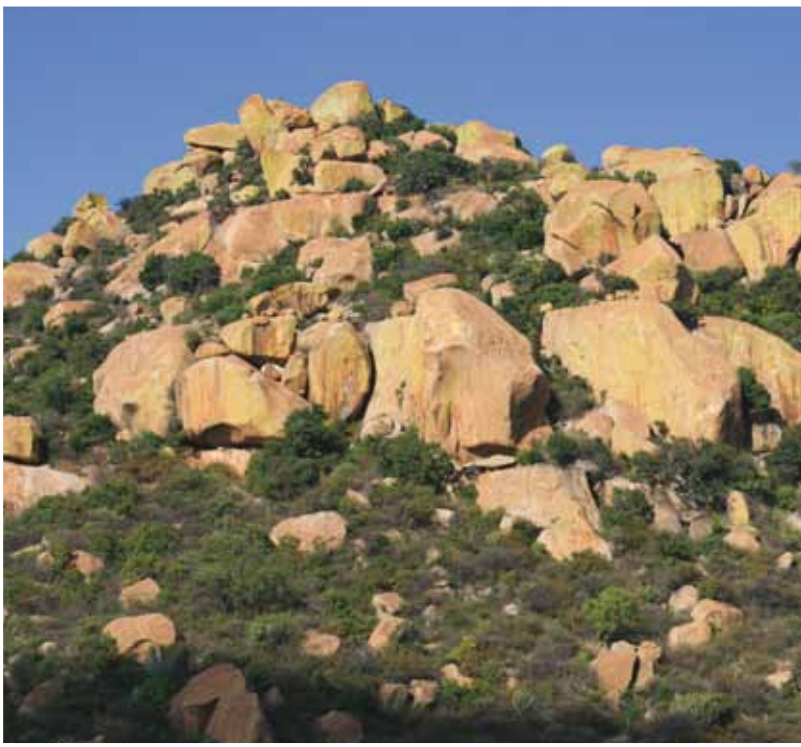
The Basement Aquifers of Southern Africa

Rian Titus, Hans Beekman, Shafick Adams & Leslie Strachan (Editors)



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The Basement Aquifers of Southern Africa

Report to the

Water Research Commission

by

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Shafick Adams and Leslie Strachan (editors)

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Preface

A significant portion of sub-Saharan Africa is underlain by basement aquifers. These types of aquifers are considered to be of minor importance in hydrogeological terms, but nevertheless provide water for millions of people in areas of sub-Saharan Africa. The development and management of groundwater resources in these types of terrains is a complex problem. It is therefore encouraging to see colleagues within the Southern African Development Community (SADC) sharing their knowledge and experiences.

There are a number of important constraints to the development of basement aquifers in Southern Africa. Some of these constraints include:

- The high failure rate of boreholes
- Low storage capacity
- Sensitivity of recharge to land-use changes (e.g. desertification)
- Association of basement aquifers with areas of low rainfall and high evaporation, which therefore have low recharge potential

Whilst these concerns may give rise to complex 'scientific' questions, it is important to recognise that the communities that depend on these water resources often live in poverty and face serious health issues. My wish is that scientists start to transcend the science-policy-implementation cycle and ensure that their knowledge is applied to addressing the huge poverty concerns in the region. In this regard, the Water Research Commission is to be congratulated for reaching beyond the South African scientific community. It is only through this cross-pollination of ideas that lasting solutions can be found.

The challenge remains to scale up these excellent ideas and to incorporate them into the broader water resource decision-making process. Can you, as scientist, respond to this challenge?

Acknowledgements

We would like to thank the Water Research Commission for making the funds available for this publication as well as the various authors who contributed papers. Elanda Botes and Edwin Whittle for the layout and proofreading. The British Geological Survey for making available their bibliography, found at the end of this publication, on basement aquifers in various countries.

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Basement aquifers of southern Africa: Overview and research needs

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Abstract

A fifth of the world's population lives in areas that are characterized by physical water scarcity. The complexity of water scarcity is expected to increase over the next few decades. The relationship between the characteristics and occurrence of groundwater that is to be found in basement aquifers and the factors that govern the management of these groundwater resources is not yet fully appreciated. This paper presents an overview of the latest research on basement aquifer hydrology in southern Africa and is based on the case study papers that are presented in this publication. The papers cover an array of topics that range from the assessment to the exploration and the management of water resources. It is estimated that 60% to 90% of the rural population in southern Africa relies on groundwater for its livelihood. However, it is generally acknowledged that groundwater management lags behind the current development of groundwater and the exploitation of the resource. Several management strategies or models are proposed for the effective management of groundwater in basement terrains.

