

TECHNICAL SERIES: 1

Crystalline Basement Aquifers in South Africa



water affairs

Department:
Water Affairs
REPUBLIC OF SOUTH AFRICA

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EXECUTIVE SUMMARY

A synopsis of modern thinking on the structure, groundwater occurrence, development and sustainability in basement aquifers are been provided. This includes a literature review encompassing national as well as international knowledge in crystalline basement hydrogeological assessment and groundwater exploration in basement aquifers. Maps provided showing the extent of South African basement aquifers.

Groundwater development and conceptual understanding of South African crystalline basement aquifers. This include an account of the assessment of crystalline basement aquifers, leading to a determination of the status quo (in terms of both water quantity and quality) of the crystalline basement aquifers of a particular WMA or catchment, and the definition the geographic extent of the aquifers. Best practice in borehole siting and design, pumping tests and groundwater resource monitoring are been included.

Groundwater protection and vulnerability in crystalline basement aquifers are covered. Basement rocks have particular characteristics in terms of vulnerability and pollution, and these are been discussed in the South African context, with special regard to steps laid down in the 2008 DWAF document "A Guideline for the Assessment, Planning and Management of Groundwater Resources in South Africa".

Special recommendations. Groundwater assessment, planning and management in crystalline basement aquifers needs to take into account the technical and other particular features of these rocks. This concentrate on special recommendations for assessment, planning and management in crystalline basement where these are necessary to supplement the steps in the 2008 DWAF document "A Guideline for the Assessment, Planning and Management of Groundwater Resources in South Africa". This include a summary checklist for groundwater managers.

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CHAPTER 1. INTRODUCTION

1.1 Context (development of the guideline)

The National Water Act (Act 36 of 1998) (NWA) was promulgated to provide for reform of the law relating to water resources, recognising that water is a scarce and unevenly-distributed national resource that belongs to all people. The NWA provides the Department of Water Affairs (DWA) with a mandate to protect, use, develop, conserve, manage and control South Africa's water resources in an integrated manner (DWA, 1998).

In southern Africa, some of the greatest groundwater needs occur in regions underlain by crystalline basement aquifers with complex hydrogeological characteristics built by two interlinked systems. A weathered and often clayey overburden with low to moderate transmissivity but high storativity and a fractured bedrock with a generally low storativity and highly variable transmissivities, resulting in significant local variations in yield and response to abstraction. The extreme heterogeneity in their hydraulic properties often leads to unsustainable use, poor borehole yields (and failure), and inappropriate water point design and management of the aquifer system.

The development and protection of this vital resource is crucial, and the protection of groundwater resources from pollution in these environments depends on a number of technical issues that are particular to these rocks. Development and protection of the groundwater resources of these basement aquifers is currently being undertaken in response to local pressures and decisions, potentially taking cognisance of the NWA but without the benefit of standard procedures. The Department therefore identified the need for the development of a guideline document (termed the Crystalline Basement aquifer Guideline) that can be followed and adhered to when undertaking assessment, planning and management of the water resources within the Basement rock areas of the country. This document will assist in sustainable development, protection and management of the groundwater resources, and will assist in achieving the overall goal of integrated water resources management (IWRM) within the Department.

1.2 Purpose (use) of the Crystalline Basement aquifer guideline

Ideally the Crystalline Basement aquifer Guideline will be structured such that it can function as an appendix to the DWA Generic Guideline "A Guideline for the Assessment, Planning and Management of Groundwater Resources in South Africa" – DWA, 2008". It is therefore envisaged that the following primary topics will be covered:

- A synopsis of modern thinking on the structure, groundwater occurrence, development and sustainability in basement aquifers will be provided. This will include a literature review encompassing national as well as international knowledge in crystalline basement hydrogeological assessment and groundwater exploration in basement aquifers. Maps will be provided showing the extent of South African basement aquifers.
- Groundwater development and conceptual understanding of South African crystalline basement aquifers. This task will include an account of the assessment

- of crystalline basement aquifers, leading to a determination of the status quo (in terms of both water quantity and quality) of the crystalline basement aquifers of a particular WMA or catchment, and the definition the geographic extent of the aquifers. Best practice in borehole siting and design, pumping tests and groundwater resource monitoring will be included.
- Groundwater protection and vulnerability in crystalline basement aquifers. Basement rocks have particular characteristics in terms of vulnerability and pollution, and these will be discussed in the South African context, with special regard to steps laid down in the 2008 DWAF document “A Guideline for the Assessment, Planning and Management of Groundwater Resources in South Africa”.
 - Special recommendations. Groundwater assessment, planning and management in crystalline basement aquifers needs to take into account the technical and other particular features of these rocks. This task will concentrate on special recommendations for assessment, planning and management in crystalline basement where these are necessary to supplement the steps in the 2008 DWAF document “A Guideline for the Assessment, Planning and Management of Groundwater Resources in South Africa”. This will include a summary checklist for groundwater managers.
 - Geographical extent of Basement aquifers systems

1.3 Geographical extent of Basement aquifers system

Crystalline basement rocks are composed of hard, crystalline or re-crystallised rocks of igneous or metamorphic origin, which vary in age from earliest Archaean to Cenozoic (Precambrian age). Therefore heterogeneous basement can be composed of a diverse number of intrusive, recrystallised and volcanic rocks within orogenic provinces (Key, 1992). They can be divided into three main suites in South Africa:

1. Ancient rocks of the Archaean cratonic nuclei (e.g Kaapvaal craton), including granites, gneisses and greenstones, such as the Halfway House Granite in Gauteng, South Africa.
2. 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).
3. Anorogenic intrusions of various ages, such as the Bushveld Igneous Complex and Cape Granite Suite.

Basement aquifers are developed within the weathered overburden and fractured bedrock of these crystalline rocks. A number of Vegter's (2000a) groundwater regions fall into this classification (**Table 1-1**).

Table 1-1: Groundwater regions based on secondary features (openings)

MAIN ROCK TYPE	AGE	REGION	REGION NAME
Crystalline Igneous and metamorphic Basement rocks	Swazian	1	Makoppa Dome
		3	Limpopo Granulite Gneiss Belt
	Swazian-Randian	7	Pietersburg Plateau
		19	Lowveld
	Mokolian	26	Bushmanland
		27	Namaqualand
Mainly Intrusive rocks	Vaalian	14	Western Bushveld Complex
		15	Eastern Bushveld Complex
		16	Northern Bushveld Complex
Mainly Extrusive rocks	Swazian-Randian	18	Western Highveld
Sedimentary Rocks	Namibian to Permian	57	Swartland (Cape Granite Suite)*
Composite Geology	Swazian to Vaalian	17	Central Highveld
	Swazian to Permian	46	North eastern Middleveld
	Namibian to Permian	47	Kwazulu-Natal Coastal Foreland

* The Cape Granite Suite is of late Precambrian to Early Cambrian age.

The delineation of groundwater regions (Vegter 2000a) was based on lithostratigraphy, physiography and climate and often encompasses a much larger physical area than the Basement rock aquifer alone. Although Vegter's (2000a) subdivision of crystalline rocks for larger intrusions and metamorphic provinces (e.g the Bushveld complex and Lowveld region) is sufficient, the composite geological areas require further delineation (e.g. Kwazulu-Natal Coastal Foreland, Central and Western Highveld). **Figure 1-1** illustrates Vegter's (2000a) groundwater regions and the delineation of basement rock outcrop based on lithology, stratigraphy and geological age. The Basement rocks were divided into three main classes:

- Mainly Intrusive rocks (e.g Rhyolite, granophyres, norite, gabbro etc.)
- Mainly Extrusive rocks (e.g Basalts, volcanic rocks, tuff, etc.)
- Undifferentiated Igneous and Metamorphic rocks (e.g. Gneiss, granite plutons, granodiorite, schist, tonalite etc.)

The crystalline rock outcrop that can be regarded as basement rock aquifers covers approximately 15% of South Africa (**Figure 1-1**). For the purpose of further discussions the most common Basement aquifer regions are highlighted in **Figure 1-1**.

