1. INTRODUCTION

1.1. Problem statement

The development of crystalline basement aquifers as a reliable source of water supply is notoriously complex, and groundwater occurrence is spatially highly variable (Wright, 1992; Chilton and Foster, 1995; Banks and Robins, 2002). Crystalline basement rock is distributed extensively throughout Africa and underlies large parts of the semi-arid Limpopo Province in South Africa (Figure 1.1) Some of the greatest groundwater needs occur in the region and groundwater is the only dependable source of water for many users. Groundwater is available and widely used throughout the Province, but in varying quantities depending upon the hydrogeological characteristics of the underlying aquifer. Due to the low intrinsic primary permeability and porosity of the bedrock, crystalline aquifers differ in important ways from other aquifer types, and demand specific knowledge and techniques if groundwater is to be extracted and managed efficiently.

Of great importance is the concept of sustainable yield and whether it can be determined for a weathered-fractured aquifer that is known for 1) high failure rates of boreholes, 2) low storage capacity, 3) low recharge potential (Clark, 1985; Jones, 1985; McFarlane et al., 1992). However, from the onset it was realised that the evolving concept of sustainability in the groundwater field presents a challenge to any hydrogeologist. In many ways this can be attributed to the divergent opinions that exist as to whether natural recharge is important (i.e. Kalf and Woolley, 2005) or not (i.e. Bredehoeft, 2002) in assessing the sustainable development of groundwater. Sustainability is a broader concept than simple sustainable pumping, and it depends on the changes to the ecology, human welfare and water quality during groundwater development ("capture"). Today, there is an open debate regarding the concept of sustainable yield and whether it can be scientifically determined.

Although the debate regarding safe groundwater development continues, the basic physical principles are all that are available to hydrogeologists when it comes to predicting or anticipating the likely outcome of groundwater exploitation. Appropriate hydrogeological application is essential to optimise the use of Africa's increasingly scarce water resources (Robins et al., 2006). One of the principal tools for these investigations is the groundwater model, but the reliability of such models depends partly on a sound conceptual model with an accurate knowledge of the geometry and the hydraulic properties of the aquifer. These aquifer properties are often determined by assessing the aquifers response to pumping and fitting the observed data to a known conceptual (theoretical) model. However, the choice of model is not easy as different models can have the same type of response.

