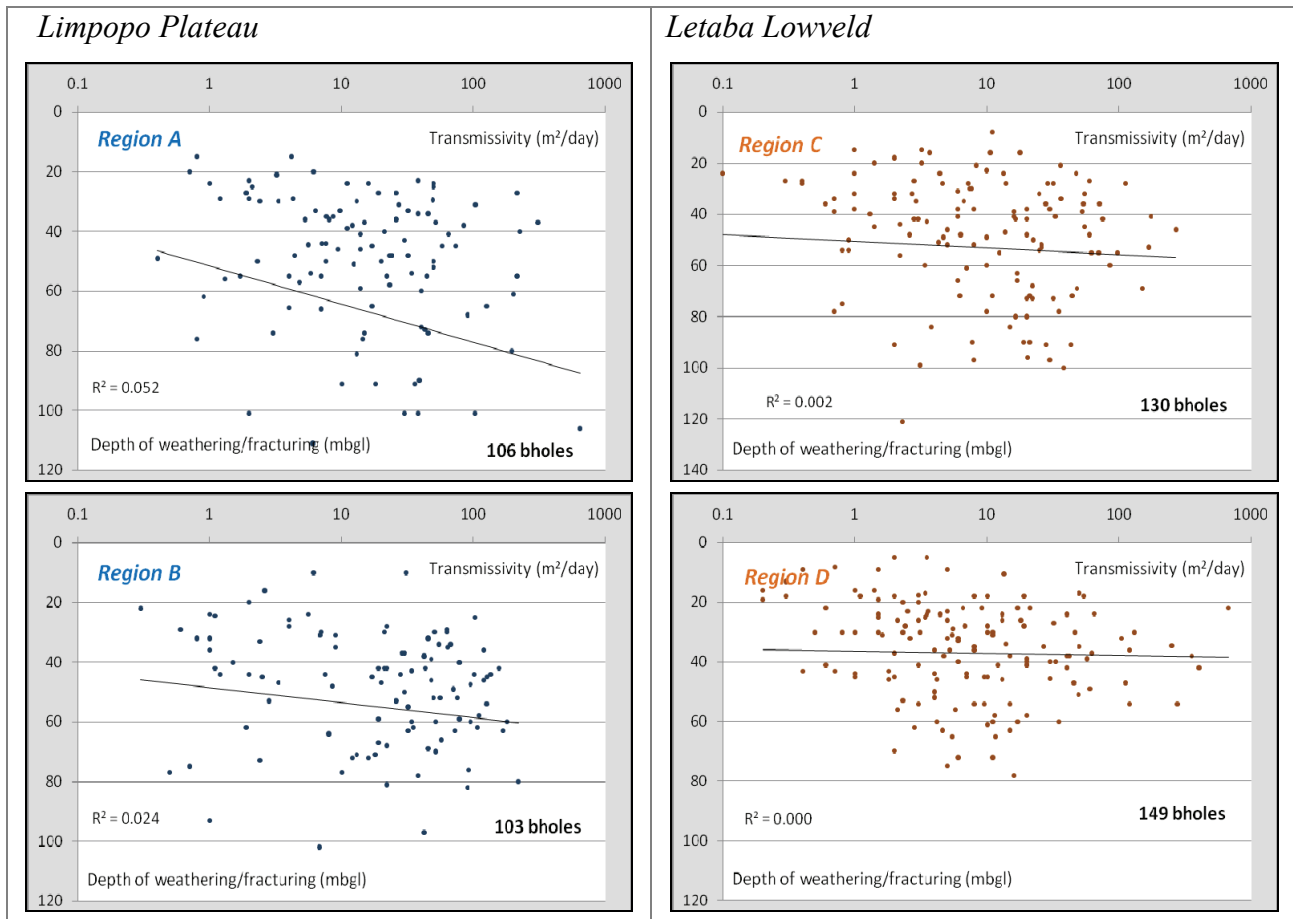


Figure 7.6. Cross-plots of transmissivity and weathering / fracturing depth for the Limpopo Plateau and the Letaba Lowveld.

7.1.4. Influence of dykes

As dykes occur extensively in the focus area it is important to establish their role in the occurrence of groundwater. The geological logs obtained were divided into boreholes encountering diabase/dolerite (presenting dykes) and boreholes with no diabase/dolerite (no dykes) (Figure 7.7). The distribution of transmissivity values of boreholes devoid of diabase/dolerite is evidently higher than boreholes associated with diabase/dolerite. The reason for this difference, typifies the paradigm of groundwater exploration in Southern Africa for the last few decades. According to Sami (2009), most boreholes are sited by ‘anomaly hunting’ using magnetic or electromagnetic traverses, often with little or no understanding of the structural geology of the target area, or a lack of understanding of the geological stresses on identified anomalies. Based on Figure 7.7, dykes should not be seen as prime regional targets for groundwater exploration.

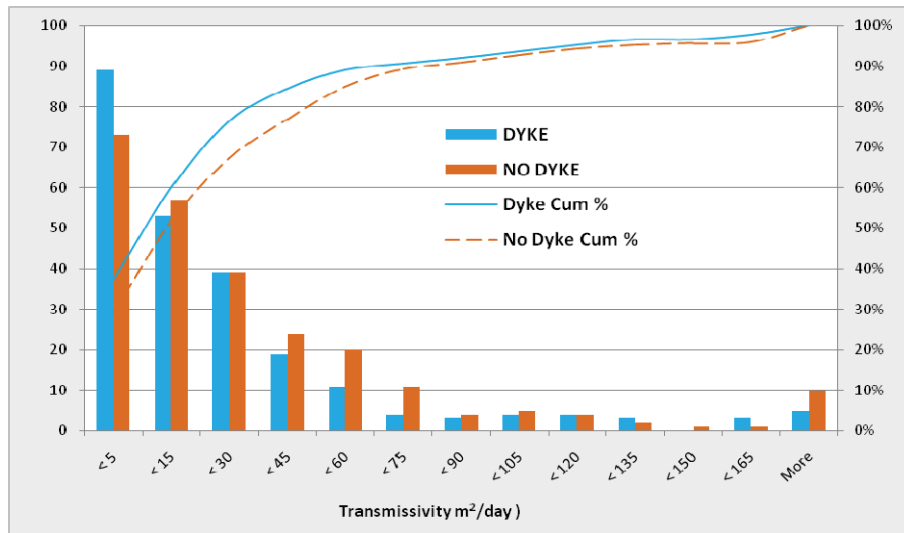


Figure 7.7. Cumulative frequency distributions showing the influence of dykes on borehole transmissivity.