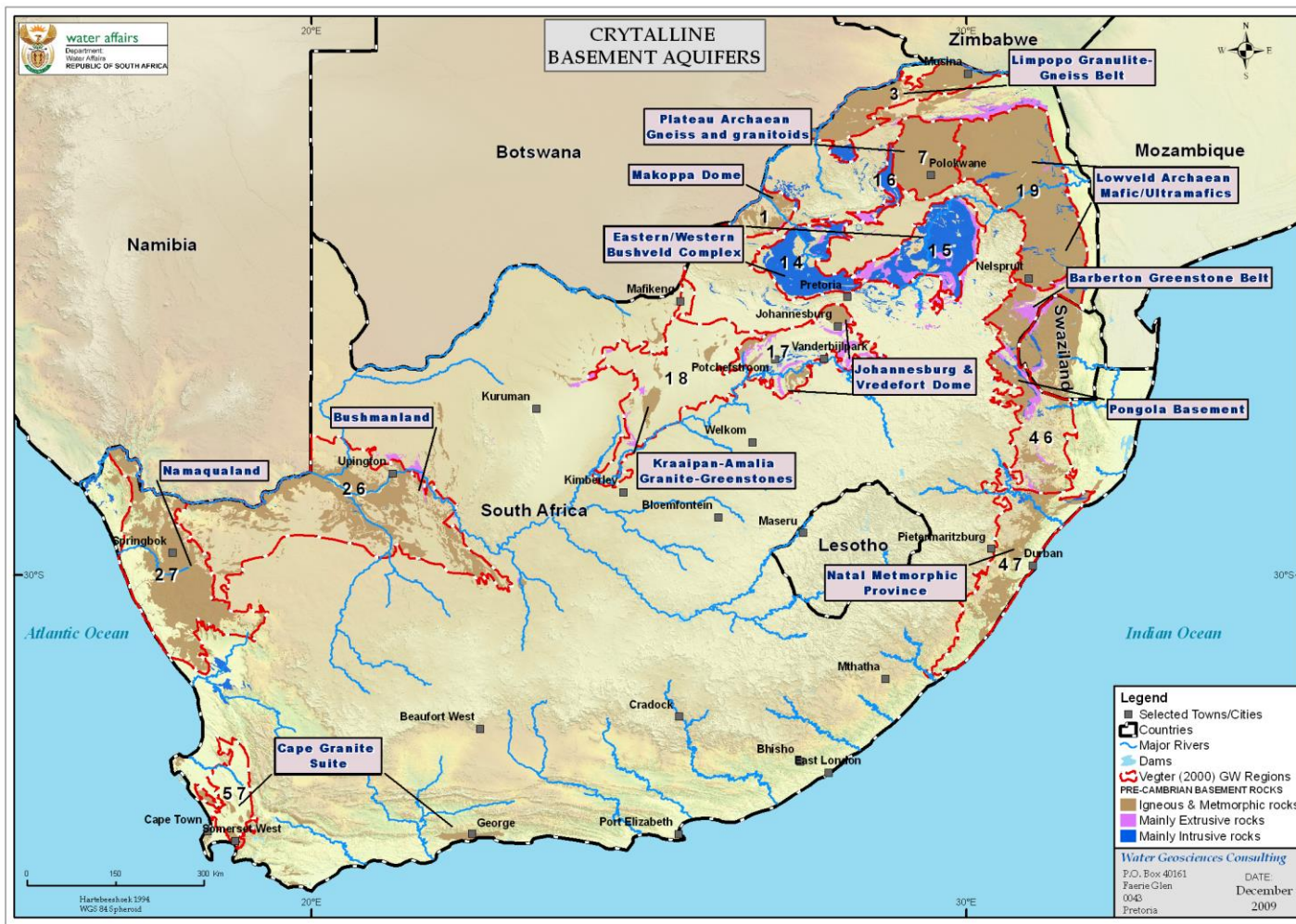


Figure 1-1: Extent of Basement rock outcrop

CHAPTER 2. DESCRIPTION OF CRYSTALLINE BASEMENT AQUIFERS

2.1 *Basement aquifer characteristics*

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 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 provide a consistent resource of water. 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.

2.1.1 What constitute a Basement Aquifer

- ***Weathering***

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.

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. Drainage is another important consideration in weathering processes (Jones, 1985). 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”, the rock may later alter to form a weathered layer or “saprolite” with high clay content (Figure 2.1). 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, and the thickness of the weathered material can reach 60 m or more in some areas (MacDonald, 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 subhorizontal) in the fresh crystalline rock below. This horizon of fracturing between the fresh rock and the clay-rich saprolite frequently has a higher permeability, depending on a number of factors including the nature of the fracturing and the presence of clay in the fractures. Weathered material derived from the base rock but including material transported from elsewhere is known as regolith (Jones, 1985). 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).

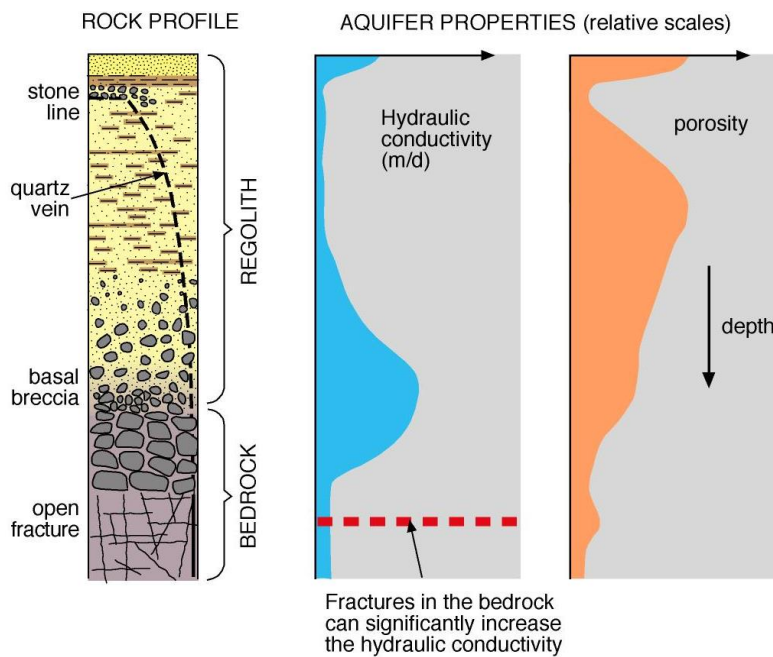


Figure 2-1: Permeability and porosity in basement aquifers (Davies 200)



Hence groundwater exploration in crystalline areas would normally pay 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.

○ **Fracturing**

Groundwater movement through low permeability bedrock takes place through open, secondary interconnected fractures. Studies on basement aquifers have predominantly focused on the development of groundwater resources in thick regolith (i.e. weathered overburden) with dominant intergranular flow in mainly tropical to sub-tropical regions (i.e. western and southern Africa, South America, Norway and Sweden). In contrast very few investigations have been conducted on the dominant fissure/fracture flow of South African semi-arid crystalline regions.

According to Sami et al. (2002) crystalline rocks in South Africa are predominantly structurally controlled and significant water movement is related to major fracture and fault zones, primarily associated with recent (Post Karoo) geodynamics. The fractures and fissures are thus not confined to any specific formation. The structural features are also extremely variable in nature (with regard to frequency, spatial extent, interconnectedness, etc.) within the relatively impervious crystalline rock mass (Gustafson & Krásný (1994). These structures can be extremely high yielding and can generate blow yields of more than 20 l/s. The Hout River Gneiss between Senwabarwana (Bochum) and Mogwadi (Dendron) in the Limpopo Province is an example of an extremely high yielding fractured Basement rock sustaining large scale commercial agricultural activities in the area.

○ **Recharge**

The quantification of the rate of groundwater recharge is important for the sustainable management of groundwater, especially in basement aquifers in semi-arid and arid regions where the storage potential is relatively low (Adams et al., 2004). Several methods have been developed over the past few decades to determine recharge and are well documented e.g. Lerner et al. (1990); Bredenkamp et al. (1995); Simmers et al. (1997); Kinzelbach et al. (2002); Scanlon and Cook (2002) and Xu and Beekman (2003). Adams et al. (2004) developed a methodological approach to recharge estimation of semi-arid basement aquifers. One critical component of this approach is a decision support framework in the form of a spreadsheet programme for the selection of the appropriate recharge estimation method(s). The suitability of a method is based on the availability of data and the potential to gather data.

Although the Chloride Mass Balance (CMB) method is the most widely used approach for estimating recharge in arid and semi-arid regions (Scanlon et al., 2006), Cook (2003) warns about the use of the CMB method in fractured rock aquifers due to the effects of the different types of porosities of the aquifer media. However, Cook (2003) also notes that the CMB method can give better estimates of recharge to fractured rock aquifers over most other methods. Other recharge methods applied effectively on Basement aquifers include qualitative

assessments of recharge (e.g statistical analysis and GIS), the Cumulative Rainfall Departure (CRD) method and the Saturated Volume Flow (SVF). However, due to the intermittent nature of recharge in these semi-arid areas, direct methods such as monitoring water levels may not show a recharge event over the period of a study. Therefore, more innovative and integrative methods for recharge assessment in these aquifers are necessary (e.g CFC sampling and the “Combined chemical and isotope mass balance approach”).

2.2 Groundwater exploration in basement aquifers

Groundwater development in basement rocks is frequently complex, since the aquifer properties often change over short distances, are highly variable and rarely behave as a single, regional unit. Borehole yields are usually low, and the resource is susceptible to drought and to contamination. Added to this spatial complexity is the temporal uncertainty of rainfall and recharge in semi-arid areas. The most favorable locations are often associated with geological features (such as fault zones and fractures), which encourage deeper weathering and may also be major recharge zones (Foster et al., 2000).