Introduction

Crystalline basement forms the largest part (40% of the land area) of the four hydrogeological zones of sub-Saharan Africa where 220 million people live in rural areas that are underlain by crystalline basement rocks (MacDonald and Davies, 2000). In southern Africa, basement aquifers constitute approximately 55% of the land area (UNEP and WRC, 2009). Literature on the characteristics of crystalline basement aquifers has increased considerably over the past few decades (e.g. UNESCO, 1984; Acworth, 1987; Howard and Karundu, 1992; Wright and Burgess, 1992; Gustafson and Krasny, 1994; Chilton and Foster, 1995; Lloyd, 1999; Taylor and Howard, 1999; Banks and Robins, 2002, Titus et al., 2002). The compendium of papers in this publication comprises case studies of basement aquifers in the following countries: Botswana, Malawi, Namibia, South Africa, Tanzania Zambia and Zimbabwe. This collection of papers will contribute to the understanding of these 'minor', but important, aquifers, including the various management options that are available in the countries concerned. Due to their low storage capacity, quality and water supply problems, basement aquifers are often described as being poor or minor aquifers. However, the case studies presented, indicate that they are often the only means of supplying water to a large number of rural communities and local authorities. More intensive development of the groundwater resources is possible at locations where favourable lithology, structural features and weathering coincide to form zones of higher transmissivity (Chilton and Foster, 1995). Braune and Mutheiwana (in this publication) indicate that between 60% and 90% of the communities in rural southern Africa use groundwater and most of the areas concerned are indeed underlain by basement aquifers. The development of basement aquifers, as a reliable source of rural water supply, is notoriously complex, especially where a thinner weathered overburden is present. Crystalline basement aquifers are generally classified as two-layer systems that comprise fractured bedrock that is overlain by a weathered/regolith zone (Chilton and Foster, 1995). Regolith is defined as the solid product of intense in situ weathering. Titus et al. (in this publication) describe the development or evolution of the weathered zone in the northwestern parts of South Africa. The extent and depth of the weathered zone is determined by factors such as susceptibility to weathering and the availability of moisture. The weathered zone in arid terrain is generally shallower than in more humid terrain. However, thick weathered zones do occur in semi-arid areas and are the result of a more humid period (UNESCO, 1984). The semi-arid to arid Namaqualand region is an example of the latter and in it the weathering can extend up to 80 meters. Fracture zones usually occur along lineaments and often correspond to the surface drainage patterns. Fractures, dykes and zones of weathering and/or overburden deposits are targets for the exploitation of groundwater.

Exploration and assessment

The quality and quantity of the available groundwater are often factors that limit development in areas that are underlain by crystalline basement terrain. Due to the inherent small storage capacity of these aquifers, favourable recharge conditions are essential if they are to be viable sources of water supply. Adams et al. (in this publication) present a framework for estimating groundwater recharge that is based on the availability of data. Their paper also demonstrates that groundwater recharge in semi-arid areas is spatially and even temporally complex and that it is a function of the prevailing climate, geology, topography and drainage. Recharge in arid and semi-arid areas mainly occurs indirectly. Recharge is generally higher in alluvial zones, which are often structurally controlled. Due to the inherent difficulties of estimating recharge, it is recommended that various estimation methods be used. It has been illustrated that, in Namibia, indirect recharge to the hard rock aquifers can be enhanced by constructing sand storage dams or "grundschwelle" in the alluvium or riverbeds (Kirchner, in this publication). Linn (in this publication) comes to the same conclusion in respect of cases in which aquifers that are connected to perennial or intermittent streams receive greater recharge. In respect of the Limpopo province of South Africa, Holland and Witthüsser (in this publication) illustrate that, in the case of, boreholes that exploit the gneisses, granitic contacts and alluvium present relatively favourable conditions while younger, less fractured and weathered granites have lower borehole productivity.

It is well known that not all fractures and fracture sets that are intercepted by drilling will yield water in hard rock terrain. The flow through rocks requires that a connected network of fractures should be present. Linn, Lovell and Sami (in this publication) and Kellet (2004) have highlighted the fact that the finding of suitable targets in often complex terrain requires the use of local knowledge; airborne and/or ground geophysics (airborne magnetic surveys, airborne radiometric surveys, horizontal loop electro-magnetic (HLEM), vertical electrical sounding (VES) and electromagnetic methods, etc.); detailed structural and geological mapping (e.g. field mapping, aerial photography and satellite imagery analyses); and exploratory drilling. The integrative approach to borehole siting has achieved a relatively high success rate (>75%) across Botswana in comparison with the 20% success rate achieved with 'conventionally' sited holes (Linn, in this publication). Sami (in this publication) proposes the implementation of an integrated exploration and development process that focuses strongly on the structural and geodynamic analyses of the fractured basement aquifers under investigation. Sami has demonstrated, by means of a case study, that the rate of drilling successful boreholes can be improved by applying an integrated exploration process. Crystalline basement rocks (usually of Precambrian age) have generally been subjected to multiple tectonic events, under varying stress conditions, which result in complex patterns of ductile folding and brittle fracturing in the near-surface regions of the earth's crust (Lloyd, 1999). Structural analysis is commonly used to identify compressional and extensional orientations. By identifying extensional orientations, structures occurring at right angles to them are considered to be more open and are therefore potential groundwater target zones. Both Titus et al. and Sami (in this publication) have shown that the reactivated NNW-SSE lineaments are the ideal groundwater targets in Namaqualand and the Bushveld areas in South Africa. Granite is considered to be more pervious than gneiss in highly fractured terrains (Stober and Bucher, 2007). Fractured rock that is likely to transmit a sufficient volume of water will receive adequate recharge; have a high density of fractures; have fractures with wide apertures (extensional); be parallel to the gravitational gradient; and be overpressured (Bisson and Lehr, 2004). The connected zones that have adequate storage, like the weathered zones and alluvial systems, are an important part of the exploration target. Due to their larger porosity, the weathered or regolith and alluvial zones act as reservoirs that slowly feed water downward into fractures in the bedrock. The deeper groundwater levels and thin saturated regolith in arid regions necessitate the drilling of deep boreholes to intercept structural features and contact zones at depth within the unweathered bedrock.

The quality of the groundwater is often variable. In respect of Namaqualand, Titus et al. (in this publication) found that the groundwater chemistry is dependent on the point of sampling, recharge, hydraulic gradients and hydraulic conductivity. Nkotagu (in this publication) found that elevated fluoride concentrations are not always attributable to the direct dissolution of fluoride-bearing minerals. In respect of the Singida region of Tanzania, he found that the main mechanism for fluoride and salinization input into groundwater is attributable to the leaching of surface and near-surface salts (i.e. trona). In most parts of Zambia, Malawi, Mozambique and Zimbabwe, large-diameter hand-dug wells and ephemeral springs are the most common water points (Kellet, 2004). These sources are susceptible to groundwater pollution and droughts.