Another useful assessment of the role of dykes on borehole productivity is its proximity to the mapped (published) dykes and regional aeromagnetic data (inferred dykes). Data from 2 500 boreholes shows no significant relationship between transmissivity and distance from aeromagnetic inferred dykes (Figure 7.8A). To closer evaluate the correlation between borehole productivity and the trend of dykes (azimuth), boreholes occurring within 150 m of dykes were examined (Figure 7.8B). NW to NNE ($N315^{\circ}W$ - $N30E^{\circ}$) striking dykes offer obviously poorer water bearing characteristics than E-W or NE trending dykes, i.e. dyke orientations need to be taken into account for borehole siting.

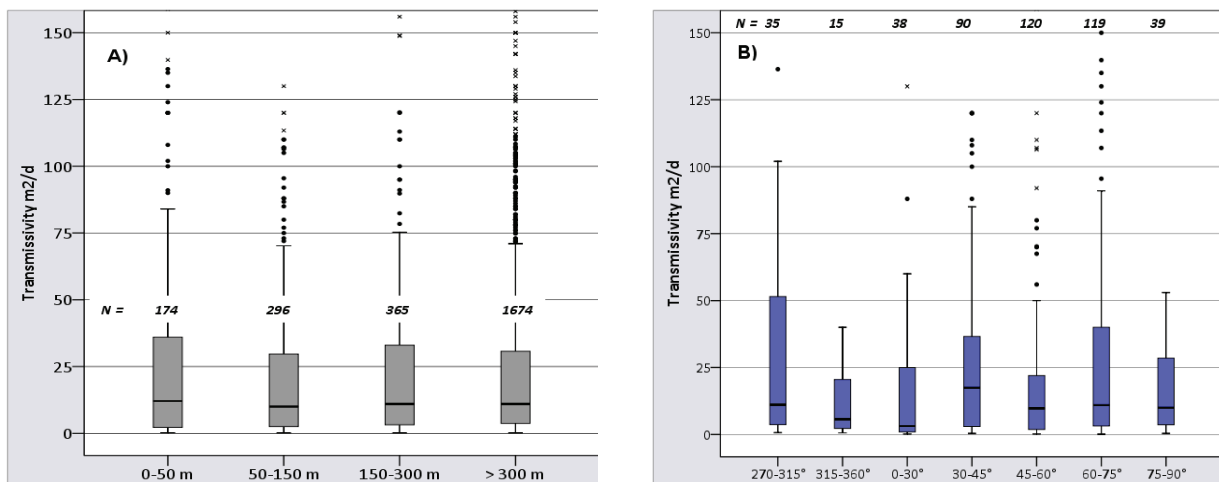


Figure 7.8. A Box plot of borehole transmissivity and proximity to a dyke. **B** Box plot of transmissivity and lineament azimuth. The *box* represents the 25 and 75% quartiles, while the median is represented by the *horizontal line within the box*. Middle outliers are *marked by circles* while extreme outliers are *marked by crosses*. The *vertical lines (whiskers)* connect the smallest and largest non-outliers.

7.1.5. Influences of Topography and proximity to rivers (drainage channels).

The borehole productivity parameters transmissivity and recommended yield were filtered according to the topographical setting on which the boreholes occur (as recorded in the GRIP database by driller). The corresponding mean are given in Table 19. As expected the

boreholes located along rivers (alluvial aquifers) have above average transmissivities and yields, i.e. they represent the most favorable borehole locations from a topographical point of view. Boreholes in mountainous areas show significantly lower transmissivities and yields, i.e. the most unfavourable topographical borehole locations. Since the topographical setting is directly related to the underlying geology it is not an independent influencing variable.

Table 19. Determined hydrogeological parameter based on the topographic setting of boreholes.

Parameter	Transmissivity m ² /d		Rec. Yield L/s per day	
	Nr. of BH's	Values	Nr. of BH's	Values
<i>All data</i>	1 449	30	1 837	1.04
<i>Along River</i>	424	33	245	1.35
<i>Significance</i>		<i>53%</i>		<i>100%</i>
<i>Mountain</i>	23	7	35	0.32
<i>Significance</i>		<i>100%</i>		<i>100%</i>
<i>Slope</i>	300	26	392	0.84
<i>Significance</i>		<i>100%</i>		<i>100%</i>
<i>Valley</i>	82	31	98	0.91
<i>Significance</i>		<i>66%</i>		<i>98%</i>
<i>Flat Surface</i>	620	38	789	1.15
<i>Significance</i>		<i>96%</i>		<i>78%</i>

Due to the generally flat topography in the Limpopo Plateau the influence of valley floors on the borehole productivity is not evident. In contrast, the more rugged topography of Letaba Lowveld shows more productive boreholes located along the valley floors in comparison to boreholes located on slopes, mountainous or flat surfaces. The influence of topography on well yield in fractured rocks has also been shown by Henrikson (1995), Fernandes and Rudolph (2001) and Verbovšek and Veselič (2008). In all cases these authors found greater well yields in low topographic settings (e.g. valleys) than in the steep slopes. Valleys are often associated with regional fracture features. In the mountainous Letaba Lowveld these topographic low valleys form furthermore the hydrological base, representing natural groundwater discharge areas.