2.2.1 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 characterisation. 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 hydrogeologically 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). A more detailed explanation of Faults, Joints and Neo-tectonic stress is provided in Appendix 6.1.

2.2.2 Geomorphology

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 (1999) further investigated the relationship of geomorphology and groundwater occurrence in Uganda. Later, Vegter (2000) 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 numbers of 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 2-2**).



Figure 2-2: The distribution of erosion surfaces in southern and eastern Africa (adapted from Jones, 1985; Partridge & Maud, 1987; Lister, 1976, Lister, 1987, Taylor & Howard, 1999 and UNDP, 1990)

2.2.3 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 replenishment and flow. The idea of remote sensing methods is to identify such structures that may be of hydrogeological significance and that cannot be seen in the field or have not been mapped yet (Sami et al. 2002). Remote sensing techniques include radar and aerial photographs, satellite images (LANDSAT) and airborne geophysics.

- Radar Image and aerial photographs

- An excellent reconnaissance tool to see what the groundwater is like around communities and maps 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 2-3**).



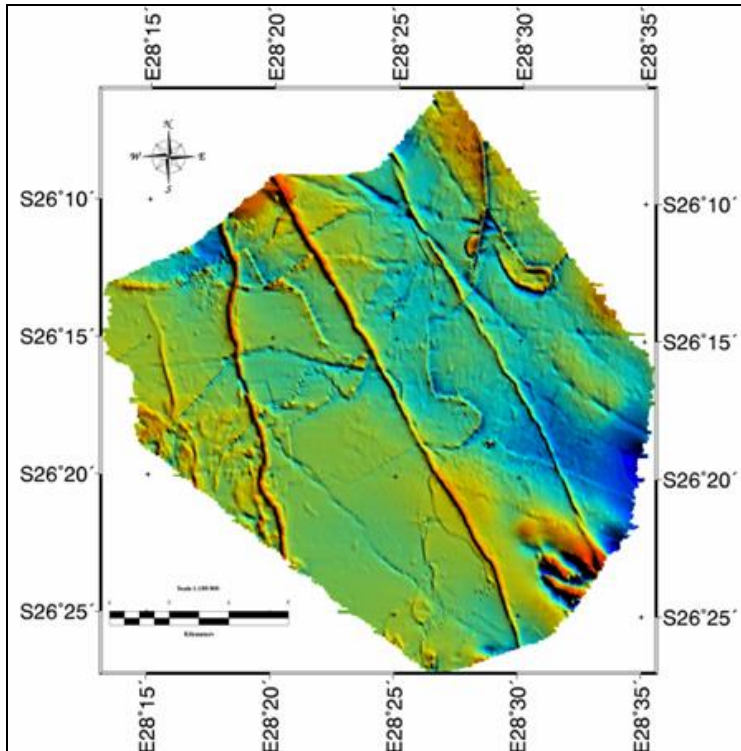


Figure 2-3: Aeromagnetic image showing linear magnetic dykes (example)

2.2.4 Geophysical methods

Geophysical methods are by far the most common methods for siting wells and boreholes for 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. 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. A list of commonly used geophysical methods in African Basement aquifers are given in **Table 2-1**.

Table 2-1: Summary of common geophysical techniques used in groundwater investigations (adapted 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 fields)	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-D vertical geoelectric section; more complex equipment gives 2-D or even 3-D 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 either 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.

The most commonly applied geophysics in South African Basement aquifers are magnetic, electromagnetic, and resistivity techniques. The following observations were made by Du Toit (2000) and Vegter (2003):

- Proton magnetometer (To determine the total magnetic field intensity).
 - Failed to distinguish between the host rock (gneiss) and the granitic batholiths.
 - Magnetic anomalies were observed over diabase intrusions (dykes).
- Geonics EM-34 and Genie SE-188 (electromagnetic systems).

- These two systems were primarily applied for the detection of the contact aureole between the various granite intrusions and the host rock (Du Toit, 2000).
 - In the absence of weathering, EM anomalies are caused by near surface weathered low-resistivity expression of fracture zones, which often entails exploratory drilling to determine the extent and depth of such fracture.
- Electrical resistivity depth probe.
- Useful in determining the thickness of the weathered and fracture zone but also gives an indication of the degree of weathering.

2.2.5 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 through geological triangulation (MacDonald et al., 2005).

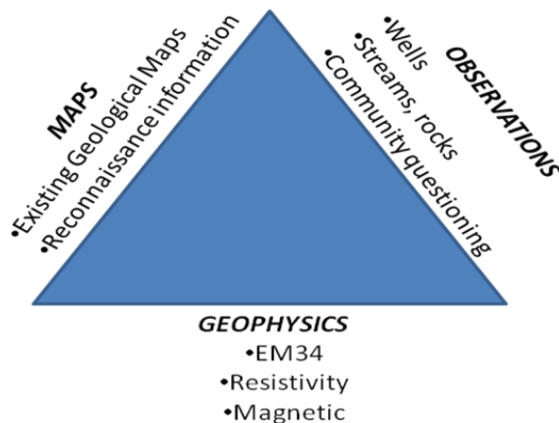
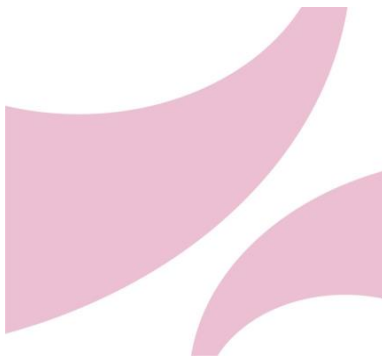


Figure 2-4: The geological triangle method (MacDonald et al., 2005)

A multidisciplinary exploration approach for basement aquifers using geophysics in combination with structural analysis to identify drilling targets, particularly in areas where weathering is thin (or absent) is presented in **Figure 2-5**. This approach developed by Sami (2007) place emphasis on comprehensive geodynamic / strain analysis, highlighting the structural control of groundwater flow in the fractured aquifer.



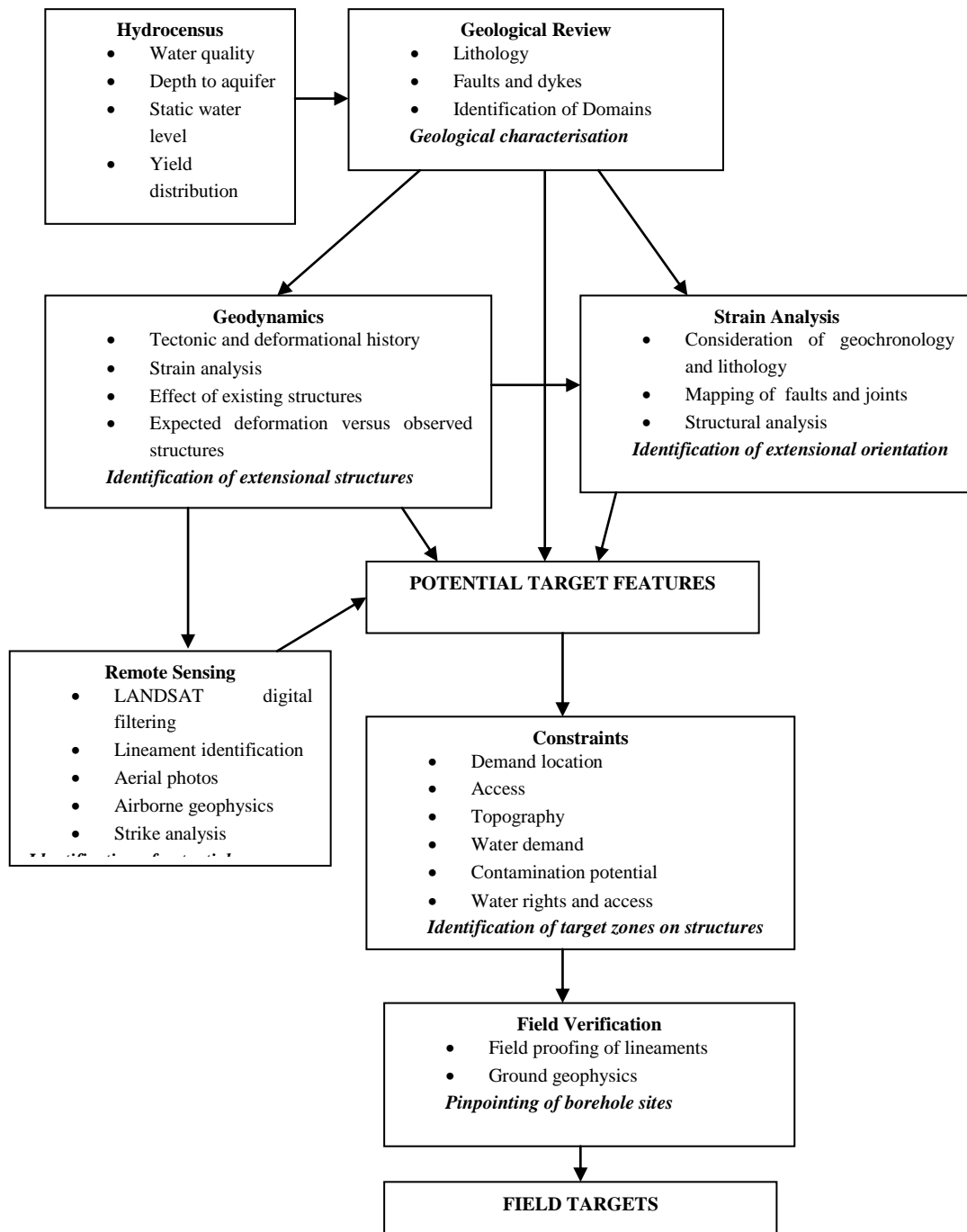


Figure 2-5: Flow chart of recommended groundwater exploration of basement aquifers (Sami, 2007)