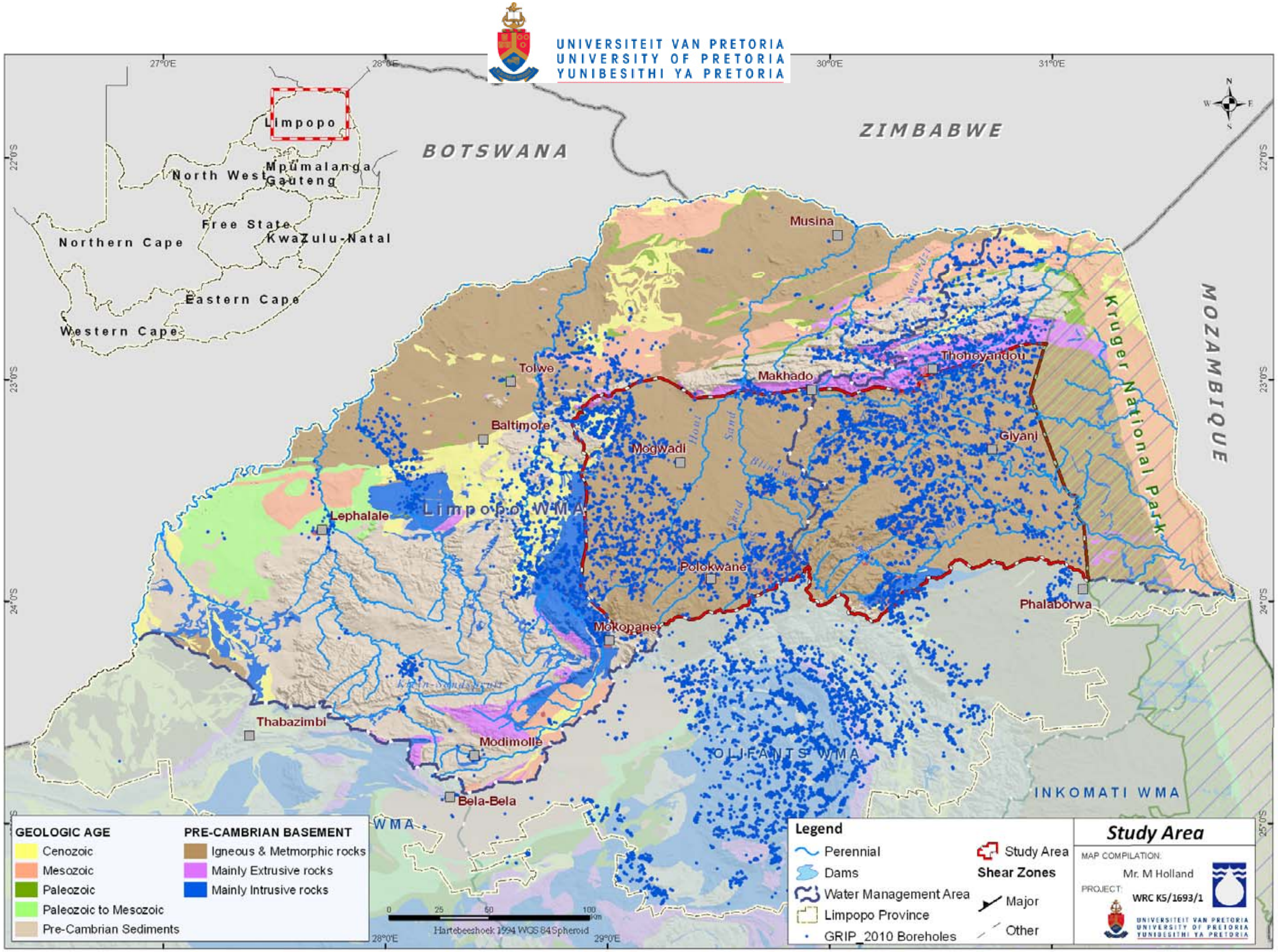

Figure 1.1. Study Area.

Across much of tropical Africa crystalline basement rocks have a thick cover of in situ, chemically-weathered overburden (Jones, 1985). Consequently, a large number of boreholes are completed in this shallow unconsolidated weathered zone (regolith). Since the regolith can be represented as a porous medium its hydrodynamic properties are easily measured with classical analytical models such as Theis (1935) and the Jacob's approximation (Cooper and Jacob, 1946). However, most crystalline basement aquifers respond as a dual aquifer system with a weathered zone overlying a fractured zone. The fractured bedrock may be more or less confined, depending on the hydraulic conductivity of the overlying material. The concept of an unconfined weathered zone overlying the fissure zone can be represented by 1) a leaky aquifer system comprising of an aquifer-water table aquitard model, or 2) a delayed gravity response assuming instantaneous drainage at the water table. Where the crystalline basement rocks are well exposed and essentially un-weathered, main groundwater occurrences are limited to fissure or fracture zones. In these regions characterisation of the flow dimension, location and connectivity of fractures is essential for interpreting the aquifer response to pumping (i.e. double porosity or single fracture models). Whilst several analytical models can be used to evaluate weathered-fractured aquifers, the difficulty is to identify the model that best represents reality. Kruseman and de Ridder (1990) accentuate that: "the choice of theoretical model is a crucial step in the interpretation of pumping tests. If the wrong model is chosen, the hydraulic characteristics calculated for the real aquifer will not be correct".

Determining hydraulic properties in basement rocks aquifers is clearly not straightforward and results are highly variable due to the intrinsic heterogeneity. Perhaps an even bigger challenge is to develop an understanding of the controls on groundwater occurrence (Clark, 1985; Jones, 1985; McFarlane et al., 1992; Henriksen, 1995; Neves and Morales, 2007). A lack of understanding of the occurrence, movement and recharge of groundwater in basement terrain has frequently contributed to the unsustainable use of this resource (Chilton and Foster, 1995). Independent or interrelated factors such as geomorphology (topography), lithology, brittle (neo-) tectonics, and surface water hydrology all play a significant role in the occurrence of groundwater in crystalline rocks, because together they control 1) the nature and depth of the regolith, 2) the development of fracture and fault zones and, 3) the presence of higher porosity material (or adjacent alluvium). Hence groundwater exploration in crystalline areas would normally pay close attention to locating weathered material, together with the geological and tectonic controls directly related to structural features which control deeper groundwater flow.