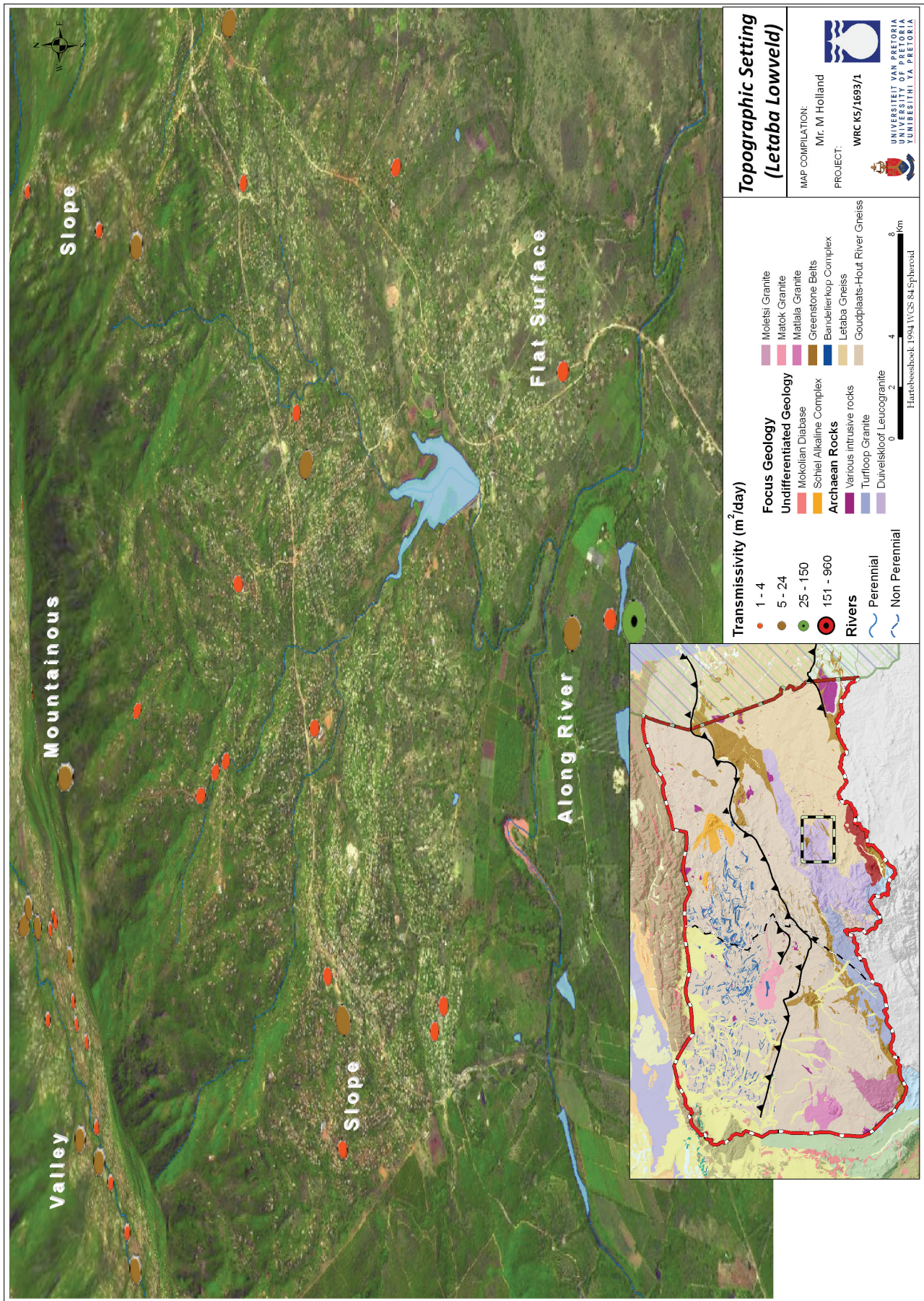


Figure 7.9. Typical setting of boreholes in relation to rivers and topography.

Proximity to Rivers

To determine the influence of drainage channels on the borehole productivity a spatial assessment of proximity was conducted. Remarkably 55% of all boreholes in the dataset are drilled within 150 m to streams or rivers as mapped on the 1:50 000 topographic maps of South Africa (Table 20). Nineteen percent of these are along the major drainage channels with remarkably enhanced transmissivities and yields.

Table 20. Influence of proximity to rivers and streams on borehole productivity.

Area	Parameter	Transmissivity m ² /d			Rec. Yield L/s per day		
		Nr. of BH's	Mean	Median	Nr. of BH's	Mean	Median
Limpopo	<u>All data</u>	<u>967</u>	<u>38</u>	<u>15</u>	<u>1137</u>	<u>1.45</u>	<u>0.8</u>
	Within 150 m (River)	177	51	26	206	2.11	1.6
	Within 150 m (Stream)	250	36	14	290	1.36	0.8
	Further than 150 m	540	35	12	641	1.28	0.7
Letaba	<u>All data</u>	<u>1542</u>	<u>24</u>	<u>10</u>	<u>1925</u>	<u>0.80</u>	<u>0.4</u>
	Within 150 m (River)	325	32	14	389	1.03	0.6
	Within 150 m (Stream)	742	23	9.1	918	0.79	0.3
	Further than 150 m	475	21	7.7	618	0.66	0.4

It can be concluded that both topography and proximity to rivers has significant influence on borehole productivity. Drainage channels follow often zones of structural weaknesses (e.g. lineaments) in the near surface; therefore rocks in the vicinity of rivers can be more intensely fractured, jointed and/or weathered. From a hydraulic point of view water levels are generally shallower at topographic lows and present discharge zones, providing more available drawdown and a larger capture zone compared to boreholes in mountainous areas drilled to approximately the same depth below ground surface.

7.1.6. Relationship of borehole productivity to lineaments.

The use of lineament mapping, especially in basement lithologies with poor primary porosity, is of major importance for groundwater exploration projects and was recently imposed by the Department of Water Affairs for the Limpopo province. However, the extent to which these lineaments influence or relate to borehole yields has not yet been formally assessed. In order to establish whether specific lineament azimuths or the proximity to lineaments are more promising for groundwater exploration, an assessment of borehole productivity and its relation to lineaments within the two sub areas was examined. ASTER image- and published lineaments were characterised spatially with standard GIS functions (e.g. near, azimuth, length etc.). The relationship between transmissivity and proximity to lineaments for both areas is shown in Figure 7.10.

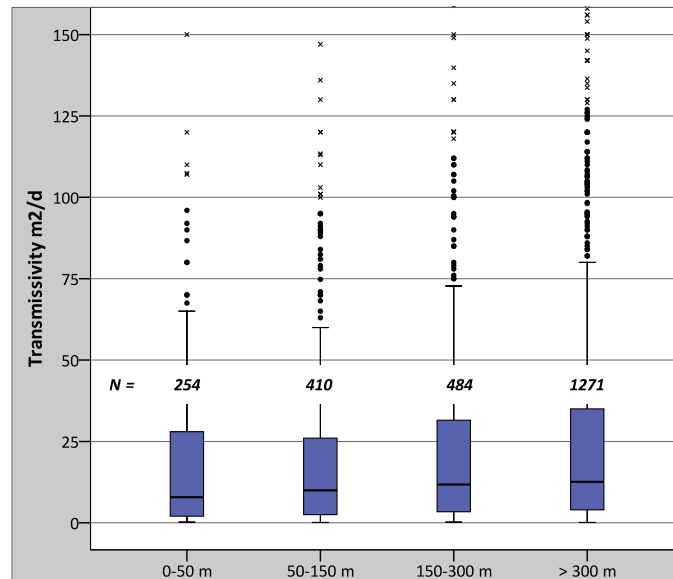


Figure 7.10. Box plot of borehole transmissivity and proximity to a lineament.