○ **Drilling exploratory boreholes**

It is also suggested that increasing use should be made of test or exploratory drilling. Trial boreholes are often used to find sites for high yielding boreholes, to be used for town supply (MacDonald et al., 2005). Trial boreholes can be drilled at several sites that have been identified using other siting techniques, drilled at sites preferred by the community or drilled randomly within the community. These trial boreholes indicate water quality, quantity and geology. Exploratory boreholes

can be worthwhile especially if a huge area needs to be explored and primary water sources have been identified for drilling.

2.3 Developing groundwater in basement aquifers

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 in real-time based on the depth and permeability of saturated weathering found. Lovell (2007) identified seven water point designs to cope with the highly variable ground conditions typical of basement aquifers.



2.3.1 Drilling methods and borehole design

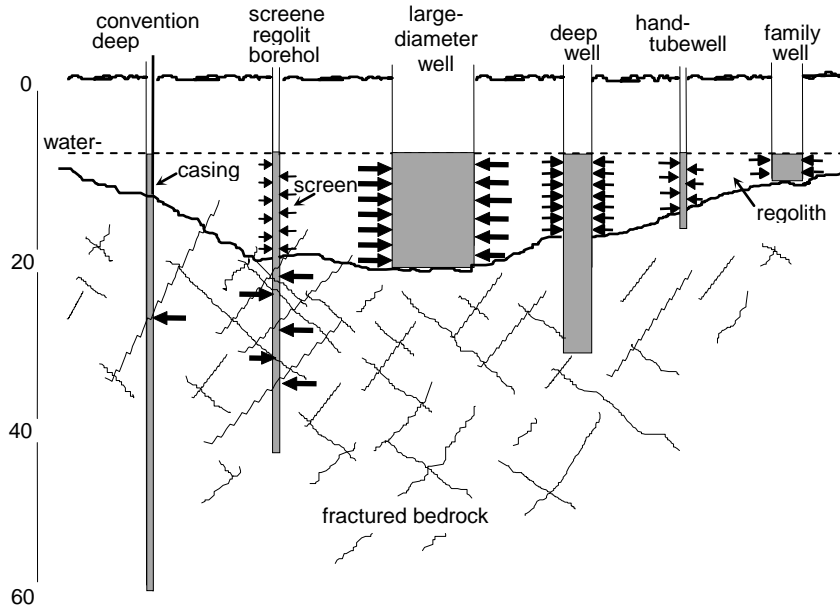
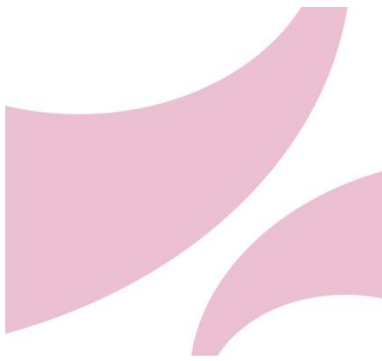


Figure 2-6: Typical water point designs for basement aquifers (Lovell, 2007)

Under South African circumstances conventional deep and screened regolith boreholes are the most common type of groundwater abstraction point used in rural water supply projects (**Photo 2-1**).



Photo 2-1: Borehole drilled 72m and 120m in the Hout River and Goudplaats Gneiss in the Limpopo Province respectively



However, some in use and remnants of large diameter wells for water supply exist in the basement aquifers of the Limpopo Province (**Photo 2-2**).



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

○ ***Drilling methods***

The choice of drilling rig for a particular site and also applicable to basement aquifers with a diverse array of rock types is determined by:

- Type of rock to be drilled
- Maximum depth of borehole to be drilled
- Types and dimension of casing and screened to be used
- Depth of water level
- Whether a gravel pack or formation stabiliser is required
- The accessibility of the borehole drilling sites.

Various drilling methods are used to construct water boreholes and several books which give detailed engineering information on the technical aspects of drilling exist. By far the most common drilling technique used in South Africa is the air rotary percussion and down the hole (DTH) hammer. This is explicable if we take into account that groundwater occurs in hard-rock formations for about 90% of the country's area (Vegter, 2000a).

○ ***Borehole design and construction***

A borehole should be designed to fulfill 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 designs 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. Quite common in South Africa is joint rural water supply and sanitation projects - groundwater in the shallow weathered zone or

laterite soil is often highly contaminated by pit latrines within the community. A sanitary seal consisting of cement grout is usually the simplest and most effective way of sealing out the contaminated shallow groundwater. A typical borehole design of a well developed regolith and fractured basement rock is illustrated in **Figure 2-7**.

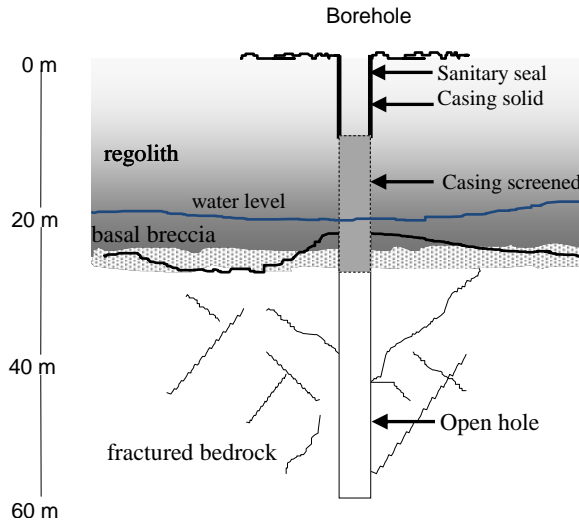


Figure 2-7: Borehole design in a typical basement aquifer system

○ **Borehole development**

A borehole must be developed before assessing whether it's successful or not. During the borehole development process various methods (e.g. surge pumping, jetting, blowing etc.) are applied to remove 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 the hydrofracturing development technique is used to open up fractures to increase well yield. Hydrofracturing 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).

2.3.2 Assessing the yield of a borehole (Pumping test)

Pumping tests involve measuring the response of water-levels in an aquifer to controlled pumping. From these measurements several pieces of information can be deduced, such as:

- The aquifer characteristics (e.g. transmissivity).
- The borehole performance and efficiency with a varying discharge.
- A rough sustainable yield of the borehole and the drawdown within the borehole in response to pumping.

There are many different types of pumping test that can be carried out in Basement aquifers due to the variations in borehole yields (e.g. simple short bailer test for a hand pump sustaining 250 people to 72 hour constant rate tests at 30 l/s). Pumping tests in South African basement aquifers depend on the planned usage, but typical tests

include a multiple discharge test (step test), a constant discharge test and a recovery test. The EXCEL-spreadsheet known as the Flow Characteristic Method (FC Method) developed by Van Tonder et al, (2002) was developed specifically to determine sustainable yields in hard rock aquifers. Although the FC method is widely accepted and used, it is often misinterpreted and some of the limitations are not taken into account by the user, such as:

- If there are more than one abstraction boreholes in the aquifer system, the sum of the sustainable borehole yields must not be higher than the annual recharge minus critical natural discharges for the area.
- The sustainable yield estimate is non-unique and will depend on the abstraction rate during the constant rate test (the higher the rate the lower the sustainable yield and vice versa).
- The choice of available drawdown in the abstraction borehole is one of the most critical parameters for sustainable yield estimations, but this parameter is often set to a specific water strike depth (known or derived from test itself) without any considerations of potential environmental impacts.

- **Sustainable yield**

The term sustainable yield is used to indicate whether a borehole can maintain a given yield and water quality in the long term, without leading to unacceptable environmental impact. In crystalline rock short-term pumping tests (e.g. 24 hrs) may be adequate to predict the sustainability of an abstraction, especially if the abstraction is small and the aquifer relatively uniform. However, unless one has good knowledge and experience of the aquifer or unless one has extraordinary good conceptual model of the aquifer it will seldom be possible to determine the sustainability of a major abstraction based on a short-term test. Even the long-term behavior and yield of a modestly yielding borehole in a marginally crystalline rock aquifer can be difficult to guarantee with any certainty. Basement aquifers are often too complex to predict from theoretical principles and the best approach to determine whether groundwater levels will stabilize or continue to decline caused by abstraction is some form of empirical long term testing (e.g. 1 to 10 days), also known as the (“suck it and see approach”). This method does require a comprehensive observation and monitoring network. Unfortunately most pumping tests in South Africa are single borehole tests with no observation boreholes, which raises concerns regarding the sustainability of recommended yields over an area or ‘basin’ as additional factors (e.g., impacts of boundaries, long-term water level trends, and other pumping wells). The British Standards Institution (2003) recommended an ideal of at least four observation boreholes spaced at geometrically increased interval, along two lines from the pumping well, at right angles to each other. However one or two observation boreholes will be more economically realistic and will suffice in most cases.