Despite some major hydrogeological investigations in the 1970s and the installation of numerous hand-pumped water supply boreholes for rural communities throughout south eastern Africa, the hydrogeology of crystalline aquifers are not yet fully understood. This can be largely be attributed to the lack of-, and poor accuracy of data. An assessment of factors influencing borehole yields is meaningless unless sufficient data are available to make statistically significant deductions. However, unless the same method of measurement (i.e. blow yield vs. tested yield) and recording is used it can be unrealistic to make any comparison between two crystalline regions as the lack of uniformity in the raw data give rise to different results rather than actual differences in hydrogeology (Houston, 1992). In addition, it is difficult to prove that for example that a specific geological lineament orientation offers higher borehole productivity if there is a lack of derived hydrogeological data such as borehole yield and transmissivity. In the absence of sound hydrogeological data surrogate information such as specific capacity is often used as a measure of the water bearing capacity of the aquifer (Fernandes and Rudolph 2001; Neves and Morales 2007). It is commonly accepted that no single unique factor will guarantee high yielding boreholes and that the relative importance of specific factors influencing borehole yield vary according to the particular characteristics of the area or geological setting. Taking this into consideration, the study of influencing factors on groundwater occurrence is an attractive proposition in the crystalline bedrock of the Limpopo Province where the the siting of boreholes remains a challenge and is a random process in many cases.

1.2. Investigation objectives

Approximately 35% of rural communities in the region are dependent on groundwater and 60% use surface- and groundwater conjunctively (DWAF, 2009). The importance of these basement aquifers makes it important to identify high yielding hydrogeological zones that can be targeted for water supply, to sustain areas of high population density with few or no alternative water sources. However, studies regarding the optimal locations for high yielding boreholes are rare. The Water Research Commission of South Africa initiated a study to determine sustainable yields of potential productive well fields in these basement aquifers, which formed the basis of this thesis. To stay clear of the conceptual ambiguities regarding the term sustainability, the focus was mainly on developing an understanding of groundwater -occurrence, -flow and -behaviour in these crystalline rocks.

The main objective was therefore to identify certain factors which may enhance borehole yields. The following factors were considered; 1) the geological and topographical setting, 2) dykes and linear anomalies (including their orientation), 3) regional tectonics (major horizontal principal stress), 4) weathering thickness, and 5) proximity to surface water drainages. The results will provide water resource planners with a number of regional groundwater exploration targets that may lead to improved borehole success rates and yields. While it is acknowledged that the basement aquifer covers the Limpopo Province extensively it is important to note that a specific study area was chosen based on the coverage of borehole data (Figure 1.1).

A secondary objective was the classification of aquifer systems (theoretical models) or “type curves” based on observed drawdown responses during hydraulic testing. Categorising these behaviours can greatly assist groundwater practitioners in choosing the correct conceptual (theoretical) model for pumping test interpretations, which will lead to more accurate parameter estimation and inevitably better decision making regarding abstraction rates.

More specific objectives of the research include:

- evaluation of sustainable yield (source vs. resource),
- identification of typical drawdown behaviours from the numerous pumping test data available from the Groundwater Resources Information Project (GRIP),
- proposed analytical methods for typical responses for basement aquifers, and
- an estimation of aquifer parameters.

These objectives can only be achieved with an adequate knowledge of the regional hydrogeology together with geology, geomorphology, and climate information. This includes an accurate description of:

- the structural geology,
- borehole success rates, yields, water strikes and depth of weathering, and fracturing,
- recharge -estimates and -processes (groundwater ages and flow mixing),
- chemical evolution of groundwater, and
- groundwater quality hazards affecting suitability (sustainability) of use.

It is foreseen that the content of this thesis will be of interest to all workers on groundwater in Precambrian bedrock, not only in the southern part of the African continent, but also elsewhere in the world.