Management

The development and management of water resources are essential elements of water security. It is evident

that our understanding of basement aquifers is improving and so, too, are the management systems that are required to access and manage groundwater in these aquifer systems. Some of the main reasons why groundwater resources in these systems are perceived to be unreliable are poor operation and maintenance; rapid pollution; sudden failure of schemes; and a general lack of capacity at the local level to manage and protect groundwater resources. In general, it is the public and policy-maker perceptions or lack of awareness of groundwater that represent an important cause of emerging problems (Burke and Moench, 2000; Quevauviller, 2007). In view of the variable hydrogeological (spatial) and climatic (spatial and temporal) conditions that are experienced in some of the areas concerned, any groundwater scheme developed within these systems should be monitored and maintained effectively. With the increase in our population, economic growth and the technological options that we have to abstract groundwater cheaper from greater depths, it has become clear that there is a need to manage groundwater resources better (Kemper, 2007). Lovell (in this publication) argues that "the greatest single challenge that faces rural water supply in southern Africa is the issue of maintenance". In the Dendron area of South Africa, significant agricultural activities are being maintained from basement aquifers, albeit through over-abstraction, (Masiyandima, in this publication). In the case of Malawi, Chimphamba et al. (in this publication) have found that, although 60% of the rural population relies on groundwater from the basement aquifer systems, there is not sufficient monitoring of water quality taking place. Sunguro and Beekman (in this publication) highlights the need to implement practical groundwater investigations as well as development and management strategies and practices that could benefit all the stakeholders concerned. The application of a combined management framework (comprising direct and indirect approaches) to basement aquifers would improve the overall management of groundwater supply schemes (Masiyandima, in this publication). Pietersen (in this publication) presents a multi-criteria decision-analysis framework for the management of groundwater in the Namaqualand region of South Africa. Standard groundwater management approaches depend on the presence of basic data and on institutional capacities (FAO, 2003). In most instances, there is a dearth of information that has been derived from collected data and from which management policies and schemes can be developed. In order to protect the resource and to generate additional supplies of water in circumstances of scarcity, effective management will have to rely on adaptive management strategies. In several of the papers, adaptive management is put forward as an option. The monitoring of groundwater remains essential for the provision of background data sets to validate and assess the outcomes of adaptive management approaches. Because groundwater issues as well as the technical, social, economic, cultural and political factors that influence management options differ from one region to the next, no single template for management can be developed (Burke and Moench, 2000).

Conclusion and research needs

Basement aquifers are complex systems; therefore information on their geohydrological behaviour is essential for their effective management. It is clear that we do have the tools and methodologies to assess aquifer systems. What is lacking is the funding and willingness to implement some of the strategies. In South Africa, there are numerous guidelines and manuals that have been issued by the Water Research Commission (www.wrc.org.za) and the Department of Water and Environment Affairs (www.dwaf.gov.za) that could be used to implement data collection, data management and assessment programmes (e.g. WRC, 1998; DWAF, 2004; Meyer, 2006; Mukheiber, 2006; Weaver, 2007). In the absence of local information, international best practices could also be adapted to local conditions. By implementing adaptive management, the guidelines, manuals and management options could be refined as more information on and knowledge of the local aquifer systems becomes available. Exploration and data collection are expensive undertakings and should be matched by the required data management systems.

The following issues are recommended for further research:

- Increasing understanding of the impacts of climate change and climate variability on groundwater resources.
- The importance and quantification of episodic recharge in, especially, arid and semi-arid regions.
- Improving groundwater management strategies and enhancing adaptive capacity in water supply programmes.
- Improving the siting techniques in respect of and design of new water points.
- Improving the collection, storage, sharing and analyses of data, particularly in respect of the need for practical and cost-effective solutions.

- The estimation of hydraulic properties for local basement aquifer systems. Knowing the type of geohydrological unit is not sufficient to estimate hydraulic parameters from existing published measurements.
- The permeability of fractured rock is generally considered to decrease with depth. Stober and Bucher (2007) have found that at some sites there is a decrease of hydraulic conductivity with depth in gneissic, but not in the granitic basement. Whether this is the case in southern Africa could be investigated.
- Mapping the occurrence and overlap of aquifers that could be sustainably exploited where there is a high prevalence of poverty and where economic activities, such as agriculture, could be promoted as a poverty-reduction stratetgy.

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A tectonic and geomorphic framework for the development of basement aquifers in Namaqualand – a review

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Abstract

The basement rocks of Namaqualand retained the imprints of mostly the Proterozoic tectonic events, although much of the present landscape appears to have developed in the Cretaceous, following the break-up of Gondwanaland. The geomorphological development of Namaqualand is thus to a great extent controlled by the underlying geology and these earlier tectonic events.Alternate geological periods of warmer humid climatic conditions, followed by cooler and drier climatic conditions, resulted in sequential and repetitive cycles of accelerated weathering and erosional periods, which were followed by periods of aridification. This succession of tectonic and geomorphic events, in association with repetitive climatic conditions, resulted in the weathered and fractured aquifer systems in Namaqualand.The aquifer systems are mostly limited to fault-controlled valleys that occur throughout the study area and that are traditionally the targets for the development of groundwater resources. The proposed geometry for the aquifer system can be described as laterally extensive, linear, structurally controlled valley systems in which weathered and fractured bedrock constitute the main aquifer systems.The effects of large-scale mantle convection beneath the African plate is currently believed to be responsible for the tectono-magmatic and geomorphological development of southern Africa since the beginning of the break-up and dispersal process of the Gondwana supercontinent at ~205 Ma. This process continues to the present time and is responsible for neoseismicity and neotectonic activity, which controls the neomorphological development of the southern African landscape. The current in situ stress field that is present in southern Africa is the result of a complex interplay between mantle convection and lithospheric basal drag, thermally induced continental uplift and ridge-push forces.In Namaqualand, a strong correlation exists between known water borehole positions and the proximity as well as the alignment of these boreholes to two prominent fault/fracture zone systems. The one is the well-known coastal-subparallel NNW-SSE striking system of brittle fault/fracture zones, which is related to the Gondwana continental break-up phase and historically proven to be associated with productive boreholes. The other is a set of NNE-SSW striking fault/fracture zones that represent continental continuations of oceanic transform faults, which also developed during the Gondwana fragmentation/dispersal phase and formed penecontemporaneously with the NNW-SSE striking fault/fracture zones. They are oriented subparallel to the direction of the present-day neotectonic crustal extension and currently undergo neotectonic reactivation/seismicity. Both fracture systems in general and specifically at, or in close proximity to, their intersection areas, represent the highest dilational zones within this Namaqualand coastal rift system and therefore the most prospective sites for well-field development.