2.4 Groundwater Monitoring

The most common factors contributing to the lack of monitoring is the lack of financial resources and lack of technical capacity to implement monitoring. Other factors that may contribute are a lack of clear institutional responsibilities and legal requirements for monitoring. These factors are quite common in South African rural water supply areas, of which many are underlain by basement aquifers. Several guidelines for the development of groundwater monitoring plans are available (both local and

international) (e.g. ASTM Standards, UNESCO, IAHS WRC, DWA Publications etc.) which can be easily applied to South African basement terrain.

2.4.1 Groundwater quality monitoring

The high to extreme intrinsic vulnerability of basement rocks and since groundwater quality can affect's people's health, monitoring of groundwater quality should be an essential component. The main objectives of groundwater monitoring are to:

- collect data documenting any change in groundwater storage over time;
- provide both long-term and short-term data necessary to assess and predict the response of hydrologic systems to natural climatic variations and human-induced stresses;
- establish as accurately as possible the baseline quality of groundwater occurring naturally in basement aquifers.

2.4.2 Groundwater level monitoring

This is to establish whether the aquifer is being over-pumped, and to establish an efficient pumping rate for individual boreholes. The response of an aquifer to recharge can be assessed by correlating water levels, rainfall and aquifer storage. Recharge in basement aquifers is influenced by temporal variability of rainfall as a result of the incidences of rainy days as well as the intensity and duration of the rainfall events. In a semi-arid to arid environment such as South Africa, with occurrence of drought, aquifer storage characteristics and recharge are crucial aspects of sustainability of groundwater abstraction.

2.5 Description of selected basement aquifers

Basement Rock Aquifers are predominantly distributed in the north-eastern and most western part of the country. Although it's fair to say that most of Africa is underlain by Basement rock it outcrops less than 15 percent of the total surface area of South Africa and is best described graphically (**Figure 2-8**). Also indicated on this map are the nineteen Water Management Areas (WMA) of the country including Vegter's (2000a) groundwater regions with the Basement rock regions labeled. Table 3 provides a summary of the more significant basement rock aquifers. The mean water level and borehole depth is based on the assessment of the NGDB data and the success rate is based on existing literature.

2.5.1 Makoppa Dome

- **Climate**
The climate is semi-arid and hot – daily maximum temperatures average about 32°C in January and 22°C in July. The corresponding daily minima are 18°C and 4°C. Average annual precipitation varies roughly between 375 mm and 600 mm per annum.
- **Occurrence of Groundwater**
Vegter (2000b) described the groundwater resources for the Makoppa Dome in the Northern Limpopo Province. The area is underlain by Swazian granite and granite-gneiss with scattered occurrences of Swazian metamorphosed metasediments and mafic intrusives. The basement rocks are covered with Cainozoic detrital deposits and calcrete. Drilling results are poor – less than

40% of the holes drilled, yielded more than 1 l/s. Borehole yields in the Gaboroen granite and the volcano-sedimentary formations are poorer than in the Swazian rocks. The deeper water levels and strike depths in the latter have to be ascribed to deeper and more advanced weathering. The optimal strike depth for groundwater in these hard-rock formations ranges between 20 m to 85 m. Vegter (2000b) suggested that more boreholes to the same depth will be more successful than deeper boreholes. The combined saturated thickness of alluvium and weathered bedrock, along the Crocodile River, ranges between 20 m to 40 m while the average yields of the boreholes were 7.9l/s.