Apparently no correlation between borehole productivity and proximity to a lineament exists. This may be due to the fact that the majority of boreholes were sited based on field observations and local geological features which are not captured in the remote sensing data or that not all captured lineaments are of geological origin. In order to investigate whether any lineaments orientation classes provide higher borehole productivities, the derived transmissivities and yields were compared between major orientation classes and within each sub-area (Table 21) and (Figure 7.11).

Table 21. Summary of transmissivity and recommended yield for selected orientation intervals.

Area	Azimuth (Interval)	Transmissivity m ² /d			Rec. Yield L/s per day		
		Nr. of BH's	Mean	Median	Nr. of BH's	Mean	Median
Limpopo	All	134	40	19	157	1.6	1.0
	270-315°	36	44	23	39	1.6	1.2
	315-360°	23	33	14	26	1.5	0.8
	0-30°	14	32	18	16	1.6	0.4
	30-45°	9	35	23	12	1.2	0.8
	45-60°	16	52	19	18	2.0	0.8
	60-75°	17	46	22	21	1.6	1.0
	75-90°	19	33	6	25	1.5	1.0
Letaba	All	530	20	7	624	0.8	0.3
	270-315°	81	18	8	93	0.6	0.3
	315-360°	34	13	6	42	0.5	0.3
	0-30°	52	23	8	55	0.9	0.4
	30-45°	79	15	4	95	0.6	0.2
	45-60°	105	14	5	127	0.8	0.3
	60-75°	109	26	10	129	0.8	0.5
	75-90°	70	27	15	83	1.1	0.4

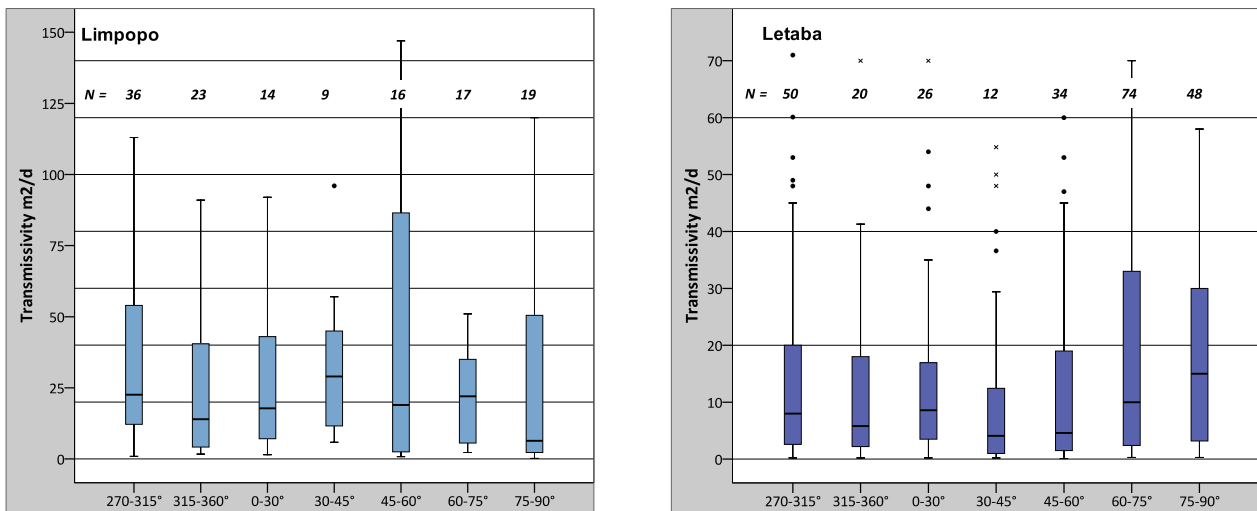


Figure 7.11. Box plot of borehole transmissivity in relation to the lineament azimuth per structural region (mean azimuth in graph title).

Region A and B (Limpopo Plateau)

The western regions A and B are predominantly characterized by the Gneissic rocks of the Goudplaats-Hout River Group with a much lower frequency of dykes and lineaments compared to the two eastern regions (Figure 7.12).