Location and extent of study area

Namaqualand consists of seven communal areas, which include the northern Richtersveld, southern Richtersveld, Steinkopf, Concordia, Komaggas, Pella and Leliefontein. Groundwater is the sole water resource for most rural communities. The Namaqualand area is classified by three physiographic regions in accordance with topography, altitude and landforms (Van der Merwe, 1995). These regions are the higher lying Bushmanland Plateau to the east, Namaqualand highlands (*i.e.* the escarpment zone), and lower lying coastal area to the west (Visser, 1989).

According to the Koeppen classification, the study area (**Figure 1**) falls in the tropical desert arid, hot (BWh) climatic region of South Africa and can be classified as arid to semi-arid. Mountainous regions receive much higher rainfall than the surrounding arid lowland and coastal plains as a result of orographic effects. Rainfall

occurs mostly during the winter months while snow in the Kamiesberg Mountains is not uncommon. The average annual rainfall generally increases from west to east until it reaches the escarpment and then decreases further inland. Potential evapotranspiration can be as high as 12 to 15 times the precipitation.

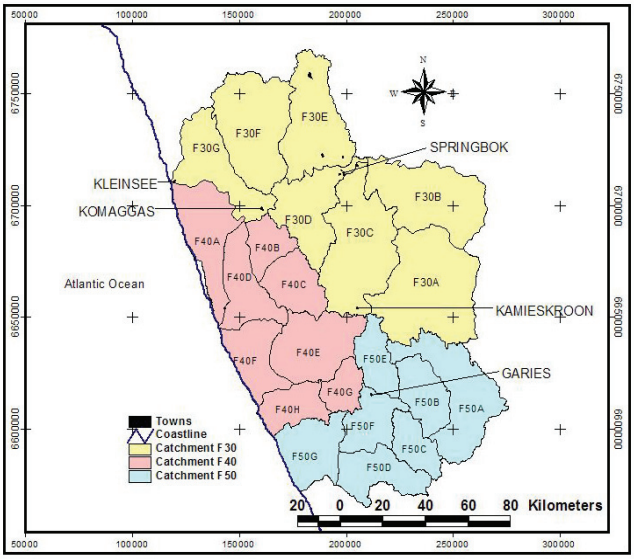

Figure 1: The study area that comprises secondary drainage catchments F30, F40 and F50.

The nature of basement (crystalline) aquifer systems

Introduction

Basement aquifers (i.e. usually fractured, Precambrian crystalline rocks) are found extensively in sub-Saharan Africa where the resource supplies many rural communities. Basement aquifers developed within the weathered overburden and fractured bedrock of crystalline rocks of intrusive and/or metamorphic origin that are mainly of Precambrian age (Wright, 1992). Gustafson and Krásný (1994) referred to crystalline rock aquifers as hard-rock aquifers that predominantly comprise fractured igneous and metamorphic rocks that have negligible matrix porosity and matrix permeability. The basal part of the regolith (i.e. approximate base of saprolite) and the top of the weathered saprock (i.e. weathered bedrock) have sufficient permeability to support successful boreholes for small-scale village water supply (Chilton & Foster, 1995; Rebouças, 1993). Groundwater within the lowermost unweathered basement rocks is stored in interconnected systems of fractures, joints and fissures that are associated with regional tectonism (Rebouças, 1993). The fractured bedrock is characterised by high transmissivity and low storativity values. More intensive development of the groundwater resources is possible at locations where favourable lithology, structural features and weathering coincide to form zones of higher transmissivity (Chilton & Foster, 1995).

Crystalline basement rocks (i.e. usually of Precambrian age) have generally been subjected to multiple tectonic events under varying stress conditions that resulted in complex patterns of ductile folding and brittle fracturing in the near-surface regions of the earth's crust (Lloyd, 1999). Near-surface fractures, to depths of 100 m and even deeper, are considered to be in a state of tension with enhanced groundwater movement.

Studies on basement aquifers have predominantly focused on the development of groundwater resources in thick regolith (i.e. weathered overburden) that have dominant intergranular flow in predominantly tropical to sub-tropical regions (i.e. western and southern Africa, South America, Norway and Sweden) in comparison with dominant fissure flow in temperate and higher latitude regions, such as Namaqualand. As a result, the weathered overburden is usually described as the main groundwater storage compartment, although productive boreholes may be developed in the underlying fractured bedrock. Basement aquifers are notoriously complex to develop, especially where a thinner weathered overburden is present or limited in extent (Lloyd, 1999; Chilton & Foster, 1995; Gustafson & Krásný, 1994; Rebouças, 1993; Olofsson, 1993; Wright & Burgess, 1992; Commonwealth Science Council TP 273, 1990), as will be illustrated in the Namaqualand case study.

The hydraulic properties of basement aquifers

Basement aquifers are furthermore characterised by poor connectivity of bedrock fractures and regions of low permeability (*i.e.* extreme heterogeneity in their hydraulic properties), which results in significant local variations in yield and response to abstraction (Chilton & Foster, 1995; Gustafson & Krásný, 1994). The hydraulic conductivity can vary, within the same rock mass, by orders of magnitude and over short distances.