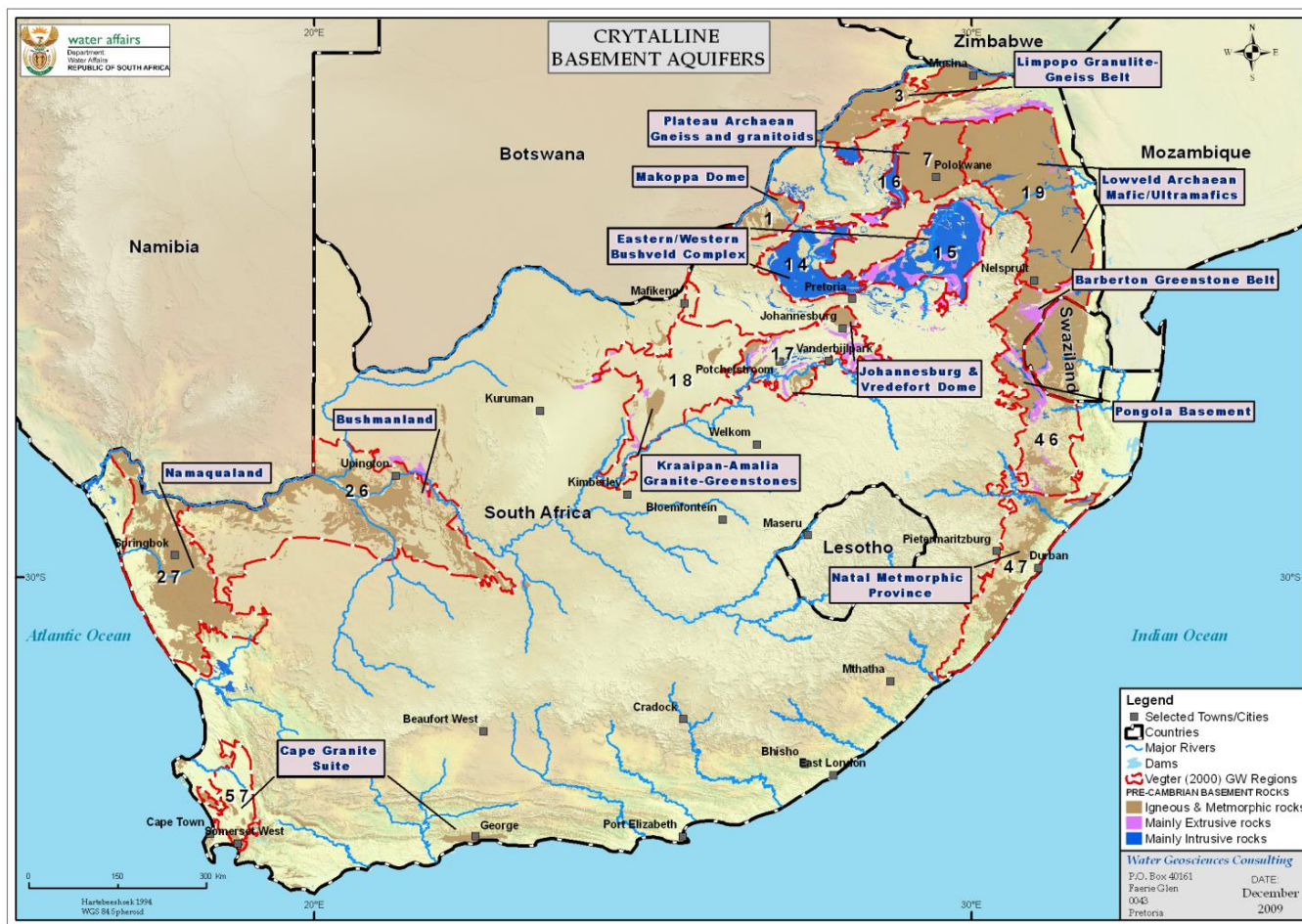


Figure 2-8: Location of Crystalline Basement Rock Aquifers in South Africa

Table 2-2: Regional Characteristics of South African Basement Rock Aquifers

BASEMENT AQUIFER REGION	SUB-REGION	PRINCIPAL WATER BEARING BASEMENT ROCK	Mean Water Levels (Nr of samples)	Mean Borehole Depth (Nr of samples)	Success Rate (Yield \geq 0.1l/s)
Makoppa Dome		Swazian granite, gneiss; Swazian metamorphosed sedimentary and igneous rock	42 (539)	85 (1229)	< 40%
Limpopo Granulite Gneiss Belt	Western portion	Swazian leucogneiss, amphibolite, metapelite; Swazian Allday gneiss, Randian Bulai gneiss.	26 (2338)	66 (3578)	< 40%
	Eastern extremities		22 (566)	65 (4447)	
Pietersburg Plateau	Northern portion	Swazian goudplaats gneiss; Swazian-Randian Houtrivier gneiss; Randian granite plutons; Subordinate metamorphosed sedimentary and igneous rocks.	17 (1273)	61 (2288)	50%
	Southern portion		30 (2281)	64 (4512)	
Lowveld	Central Part	Swazian Goudplaats and Makhutswe gneiss; Swazian Nelspruit Suite granite and migmatite; Randian granite plutons; Subordiante metamorphosed sedimentary and igneous rocks	19 (4086)	66 (7054)	40-60%
	Southern limb		20 (2085)	65 (3454)	
Bushmanland	Central portion	Mokolian metasedimentary and metvolcanic rock units consisting of a variety of gneisses, schists, amphibolites etc. and intrusive rocks of granite and gneisses	25 (644)	60 (953)	30-40%
	Western portion		34 (205)	76 (527)	
	Eastern region		26 (212)	55 (307)	
Namaqualand		Mokolian metasedimentary and metvolcanic rock units consisting of a variety of quartzites schists, paragneisses etc. and intrusive rocks comprising of gnaites, orthogneisses, granodiorite etc.	19 (1474)	59 (2794)	40%
Western Bushveld Complex		Rustenburg Layered suite Mafic Rocks; Rashoop suite granophyre; Lebowa Suite granites; Pilanesberg Syenite and tuff	17 (1362)	54 (2165)	-
Eastern Bushveld Complex		Rustenburg Layered suite Mafic Rocks; Rashoop suite granophyre; Lebowa Suite granites; Rooiberg Rhyolite; Vaalfontein gneais and mogmatite	14 (2161)	70 (2973)	-
Northern Bushveld Complex		Rustenburg Layered suite Mafic Rocks; Rashoop suite granophyre and Rooiberg Rhyolite	18 (612)	68 (942)	
Western Highveld	Kraaipan-Amalia Area	Swazian granite and gneisses	19 (450)	50 (652)	-
Central Highveld	Johannesburg granite dome	Swazian granite and gniess	16 (1037)	50 (1199)	-
	Vredefort dome		14 (206)	41 (302)	
Northeastern Middleveld	Pongola Basment	Swazian Supergroup lava and pyroclastic rocks; Nondweni Group schist and amphibolite; Various Swazian granites and gneisses; Randian Usushuwa complex gabbro, granite	17 (793)	58 (1298)	-
Kwazulu-Natal Coastal Foreland	Natal Metmorphic Province	Tugela Group amphibolites, gneiss, shcist, quartzite itruded by granite gniess and complexes consisting of schist, gabbro,norite etc.; Mapumulo Group gniess and granulite; Mzimkulu Group marble, gneiss and granulte intruded by garnet-biotite augen gneiass and porphyritic granite	29 (462)	97 (940)	60%
Cape Granite Suite		Biotite granite; leucocratic granites.	13 (440)	64 (401)	-

2.5.2 Limpopo Granulite Gneiss Belt

- **Climate**
The climate is semi-arid subtropical; the summers are very hot whilst the winters are mild. The Region enjoys summer rainfall that tends to be erratic. Mean annual rainfall varies from between 425 mm in the vicinity of Beauty in the west to about 300 mm in the east.
- **Occurrence of Groundwater**
Similar conclusions were reached for the Limpopo granulite-gneiss belt as for the Makoppa dome in the Northern Limpopo Province by Vegter (2000c). The area is underlain by highly deformed supracrustal and intrusive rocks of Swazian age with widespread occurrences of surficial Tertiary and Quaternary deposits. The Archaean rocks are part of the Central Zone of the Limpopo Belt or Metamorphic Province which is situated between the Zimbabwean (Rhodesian) and Kaapvaal cratons and which straddles eastern Botswana, southern Zimbabwe and the Northern Province of South Africa.

Except for the larger rivers, which do not necessarily have year round flows, this region is practically solely dependent on groundwater. The drilling results for the hard-rock aquifers were poor with approximately 40% of boreholes yielding more than 0.1 l/s. The optimal strike depth, in certain localities, ranges between 50 m to 85 m below surface or between 15 m to 25 m below the water level. The depth of weathering may extend deeper than 100 m below surface in certain localities. The water-bearing properties of the supracrustal and intrusive rocks of the Limpopo granulite-gneiss belt are the result of brittle deformation, weathering and unloading. According to Vegter (2000c), the probability of striking water is the greatest where weathering extends to below the piezometric level, where the depth of weathering and of the piezometric surface do not exceed 40 m below surface and within the first 10 m below the piezometric level.

2.5.3 Pietersburg Plateau

- **Climate**
The climate is semi-arid. Average daily maximum temperatures are about 32°C in January and 22°C in July. The average daily minima are about 18°C in January and 4°C in July. Frost occurs on average during the months of June and August.
- **Occurrence of Groundwater**
The northern portion of the region is part of the Southern Marginal Zone of the Limpopo Mobile Belt. The boundary between it and the Kaapvaal Craton to the south is taken as the ortho-amphibole isograd, which has been poorly established in the field. The Archaean rocks consist of mainly; the Goudplaats Gneiss of Randian age mainly confined to the northeastern part of the Region and the Hout River Gneiss which includes a variety of granitoid rocks that show clearly intrusive relationships. It includes leucocratic migmatite and gneiss, hornblende-biotite gneiss, biotite gneiss and pegmatite. Younger Randian granitic intrusions occur as scattered bodies (batholiths) throughout the region.

According to Vegter (2003b) boreholes should ideally be sited where weathering/fracturing extends to below the groundwater level. Weathering and fracturing on the Pietersburg Plateau generally extend to between 15 and 50 metres below surface. It exceeded 50 m in 1 out of 6 boreholes. The most prolific aquifers are found in weathered and fractured xenoliths and Hout River Gneiss. Generally speaking drilling depths should not be predetermined but be based on the conditions encountered during the course of drilling.

2.5.4 Lowveld Area

○ **Climate**

The climate is warm to hot and a fairly high humidity makes summer days very oppressive. Cooler weather obtains against the Escarpment. Average daily maximum temperatures are of the order of 30°C in January and 23°C in July.

○ **Occurrence of Groundwater**

The older rocks especially the Swazian migmatites and gneisses as well as the Giyani, Pietersburg and Gravelotte greenstone belts underwent several periods of deformation during which they were intensely folded and metamorphosed. The younger intrusive granites were less deformed.

Groundwater in the Letaba area is found generally in weathered or fractured granite, gneiss, pegmatite and dolerite (Vegter, 2003a). With the exception of amphibolite and quartzitic rocks, other rocks mainly various schists that belong to the Giyani, Gravelotte and Pietersburg Groups have proven considerably poorer drilling targets. Weathering in the Letaba area seldom extends deeper than 36 metres. Rocks are less weathered on higher-lying ground and in the foothills of the Escarpment than in the valleys.

- The occurrence of groundwater is principally associated with the near-surface zone of weathering and fracturing.
- The chances of striking water are better in the supracrustal rocks as a unit (amphibolite, quartzite, sandstone, shale schist) than in the granitic rocks. Yields are also higher. Schist however has been found a poor groundwater target.
- The Nelspruit Granite Suite as a whole appears to be the least favourable of the granitic lithostratigraphic units.

The optimal strike zone below the base of weathering/fracturing decreases with the depth of the base. It ranges from 35 meters for less than 10 metres of weathering/fracturing to 0 meters for a depth of 50 meters and more of weathering/fracturing.

2.5.5 Bushmanland

○ **Climate**

Temperatures are subject to great variation both seasonal and diurnal. Rainfall is highly unreliable. Rainfall increases from west to east. As far east as 20° longitude the mean annual rainfall is less than 100 mm except in the far southwest near the edge of the interior plateau where it approaches a mean of 150 mm. Rainfall increases from 20° longitude eastwards to just over 200 mm in the extreme southeast.

○ **Occurrence of Groundwater**

This region is composed basically of Mokolian metasedimentary, metavolcanic and intrusive rock units of the Namaqua Metamorphic Province. Additionally included in the Region are:

- a strip of volcano-sedimentary rocks and granite of Swazian-Randian age and part of the Kaapvaal craton in the Marydale – Omdraaisvlei area.
- the Koras Group of largely unmetamorphosed inorganic volcano-sedimentary rocks east of Upington and Namibian-Mokolian intrusives.

On structural grounds the Metamorphic Province is divided into four sub provinces: Kheis, Gordonia, Bushmanland and Richtersveld.

According to Vegter (2006) higher drilling success rates were obtained where the formation is weathered or fractured regardless whether logged weathering / fracturing is deeper or shallower than the water level. Most water strikes are made within 25 meters below water level; optimum strike frequency is around 10 m meters below water level.

Despite the great variety of metamorphic and igneous rocks, they are homogeneous in two respects they have; a) virtually no primary porosity and b) a secondary porosity due to fracturing and weathering. The water-bearing capacity of unweathered hard rock is restricted to an interconnected system of fractures that is mainly the result of tectonic phenomena. Weathering processes – mechanical disintegration, chemical solution and deposition – modify the porosity of the original fracture system. These actions imply either an increase or decrease in porosity and / or permeability.