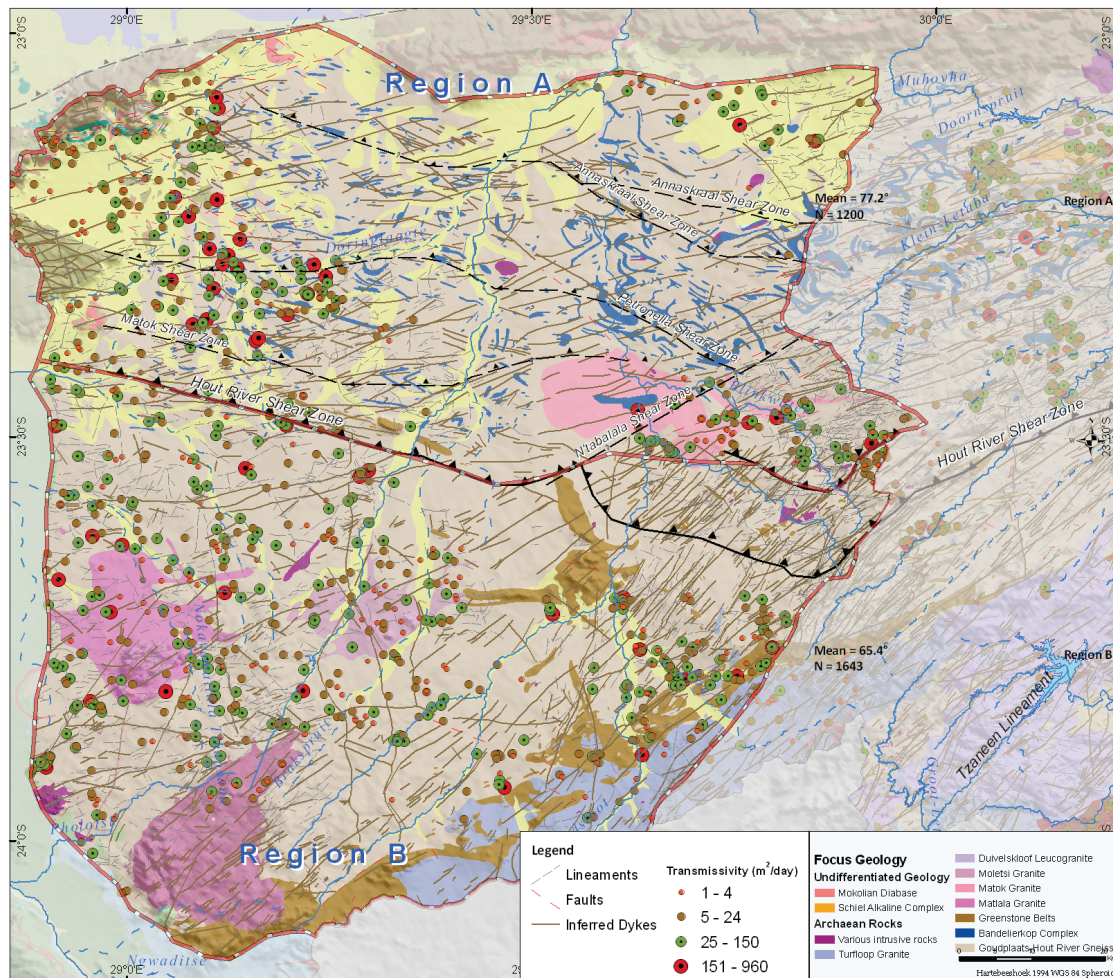
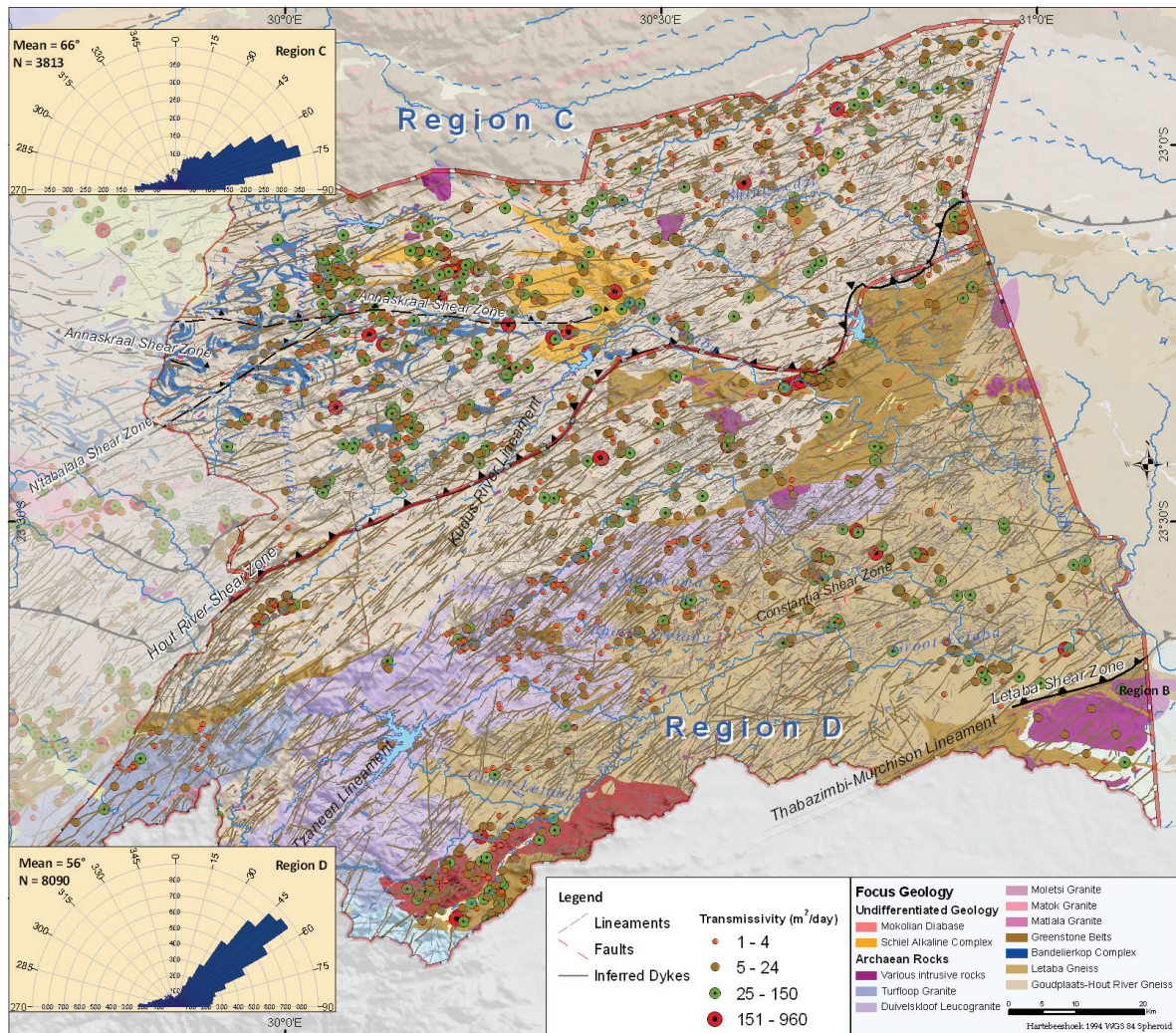


Figure 7.12. Distribution of shear zones dykes, faults and lineaments in Region A and B, with the lineament frequency rose diagram showing main structural trends.