Structural features, such as fractures and fissures in crystalline rock (**Figure 2a**), are described as hydraulic conductors, while zones of intense fracturing are described as compound conductors (Gustafson & Krásný, 1994). The fractures and fissures are a result of tectonic processes and are therefor 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).

Figure 2: (a) Typical appearance of basement aquifers in Namaqualand that are characterised by hydraulic conductors (fractures and fissures) that developed in Precambrian basement lithologies;

(b) Water flowing from regularly spaced horizontal joint planes. Note: The surface planes of the vertical joints are clearly visible. ithostratigraphic and structural development

They are referred to as hydraulic conductors within fractured crystalline rocks, rather than aquifers, to describe the storage and flow of groundwater in these rocks. The term aquifer implies that the groundwater reservoir is related to the formation rather than the structures within it. A hydraulic conductor includes single fractures and fracture zones and is defined by its ability to transmit groundwater.

Infiltration for the fractured crystalline rocks in Namaqualand occurs along the vertical to sub-vertical fractures, with lateral flow occurring predominantly along the horizontal to sub-horizontal fractures (**Figure 2b**). Fractured crystalline rocks in Namaqualand are characterised by extreme heterogeneity in their hydraulic properties with poor connectivity between fractures. Water is stored and transmitted in these fractures and fissures, which serve as hydraulic conductors, through a relatively impermeable matrix.

Lithostratigraphy

The north-western Cape region (*i.e.* Namaqualand) can be subdivided into three major geological provinces (Tankard *et al.*, 1982). These provinces are the basement rocks of the Namaqua Metamorphic Province (further subdivided into three zones), volcano-sedimentary rocks of the Gariep Complex (Visser, 1989) in the northwest, and a Phanerozoic cratonic cover (**Table 1**). The Namaqua Province (**Table 1**) comprises most of the Proterozoic crystalline basement in the northern Cape and southern Namibia (Tankard *et al.*, 1982).

In Namaqualand, the margins of the Namaqua Province are largely obscured by younger cover rocks of the Gariep and Nama groups and Karoo Supergroup as well as by Cenozoic surficial sediments to the east and west. In the west and extreme north, rocks of the Namaqua Province and its correlatives are bordered by formations of the late Proterozoic Gariep Complex and in the east abut the Kaapvaal craton with marked structural discordance in both cases. In the south, rocks of the Nama Group, the Cape Supergroup and the lowermost units of the Karoo Supergroup cover rocks of the Namaqua Province (Albat, 1984).

The central zone of the Namaqua Province, a complex deformed heterogeneous group of gneisses and intrusions of medium to high grade metamorphism (Tankard *et al.*, 1982) covers most of the Namaqua Province and comprises an assemblage of metasedimentary, metavolcanic and intrusive rocks.

Structural evolution

Late palaeoproterozoic tectonism

The ancient geological evolution of southern Africa can be regarded as a sequence of accretion onto a stable Kaapvaal craton during both extensional and compressional tectonic periods (Partridge & Maud, 2000; Tankard *et al.*, 1982). The accretion of the Mesoproterozoic Namaqua-Natal mobile belt occurred between ~1200 Ma and ~1000 Ma.

The rocks of the Namaqualand Metamorphic Province were subjected to the ~1200–1000 Ma Namaquan orogeny (Blignault *et al*., 1983; Van der Merwe, 1995) and underwent several phases of intensive folding and faulting and were intruded on a large scale by syntectonic

Table 1: Classification of the major geological provinces (according to Tankard *et al*., 1982, Visser, 1989).

Geological Province		Group	Age	Locality	Orogenies & Subprovinces
Phanerozoic Cover Rocks		Sand, alluvium and calcrete Karoo Supergroup 1. Prince Albert Fm 2. Dwyka Formation Nama Group 1. Kuibis Formation 2. Schwarzrand Fm	Late Phanerozoic (Cenozoic) Early Phanerozoic (Middle/Late Palaeozoic) Late Proterozoic (Late Namibian)	Along coast. Most of western Bushmanland South-eastern corner of Namaqualand Isolated strip north of Springbok	
Gariep Province		Gariep Group (6 Formations)	Late Proterozoic (Early/Middle Namibian)	Central and Western Richtersveld	PAN-AFRICAN Gariep sub-province
	Central zone	Namaqua Metamorphic Complex/ Province	Middle Proterozoic (Middle Mokolian)	Most of Namaqualand and parts of Bushmanland	NAMAQUAN Bushmanland & Gordonia Subprovinces
Namaqua Province	Western zone	Vioolsdrif Intrusive Suite	Middle Proterozoic (Early Mokolian)	North-eastern and eastern Richtersveld Northern Namaqualand	EBURNIAN Richtersveld Subprovince
		Orange River Group	Middle Proterozoic (Early Mokolian)	North-eastern part of Richtersveld	
	Eastern zone			Upington	

granites (Visser, 1989). Researchers such as Albat (1984), Blignault *et al*. (1983), Lipson (1978), Moore (1977) and Joubert (1971) recognised four deformation phases within the rocks of the Namaqua Metamorphic Complex. The interpretation of both vertical and lateral stratigraphic and structural relationships, as well as possible lateral correlatives, is extremely difficult. The high-grade metamorphism and multi-phase deformation that these rocks experienced, destroyed the normal stratigraphic criteria and produced generations of tight and isoclinal folding (Joubert, 1971; Jack, 1980). Most of the area was covered by sediments that were later stripped off with the subsequent re-exposure of the gneisses and its varying intrusive rocks (Joubert, 1971). The rocks of the Namaqualand Metamorphic Province represent most of the crystalline basement in Namaqualand.

The crystalline basement rocks of Namaqualand retained imprints of mostly the Proterozoic tectonic events. However, much of the present landscape appears to have developed later, namely after the break-up of Gondwanaland in the Cretaceous.