2.5.6 Namaqualand Basement Rocks

○ **Climate**

The area falls in the tropical desert arid, hot climatic region of South Africa. The mean annual precipitation varies from 44 mm in the coastal zone to 480 mm in the Kamies Mountains. Rainfall mostly occurs during the winter months. Large variations between the maximum and minimum temperatures, as well as daily and seasonal temperatures exist for the region.

○ **Occurrence of Groundwater**

The Northwestern Cape Region (i.e. Namaqualand) can be subdivided into three major geological provinces (Adams et al., 2004). These are the basement rocks of the Namaqua Province; the volcano-sedimentary rocks of the Gariep Complex in the northwest, and a Phanerozoic cratonic cover. Groundwater occur in three different aquifer systems in the Namaqualand area, they are: 1) fractured bedrock, 2) the weathered zone or regolith and 3) the sandy alluvial aquifers. These aquifers are closely interlinked. Average yields for Namaqualand vary approximately between 0.2 to 2 l/s (Toens et al., 1996). Boreholes with yields of 0.1 – 0.5 l/s constitute 37%, while boreholes with yields of more than 10l/s constitute only 5.5% of boreholes exploited (Toens et al., 1996).

2.5.7 Natal Metamorphic Province

○ ***Climate***

The climate in the study area is characterized by hot, humid and fairly wet summers and cool, dry winters. The wet season lasts approximately from October to April with rainfall mostly derived from heavy showers during thunderstorms. The mean annual precipitation (MAP) varies between 533 mm and 1332 mm throughout the area.

○ ***Occurrence of Groundwater***

The Natal Metamorphic Province is situated in the coastal belt of KwaZulu-Natal. It consists of rocks varying in age from 1400 to 900 Ma. The northern Tugela Terrane consists of layered amphibolites and subordinate quartzofeldspathic gneisses intruded by plagiogranites, mafic-ultramafic complexes and serpentinites. In the Margate and Mxumba Terranes, the oldest rocks consist of supracrustal gneisses with subordinate paragneisses known as the Mapumulo Group. Later magmatic events in the Mzumba and Margate Terranes resulted in the emplacement of granitoid and charnockite plutons.

The low primary porosity of this hard rock aquifer restricts groundwater flow to fracture zones or deeply weathered profiles, where successful boreholes can be established. Besides fracture zones, the most important water-bearing features in the study area are deep weathered profiles. The occurrence of deeply weathered zones is strongly linked to the geomorphology of the area. According to Sami et al. (2002) water strikes are generally deep, with 50% of water strikes occurring below 70m. A general trend of decreasing borehole yields and success rate with increasing distance from structural features can be observed, highlighting the importance of secondary features on drilling success and borehole yield. Of the successful boreholes (>0.1 l/s), 77% have a yield between 0.1 and 1 l/s and only 23% of the holes have yields greater than 1 l/s (Sami et al., 2002).

2.5.8 Cape Granite Suites

The late Pre-Cambrian to Early Cambrian Cape Granite suite intruded into greenschist facies metasedimentary and metavolcanic rocks of Neo-proterozoic age. The Cape Granite Suite north of Cape Town covers a very small area and only 5% of boreholes yield more than 5 l/s, while 42% of boreholes yield less than 0.5 l/s. ECs vary between 30 and 350 mS/m and the groundwater has a sodium-chloride-sulphate nature. In general, aquifers of the Cape Granite Suite are low yielding and are known to produce poor quality groundwater in places.

2.6 Groundwater quality of selected Basement aquifers

Table 2-3 shows overall classification of the major ion chemistry of water from the different basement aquifer regions using the SANS (2006) drinking water guideline. The table is based on the latest NGDB quality data. Six of the thirteen identified Basement aquifer regions show major ion concentration far from ideal where more than 50% of samples exceeding the maximum allowable drinking water quality guideline.

Table 2-3: Potability Classification of South African Basement aquifers (SANS, 2006)

BASEMENT AQUIFER REGION	Samples	Class I	Class II	Exceeding Class II
Makoppa Dome	102	10%	34%	56%
Limpopo Granulite Gneiss Belt	811	5%	30%	65%
Pietersburg Plateau	2253	19%	48%	33%
Western Bushveld Complex	402	39%	35%	27%
Eastern Bushveld Complex	1051	24%	26%	50%
Northern Bushveld Complex	341	12%	30%	58%
Central Highveld (Vredefort, JHB domes)	58	81%	14%	5%
Western Highveld (Kraaipan-Amalia area)	28	25%	50%	25%
Lowveld	3403	34%	29%	37%
Bushmanland	620	5%	17%	78%
Namaqualand	528	5%	8%	87%
Northeastern Middleveld	168	71%	20%	9%
Natal Metamorphic Province	206	43%	25%	32%
Cape Granite Suite	126	48%	21%	32%

According to **Table 4-1** nitrate and fluoride are the most harmful constituents for nearly all Basement aquifer regions. The presence of fluoride in groundwater is generally a natural phenomenon, influenced by local and regional hydrogeological conditions. The main inputs of nitrate to groundwater are derived from anthropogenic activities such as fertilizer application to land, sewage sludge application to soil, wastewater irrigation, on-site sanitation, deforestation, and mineralization and mobilization of natural soil nitrogen by tilling of the soil (Tredoux 2004). Sodium and chloride together with fluoride are the most harmful constituents in the Namaqualand and Bushmanland regions. Both these regions show that 70% of the water samples are not suitable for drinking (**Table 2-4**). In these regions the high potential evaporation to precipitation ratio, leaves highly soluble salts to accumulate on the surface and as well as in the near surface environment. These salts are periodically flushed into the saturated zone affecting water quality resulting in a typical NaCl character.

Table 2-4: Distribution of harmful ion concentrations – Domestic Use*

BASEMENT AQUIFER REGION	Samples	EC	Ca	Mg	K	Na	SO4	Cl	NO3 as N	F
Makoppa Dome	102	8%	1%	30%	0%	7%	1%	10%	25%	10%
Limpopo Granulite Gneiss Belt	811	7%	3%	18%	0%	6%	2%	8%	40%	23%
Pietersburg Plateau	2253	1%	0%	8%	0%	2%	0%	3%	16%	9%
Western Bushveld	402	2%	3%	10%	0%	3%	5%	2%	10%	11%

Complex										
Eastern Bushveld Complex	1051	3%	1%	12%	0%	3%	1%	6%	25%	24%
Northern Bushveld Complex	341	2%	1%	19%	0%	2%	0%	6%	26%	22%
Central Highveld (Vredefort, JHB)	58	0%	0%	0%	0%	0%	0%	0%	3%	2%
Western Highveld (Kraaipan-Amalia area)	28	0%	0%	0%	0%	0%	0%	0%	25%	0%
Lowveld	3403	3%		8%	0%	4%	0%	5%	17%	4%
Bushmanland	620	25%	9%	22%	0%	29%	20%	29%	25%	55%
Namaqualand	528	56%	15%	54%	3%	57%	11%	69%	7%	66%
Northeastern Middleveld	168	0%	0%	1%	0%	0%	0%	0%	2%	3%
Natal Metamorphic Province	206	4%	0%	5%	0%	4%	2%	4%	7%	22%
Cape Granite Suite	126	16%	2%	12%	0%	25%	2%	29%	1%	6%

* Based on values exceeding the maximum allowable limit for drinking water (SANS, 2006).

CHAPTER 3. VULNERABILITY OF BASEMENT AQUIFERS

3.1 *Groundwater resource quality of basement aquifers*

3.1.1 Natural water quality

The natural groundwater chemistry, being the product of various weathering processes, will exhibit vertical differences in chemical composition due to varying mineral assemblages at different stages of weathering and leaching in the regolith (Chilton and Foster, 1995). 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. However, salinities are elevated in areas of low recharge and/or prolonged residence times in the subsurface. There is often little to buffer acidity in basement rocks. 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 aluminium 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). It is therefore necessary to test groundwater for natural quality, and groundwater development in a new area should always take water quality into account. 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.

3.2 *Vulnerability to pollution*

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. Pollution is the 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. 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. There are standard procedures and guidelines available for the siting of boreholes in basement rocks, and for assessing the vulnerability of the resource (e.g. ARGOSS, 2001), but these will need to be “fine-tuned” when developing new areas, and perhaps upgraded completely when considering higher yielding boreholes.

3.2.1 Groundwater protection zones

In South Africa there is currently no policy that directly addresses the protection of groundwater used for drinking water (DWAf, 2008b). Due to the intrinsic vulnerability of Basement aquifers and the widespread distribution of rural areas on these rocks, protection zoning is an important measure for the mitigation of water resource pollution. Protection zones can be defined in various ways, ranging from simple circles drawn

around boreholes (assuming a homogeneous, isotropic aquifer and no regional groundwater gradient) to zones of complex shape derived using numerical groundwater modeling and taking into account aquifer properties (including stochastic variations of aquifer parameter), topography, groundwater flow direction and recharge.