Region A has a complex tectonic history and intense shearing and fracturing of the basement rocks has created highly productive fractured aquifers. The most common lineament strike direction is ENE (between N70°E and N80°E) and is controlled by a series of northward-dipping shear zones (Figure 7.12). Towards the south of the HRSZ (Region B) the Kaapvaal Craton compose of lower grade metamorphic gneisses and has generally lower water bearing characteristics. The region is characterized by a number of batholiths, forming distinct inselbergs. These younger intrusions provide potentially high water bearing zones along the contact aureole. Although no single preferred orientation for highly productive boreholes is clearly distinguishable from the transmissivity ranges in Figure 7.11 above, average transmissivities area are associated with lineaments striking NE to NNE (N45°E to N75°E) and WNW (N270°W and N315°W). The latter is significant as it is orientated parallel to the Hout River Shear Zone, which represents the boundary between the Kaapvaal Craton and the SMZ of the Limpopo Mobile Belt. Despite a relatively small number of lineaments with WNW trends compared to ENE trends, the number of boreholes targeting the former is higher. A limited number of lineaments strike parallel to the NW-SE directed maximum horizontal neo-tectonic stress, but the observed transmissivities and yields indicate that these structures are not significant conduits for groundwater flow. In return, lineaments striking NE to NNE, i.e. perpendicular to the NW-SE directed neo-tectonic stress, seem to be favourable borehole targets with above average transmissivities and yields, suggesting a reactivation of strike slip faults, representing dilation zones.

Region C and D (Letaba Lowveld)

The eastern regions C and D are characterised by larger elongated batholiths and the Giyani greenstone belt with the Schiel Alkaline complex as main geological features (Figure 7.13). The lineaments in regions C and D show pronounced preferred orientations. The prominent ENE (N60°E-N75°E) strike direction in region C is parallel to the Hout River Shear zone. According to Stettler et al. (1989) the orientation of these linear features (in most case dykes) is not only the result of the instantaneous stress field at the time of emplacement, but that the inherited fracture pattern played a decisive role. Region D has a high dyke and lineament frequency with a strong NE trend (N45°E to N50°E), coinciding with the regional Kudus River and Tzaneen Lineament (sub-parallel to the Hout River Shear zone). Based on Figure 7.11 higher transmissivities and yields are associated with lineaments striking ENE to E (N60°E to N90°E), depicting an orientation oblique to the present day NW-SE maximum horizontal stress. Boreholes associated with trends perpendicular to the neo-tectonic stress regime show below average yields and can be attributed to the closing of older discontinuities due to compressive stress.



7.2. Summary and recommended drilling targets

The tectonic history of the rocks of the SMZ is complex, involving periods of stability, extension and compression (orogeny) (Barton et al., 1990). A conceptual understanding of the most significant features controlling borehole yields in the Limpopo basement lithologies is illustrated in Figure 7.14. A summary of the potential groundwater targets based on the knowledge obtained during this investigation is listed in Table 22 and presented spatially in Figure 7.15. The occurrence of alluvium aquifers was discussed in previous chapters and while this remains a prime target for groundwater exploration in all regions of the study area it is excluded from the list in Table 22.

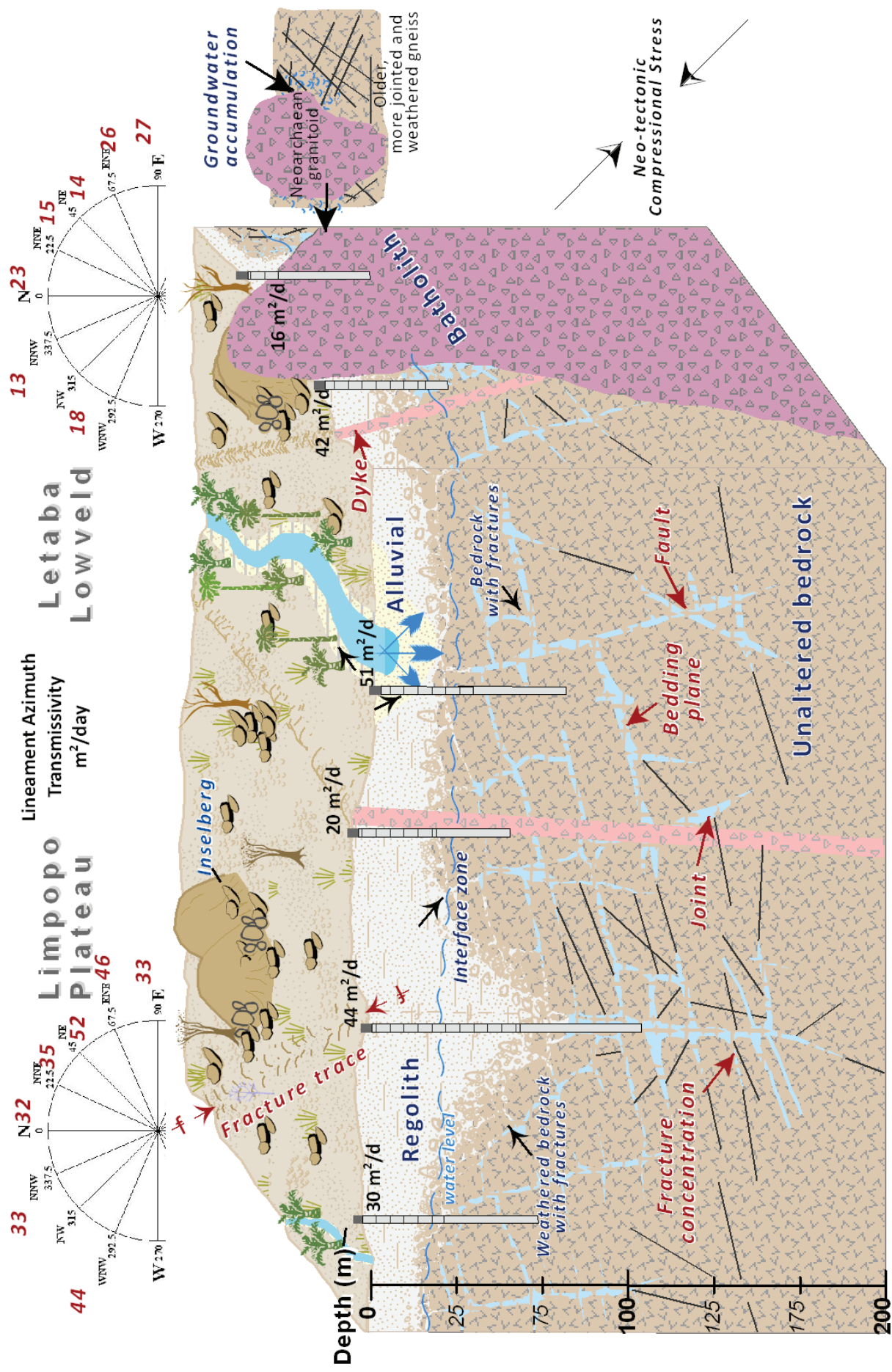


Figure 7.14. Conceptualisation of transmissivity values obtained from various borehole settings in the Limpopo Plateau.