Neotectonic activity and far field stress

Neotectonics, the study of young typically Neogene and Quaternary deformation, has been a long-neglected independent discipline and has its roots in seminal geomorphologic investigations (e.g. Du Toit, 1933; King, 1963; Partridge & Maud, 1987). However, in recent years the distribution of in situ stress, seismicity and neotectonic activity across the subcontinent has attracted increasing attention and intense research (e.g. McCarthy et al., 1993; Andreoli et al., 1996; Brandt, 1998; Stacey & Wesseloo, 1998; Partridge & Maud, 2000;

De Kock, 2000; Spönemann & Hagedorn, 2000; and references therein), especially as a result of major hydroelectric, nuclear engineering and mining projects. Such investigations have begun to identify a pattern of neotectonic history that was much more extensive than was ever imagined possible within a "stable" cratonic environment. Furthermore, a multidisciplinary set of data has emerged that enables the development of better constrained geodynamic models for the geologic evolution of the African subcontinent over its recent past, thereby providing a framework for long-term seismic risk assessment in southern Africa.

The break-up of Gondwana since the Early-Jurassic (~205 Ma) is generally accepted as the last major tectonic episode to have affected southern Africa. As a result of the continuation of the Gondwana fragmentation process during the Cretaceous and Cenozoic up to the present, the beginning of the neotectonic period in South Africa has never been formally established. In the past, the term neotectonics has been used to imply a generic Cenozoic (especially Quaternary) crustal deformation (*cf.* Hartnady, 1985; Andreoli *et al.*, 1990; Ransome & De Wit, 1992; Ransome *et al.*, 1993) and Andreoli *et al.* (1996) have proposed neotectonic activity in South Africa to have been initiated in the Miocene (~25 Ma). Nowadays, the beginning of neotectonic activity in southern Africa is envisaged to have started with the beginning of the Oligocene at ~35 Ma which coincides with the African continent having become stationary over the so-called African Superplume (*cf.* Burke, 1996). The behaviour of the African Plate has changed during the Oligocene at ~35-30 Ma and many, if not all, of the phenomena that have characterised Africa over the past ~35-30 Ma have been induced by the cessation of plate motion (i.e. a reduction to below a velocity of ~10 mm/year). Significant erosional and depositional changes on the African Plate over the past ~35-30 Ma have been dominated by responses to changes in topography that were induced by the action of a single or numerous underlying plume(s) (Burke, 1996).

In recent years, intense research regarding neotectonic activity in southern Africa has revealed that there is a striking match between the tectonic fabric of the south-east Atlantic and south-west Indian Ocean on the one hand and the tectonic fabric of the African subcontinent on the other (*e.g.* Andreoli *et al.*, 1989, 1990, 1993, 1994, 1995, 1996). It is evident that a number of major oceanic transform faults or fracture zones, *e.g.* the Cape/False Bay, Falkland-Agulhas, Trans-Indian/Ceres-Prince Edward and Mozambique-Madagascar fracture zones, continue into the on-shelf and on-shore joints/faults of the South African continent (**Figure 3**).

In addition, neotectonic activity in southern Africa has been analysed in terms of known stress fields and it is clear today that the African plate south of the equator appears to be divided in two zones of compressive stress orientation. The one is the zone of predominant NNE-directed trends that corresponds to the East African Rift system. The second zone is southern and south-western Africa, including the south-west Indian Ocean, and is characterised by NW-WNW trends (Zoback *et al.*, 1989, Zoback, 1992; Andreoli *et al.*, 1996) **(Figure 4).**

In South Africa, the boundary between these two zones coincides with the apparent southern termination of the Rift System in southern Mozambique, near Richards Bay, and in the Northern Transvaal. Most of South Africa, Namibia and the ocean floor between the Bredasdorp Basin and the Southwest Indian Ridge is dominated by this pervasive, NW-WNW-trending, horizontal compressive stress field of deep-seated, until recently undetermined origin for which the term Wegener Stress Anomaly (WSA) was proposed (Andreoli *et al.*, 1996) (**Figures 3 & 4**). The WSA appears to have already existed in the Jurassic, before the break-up of Gondwana, which is indicated by the orientation of major Jurassic dyke swarms in South America, South Africa and Botswana. It has persisted during the south Atlantic break-up phase in the Cretaceous (indicated by WNW-trending Cretaceous kimberlite dykes in Lesotho) until today. Offshore fault zones that were caused by the WSA include the WNW-trending so-called Ceres-Prince Edward and Trans Indian Fractures Zones in the south-west Indian Ocean. Short periods of waning during the Late Cretaceous caused the stress field to be dominated by NE-directed ridge push, which led to strike-slip along the Falkland-Agulhas Fracture Zone and the formation of the Cape-Tzaneen Fracture Zone, the on-shore continuation within the South African continent of the False Bay Fracture Zone (Andreoli *et al.*, 1996) (**Figures 3 & 4**).

Pavoni's (1997) proposed model of bicellular, whole-mantle convection and associated global geotectonic and geophysical bipolarity explains both the orientation and the deep-seated, until now undetermined, origin of the WSA. According to this model, two torus-like convection cells, the Pacific cell and the African cell, with ascending flow in the mantle underneath the central Pacific and African plates respectively, and converging and descending flow beneath Indonesia and Central America, are responsible for the formation of two large-scale zones of both the lithospheric divergence (marked by growth of the Pacific and African plates from two spreading centres) and convergence (marked by the belt of young folded mountains) since the mid-Jurassic.

The effects of large-scale mantle convection beneath the African plate is currently believed to be responsible for the tectono-magmatic and geomorphological development of southern Africa since the beginning of the break-up and dispersal process of the Gondwana supercontinent at ~205 Ma.