3.3 Drought Vulnerability

The failure of wells and boreholes during drought is a function of both increased demand on low yielding sources and reduced recharge to the aquifer. This is most likely to occur in areas underlain by low permeability rock where the transmissivity of the aquifer is low. 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. This together with long-term monitoring of water levels provides a more proactive approach to groundwater management and drought preparedness before serious problems arise.



CHAPTER 4. MANAGEMENT OF BASEMENT AQUIFERS

4.1 *Groundwater Management issues*

The Department of Water Affairs (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. This means that in order to achieve sustainable groundwater use, the management of groundwater resources need to balance economic, environment and social considerations. The management issues are identified as (MacDonald and Davies 2000; Pietersen, 2004):

- Sustainability of groundwater from basement aquifers, particularly during extended drought periods;
- Low rainfall and high evaporation rates affect recharge to basement aquifers resulting in the slow circulation of groundwater causing groundwater quality and quantity problems
- The poor natural water quality of basement aquifers associated with low rainfall areas has a health impact on the affected communities
- The vulnerability of shallow aquifers to pollution, particularly with the rapid increase of onsite sanitation and intensification of agriculture in some areas;
- The lack of suitable institutional arrangements at the local level and at catchment scale hinders proper resource management
- The relative performance and operational costs of boreholes, wells, family wells and collector wells;

4.1.1 **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 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 sustainable.

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 (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 (small scale irrigation or industrial use, for example) the requirement to reduce risk grows.

4.1.2 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 end users of water points into 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 lacking 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 of their water supplies remains a challenge for any development specialist. Rural councils or village water committees should not take on any water supply or management responsibilities.

Whilst South African hydrogeology has many challenges, we are by no means unique in most of these. In general, we lack experience in the “rest of Africa”, and in particular we lack experience of rural water supply in basement rocks in which communities, are fully integrated into the development process. There is also a danger that our considerable experience in developing and managing consolidated sedimentary aquifers (e.g. the Karoo rocks) will be applied to basement aquifers without sufficient consideration of the differences.

4.1.3 Groundwater management approaches

Management strategies are required to address the unique characteristics and functions of groundwater located in basement aquifers. The premise for these management options in should be based on achieving socio-economic developmental targets. The need for an integrated approach to the management of basement aquifers has been shown by various authors. The objectives for groundwater management 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.

Management recommendations for specific basement aquifer cases can be made from the various models available (e.g. Moriarty, 2000; UNEP, 2003; Pieterse, 2004) and formed in line with integrated water resources management (IWRM) principle.

4.2 Framework for management of basement aquifers

Groundwater resources 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 resource availability and quality). The proposed groundwater management framework of basement aquifers is presented in **Table 4-1**.

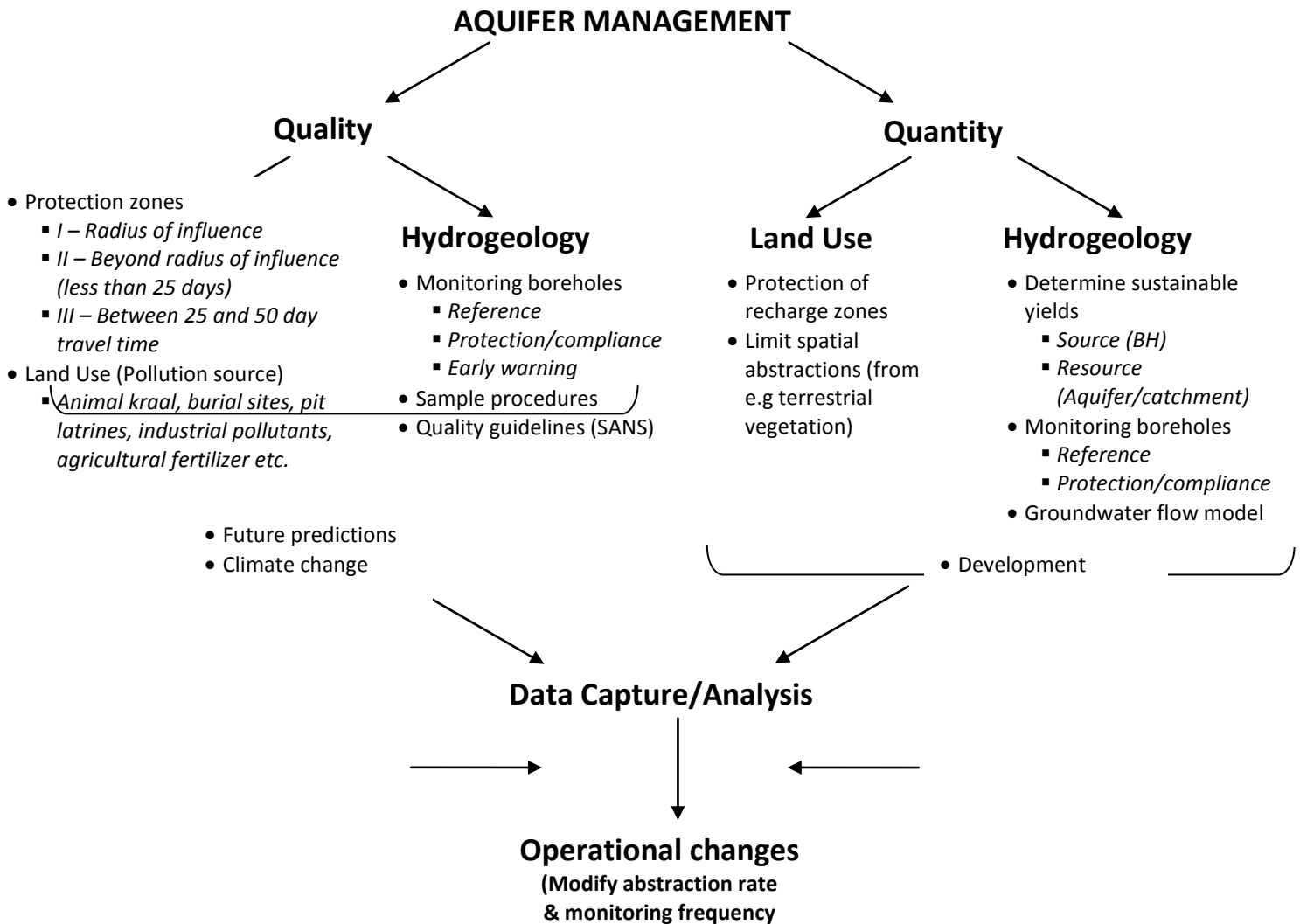


Figure 4-1: Groundwater Management for Basement rock aquifers

4.3 Concluding comments

In South Africa most basement aquifers supply rural communities with water. Therefore emphasis should be placed on rural groundwater management. Ideally, management of the water resources should include mechanisms that allow technical developments to be fed back into policy. For example, if water levels drop considerably following extended periods of low rainfall, then there needs to be a plan to cope with possible reduced borehole output. The technical data collection would act as an “early warning” system, so that adaptation measures could be smoothly adopted. The success and failure of rural water supply is very much in political hands and it is up to those in the field to recognize they have a dual role of promoting technical aspects as well as the social awareness at all levels.

4.4 Basement aquifer management checklist

DWAF Generic Guideline (DWAF, 2008) provides detailed procedures in the form of checklists with guiding notes for carrying out the assessment, planning and management functions. However, basement aquifers provide some unique characteristics that need special recommendations when it comes to assessment, planning and management of these aquifers. A summary checklist of additional aspects of basement aquifers not found in the generic guidelines is presented in **Table 4-1**.

Table 4-1: Specific assessment, planning and management issues relating to basement aquifers

Stage	Activity	Comment	Done
Assessment	Lineament mapping	ASTER (Landsat Imagery)	
	comprehensive geodynamic / strain analysis	Section 2.2.1	
	Ground truthing of drilling targets (appropriate geophysics)	Section 2.2.4	
	Drilling of exploration boreholes based on conceptual understanding	Assess the need for exploratory boreholes	
	Borehole design according to specifications	Section 2.3.1	
	Undertake testing of boreholes (emphasis on observation boreholes)	Section 2.3.2	
	Vulnerability mapping	Section 3.2	
	Establish groundwater protection zone	Section 3.2.1	
	Drought vulnerability assessment	Section 3.3	
Assess monitoring programme	water levels; water quality; water consumption and rainfall		
Planning	Land Use planning (based on groundwater protection zones)	With each protection zone comes land use constraints	
	Identify potential high yielding areas based on geodynamic model	Augmenting surface water scheme (during drought)	
Management	Initiative to create awareness of the importance of groundwater	Local communities	
	Confirm distribution of monitoring network	Frequency of monitoring and constituents to monitor	
	Transfer of information (to decision makers)	Establish data management framework	
	Operation & maintenance of groundwater supply scheme (e.g borehole development)	Establish functions and procedures	

CHAPTER 5. REFERENCES

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