The tectonic history of the rocks of the SMZ is complex, involving periods of stability, extension and compression (orogeny) (Barton et al., 1990). In the Letaba Lowveld the pronounced NE to ENE lineament trend relates to an inherited fracture pattern caused by an eastward extensional event in the geological past. Regional lineament orientations north of the Hout River Shear zone are related to deformation patterns within the Limpopo Mobile Belt, coinciding with the northward-dipping thrust zone of the SMZ, while lineaments to the south are rotated approximately 15° anticlockwise of this pattern. As a result, despite the evidence of tensional joints in the NW-SE direction potentially producing open discontinuities under the present day neo-tectonic stress regime, older structures might have remained open throughout geological history. The relatively higher transmissivities observed in boreholes targeting lineaments striking parallel to the inherited fracture pattern in Region A and B support this assumption.

Table 22. Recommended drilling targets per structural region.

Area	Region A		Region B
Limpopo Plateau	<i>Lineaments</i>	NE lineaments although not greatly important (anomaly hunting generally successful)	No preferred orientation, although NE lineaments seem more favourable
	<i>Dykes</i>	Generally more successful compared to other regions	Target in conjunction with lineaments and surface water drainages
	<i>Shear Zones</i>	E-W shears (zones of highly weathered fractured material)	-
	<i>Greenstones Belts</i>	-	Potentially slightly higher than in the Gneiss
	<i>Bandelierkop Complex</i>	Pegmatite, quartz and metapelite units are prime targets	-
	<i>Aureole of Batholith</i>	Matok Granite	Moletsi-, Utrecht- and Matlala Granites
Area	Region C		Region D
Letaba Lowveld	<i>Lineaments</i>	NNE to NE- and ENE to E lineaments	ENE to E lineaments (orientation a major influence on groundwater potential)
	<i>Dykes</i>	NNE trending dykes in association with lineaments and surface water drainages	In conjunction with lineaments and faults
	<i>Shear Zones</i>	Annaskraal shear zone and Kudus River lineament (in conjunction with faulting)	Constantia shear zone in conjunction with preferred lineament orientation Tzaneen lineament very poor groundwater potential
	<i>Greenstones Belts</i>		Potentially slightly higher than in the Gneiss
	<i>Bandelierkop Complex</i>	Insignificant groundwater potential compared to Region A	-
	<i>Schiel Alkaline Complex</i>	Potentially higher than in the Gneiss	-
	<i>Valley and slope</i>	Gneisses in the lower reaches of the escarpment (e.g. Shingwedzi catchment)	Gneisses in the lower reaches of the escarpment (e.g. Middle Letaba catchment)

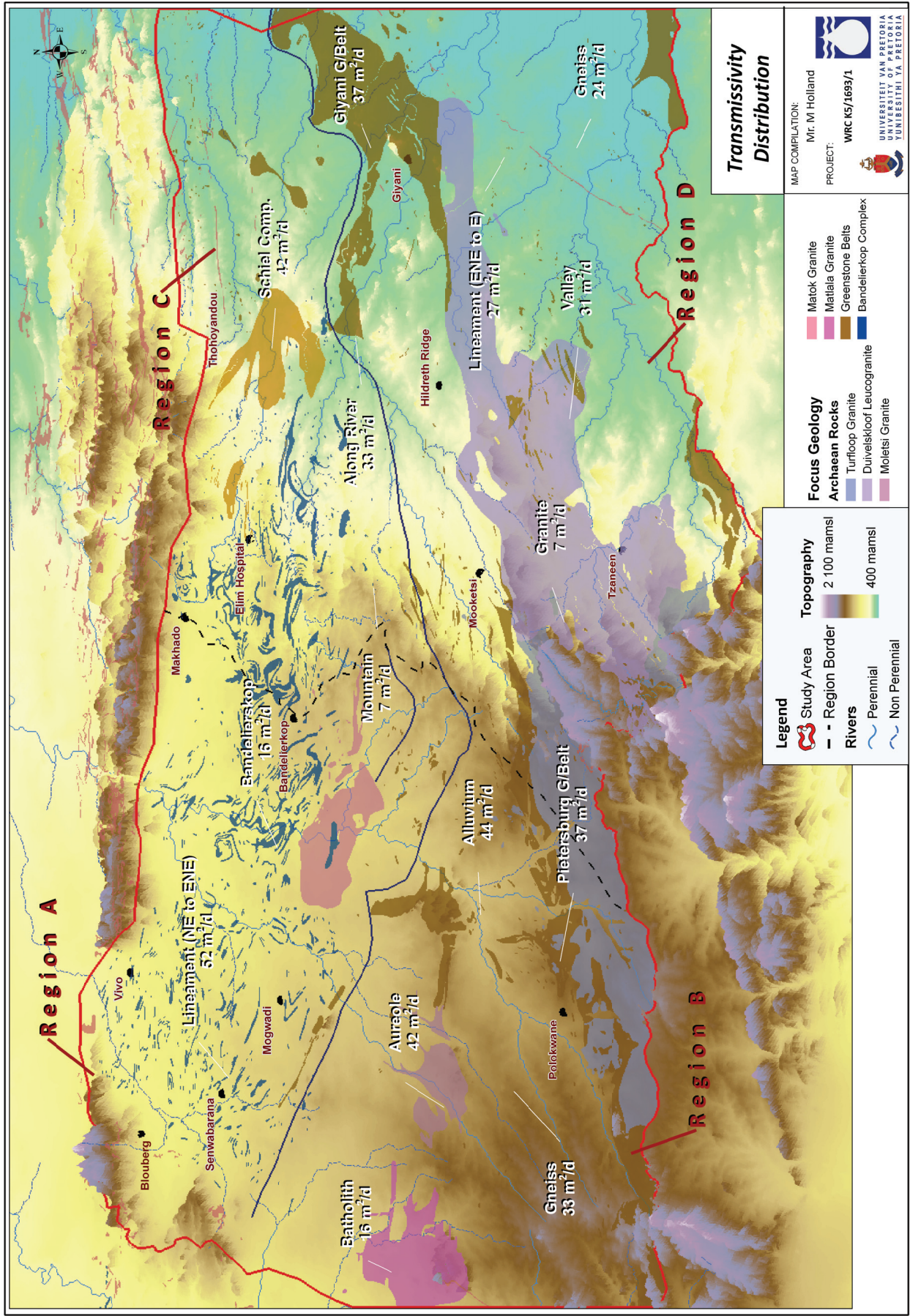


Figure 7.15. Regional conceptualisation of transmissivity within the study area.