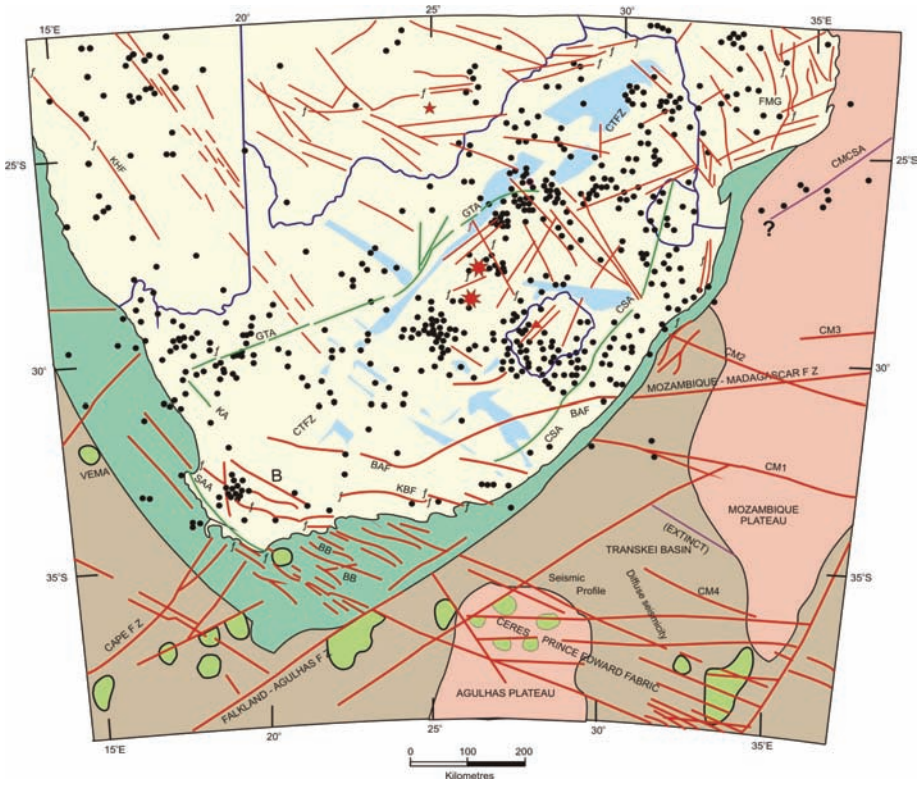

Figure 3: Seismic epicentres in relation to the post-Karoo tectonic framework of South Africa and nearby regions (according to Andreoli *et al.*, 1996; and references therein).

Note: yellow & dark green = continental crust; red = continental crust invaded by oceanic basalt; brown = oceanic basalt crust; light green = offshore volcanic domains; blue = lineament belts; ET = eastern Transvaal; GA = Gauteng; KN = KwaZulu-Natal; NT = northern Transvaal; KFB = Koega-Bavianskloof Fault; FMG = Funhalouro-Mazenga Graben; KHF = Kuiseb-Hebron Fault; CTFZ = Cape-Tzaneen Fracture Zone; BB = Bredasdorp Basin; lines with opposing daggers = uplift axes; SAA = Saldanha-Agulhas Axis; KA = Kamiesberge Axis; GTA = Griqualand-Transvaal Axis; CSA = Ciskei-Swaziland Axis; BAF = Beattie Anomaly Fracture; CMCSA = Central Mozambique Channel Seismic Axis; barbed line = spreading/extinct axis; f--f = neotectonic faults active since the Miocene; dashed lines = lineaments/possible neotectonic faults; lines with single dagger = Cenozoic geomorphological gradients with daggers on downslope; open stars = localities affected by catastrophic Pleistocene (?) earthquakes; open triangle = proposed neovolcanic centre of Lesotho.

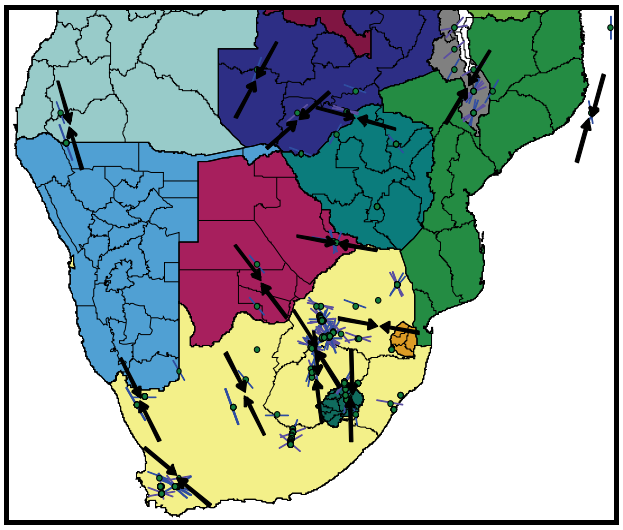

Figure 4: Neotectonic stress orientation map for southern Africa (Stacey & Wesseloo, 1998).

It continues up to the present and is responsible for neoseismicity and neotectonic activity, which controls the neomorphological development of the southern African landscape. The current *in situ* stress field that is present in southern Africa is the result of a complex interplay between mantle convection and lithospheric basal drag, thermally induced continental uplift and ridge-push forces.