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9. Appendixes

9.1. Appendix A

Microbiological analysis of groundwater samples.

Sample Name	Location	Heterotrophic plate count [1 ml]	Total Coliform Bacteria [100 ml]	Total Faecal Coliform Bacteria [100 ml]
Chauke unknown 001	Nwamatatani	15120	0	0
H10-0015	Olifantshoek	3240	0	0
H10-0019	Olifantshoek	24080	0	0
H10-0028	Raphalele	17360	0	0
H10-0165	Mamaila	2780	0	0
H10-0423	Itieleng	23880	0	0
H10-0437	Tshebaleng	6720	0	0
H10-0461	Lemondokop	2240	0	0
H10-0580	Lemondokop	12320	0	0
H10-0614	Magoro	5040	0	0
H10-0629	Magoro	2840	0	0
H10-0645	Itieleng	11760	1200	0
H10-0661	Olifantshoek	11200	0	0
H10-0674	Tshebaleng	8400	0	0
H10-0715	Phooko	10640	0	0
H10-0752	Itieleng	38160	1400	0
H17-0098	Tshivade	2080	0	0
H17-0103	Bungani	1040	0	0
H17-0120	Mashamba	13120	3200	0
H17-0140	Valdezia	5880	0	0
H17-0179	Tshivade	510	0	0
H17-0180	Tshivade	430	300	0
H17-0210	Valdezia	2280	0	0
H17-0211	Valdezia	220	0	0
H17-0212	Valdezia	60	0	0
H17-0215	Valdezia	1720	0	0
H17-0420	Majosi	1460	3800	1500
H17-0612	Sereni	3920	0	0
H17-0654	Bungani	49	0	0
H17-0925	Masia	140640	0	0
H17-School001	Mojosi	3280	0	0
H17-School002	Nwamatatani	21280	400	0
H17-unknown	Sereni	10620	0	0
J.Sc07	Schoonuitzicht	1280	0	0
Mernust 001	Mafeba	28560	100	0
H04-0113A	Marowe	13960	0	0
H04-0665	Ngwanalalen	3540	0	0
H04-0910	Chloe 2	4760	0	0
H04-1472	Vianen	7760	0	0
H04-1473	Harriet's wish	1630	0	0
H04-1489 (H04-1485)	Vianen	4760	0	0
H04-1566	Diana	320	100	0

Sample Name	Location	Heterotrophic plate count [1 ml]	Total Coliform Bacteria [100 ml]	Total Feecal Coliform Bacteria [100 ml]
H11-0818	Poopedi/Koekoek	15840	0	0
H11-0833	Schoonveld 2	11040	0	0
H11-0885	Witten	1640	0	0
H11-1882	Prespan	8640	100	0
H11-2212	Ga-Gare	25440	100	0
Handpump P001	Welgelegen	8160	0	0
Handpump P008	Tibane	910	400	0
H-Pump 005	Aurora	720	0	0
H-Unknown P001	Harriet's Wish	12960	0	0
Jupiter private 001	Jupiter	7680	100	0

9.2. Appendix B

Stable isotope analysis for the groundwater samples

Sample Name	Location	WMA	$\delta^{18}\text{O}$ [‰]	$\delta^2\text{H}$ [‰]
Chauke unknown 001	Nwamatatani	Luvuvhu\Letaba	-3.20	-32
H10-0015	Olifantshoek	Luvuvhu\Letaba	-4.51	-24
H10-0019	Olifantshoek	Luvuvhu\Letaba	-4.48	-26
H10-0028	Raphalele	Luvuvhu\Letaba	-4.94	-29
H10-0165	Mamaila	Luvuvhu\Letaba	-6.74	-33
H10-0423	Itieleng	Luvuvhu\Letaba	-4.74	-27
H10-0437	Tshebaleng	Luvuvhu\Letaba	-5.19	-29
H10-0461	Lemondokop	Luvuvhu\Letaba	-4.63	-26
H10-0580	Lemondokop	Luvuvhu\Letaba	-2.12	-14
H10-0614	Magoro	Luvuvhu\Letaba	-4.72	-28
H10-0629	Magoro	Luvuvhu\Letaba	-4.22	-23
H10-0645	Itieleng	Luvuvhu\Letaba	-5.07	-26
H10-0661	Olifantshoek	Luvuvhu\Letaba	-4.34	-18
H10-0674	Tshebaleng	Luvuvhu\Letaba	-5.36	-27
H10-0715	Phooko	Luvuvhu\Letaba	-5.05	-27
H10-0752	Itieleng	Luvuvhu\Letaba	-4.68	-27
H17-0098	Tshivade	Luvuvhu\Letaba	-4.30	-25
H17-0103	Bungani	Luvuvhu\Letaba	-4.20	-25
H17-0120	Mashamba	Luvuvhu\Letaba	-4.30	-22
H17-0140	Valdezia	Luvuvhu\Letaba	-4.35	-23
H17-0180	Tshivade	Luvuvhu\Letaba	-4.31	-25
H17-0210	Valdezia	Luvuvhu\Letaba	-4.55	-31
H17-0211	Valdezia	Luvuvhu\Letaba	-4.60	-32
H17-0212	Valdezia	Luvuvhu\Letaba	-3.22	-23
H17-0215	Valdezia	Luvuvhu\Letaba	-4.49	-23
H17-0612	Sereni	Luvuvhu\Letaba	-3.96	-22
H17-School001	Mojosi	Luvuvhu\Letaba	-4.75	-28
H17-School002	Nwamatatani	Luvuvhu\Letaba	-3.07	-18
H17-unknown	Sereni	Luvuvhu\Letaba	-4.65	-26
J.Sc07	Schoonuitzicht	Luvuvhu\Letaba	-3.94	-17
LD-001	Luvuvhu River	Luvuvhu\Letaba	1.26	1
Mernust 001	Mafeba	Luvuvhu\Letaba	-4.55	-27
Average (without LD-001)			-4.43	-25.26