In Namaqualand In, a strong correlation exists between known water borehole positions and the proximity and alignment of these boreholes to two prominent fault/fracture zone systems. In addition to the well-known coastal-subparallel, NNW-SSE striking system of brittle fault/fracture zones, that is related to the Gondwana continental break-up phase and historically proven to be associated with productive boreholes, a set of NNE-SSW striking fault/fracture zones represents continental continuations of oceanic transform faults. The latter also developed during the Gondwana fragmentation/dispersal phase and formed penecontemporaneously with the NNW-SSE striking fault/fracture zones. They are oriented subparallel to the direction of present-day neotectonic crustal extension and currently undergo neotectonic reactivation/ seismicity. Both fracture systems in general and specifically at, or in close proximity to, their intersection areas represent the highest dilational zones within the Namaqualand coastal rift system and are therefore the most prospective sites for well-field development (Friese *et al*., 2004)

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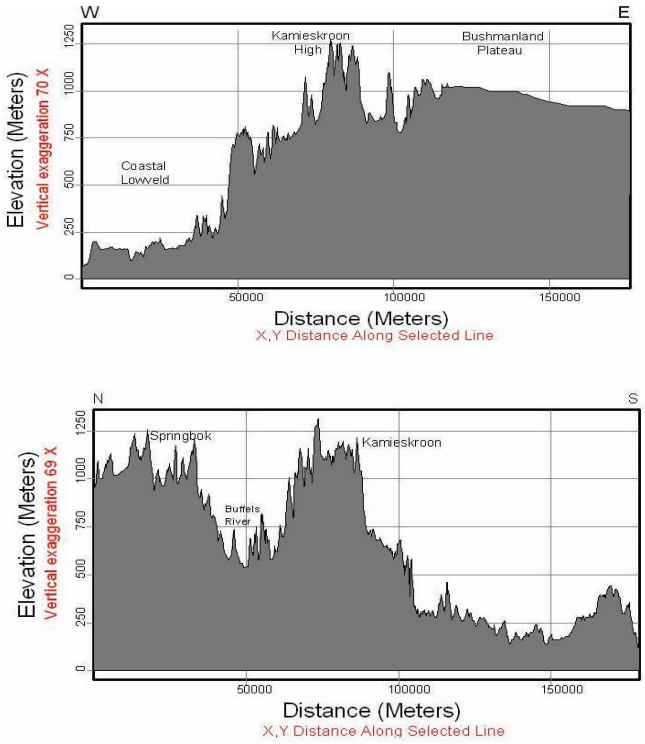

Figure 5: N-S and W-E cross-sections of the study area

Geomorphic development and climate change

Introduction

The macro-scale geomorphological evolution of southern Africa is the result of an Archaean geological history that includes changing climatic conditions, massive fluvial erosion that was associated with the evolution of major drainage networks and the formation of elevated interior plateaus during the late Mesozoic (*i.e.* the Cretaceous period) and Cenozoic eras (Partridge & Maud, 2000).

Three physiographic regions (Visser, 1989), viz. the western Coastal Lowveld (or western plateau slopes), the Great Escarpment zone (or Namaqua Highlands) and the extensive Highveld (or Bushmanland Plateau), can be distinguished in the Northern Cape region (**Figure 5**). The Great Escarpment of southern Africa is a prominent geomorphic feature that appears along the edge of the southern part of the African continent (Moon & Dardis, 1988).

Prominent geomorphological features

Bornhardts (Twidale, 1976, 1982, 1988; Ollier, 1984; Rice, 1988; Bridges, 1990) are the most prominent geomorphologic features of the escarpment zone. Bornhardts are inselbergs or 'island mountains' that have rounded dome-shaped forms that are usually prominent in the granitic and gneissic rocks of Namaqualand. The shapes of the bornhardts are determined by the orthogonal fracture systems and by the upward-arching sheeting planes. The orthogonal fracture systems developed during either emplacement or subsequent tectonic events that affected the crystalline rocks. Bornhardts can be massifs or juxtaposed groups of domes that are arranged in an orderly pattern due to the structural control on its development, such as the Kamiesberg mountain range. The bornhardts are separated by valleys and narrow plains that were formed by pronounced weathering and erosion of the fracture zones. Deep subsurface weathering is essential for the development of bornhardts.

Several hypotheses have been proposed to explain the development of bornhardts (Twidale, 1976, 1982, 1988; Ollier, 1984; Rice, 1988; Bridges, 1990). The most likely hypothesis for the development of bornhardts in Namaqualand is the variations in the spacing of fractures (*i.e.* fracture density) from hills to plains.

Fractures are preferred pathways for the infiltration of water and more densely fractured materials are more prone to weathering processes than massive, dense material.

The more transmissive and especially larger fault zones have been weathered and eroded more intensely to form the valleys that separate the massive domes. Within the weathered sections, core stones of fresh granite are present in a matrix of weathered rock that was derived from *in situ* weathering of the host rock. The variation in fracture density is probably due to recurring stresses that resulted in rhomboidal shaped fracture patterns and the propagation of secondary fractures. Such recurrent stresses resulted in bornhardts as massive, compressionally stressed core zones (such as the compressive core zones of anticlines) in a matrix of highly weathered fractured rock. On a regional scale, the massive and stressed core zones (*i.e.* massive domes) can be regarded to be enormous core-stones within and surrounded by a matrix of weathered rock that is expressed as the fault-controlled valleys and narrow plains.

The hypothesis that bornhardts are composed of massive, compressional core zones accounts for both:

- The observed paucity of open fractures in bornhardt masses; and
- The association of bornhardts and sheet structures. The development of sheet structures can be attributed to both erosional off-loading and compressional stresses.

The landscape of crystalline terrains can be attributed to two stages of development (Twidale, 1982), viz:

1. Differential subsurface weathering (*i.e.* moisture-controlled weathering) that exploited varying rock composition and texture as well as variations in the fracture density. Differential subsurface weathering results in a highly irregular weathering front (or lower limit of significant weathering). Moisture is responsible for both the chemical alteration (which occurs when there are reactions between water and rock) and physical disintegration of the crystalline rocks. Humid to sub-humid palaeo-climates are responsible for ancient differential subsurface weathering.
2. Subsequent erosion and exposure of the more resistant rocks (*i.e.* the bornhardts). The massive bornhardts are therefore protrusions of the dynamic weathering front (which is the exposed parts of the lower limit of significant weathering) upward into the regolith or overlying weathered material. Fluvial

erosion is primarily responsible for erosion and the exposure of the bornhardts.

African erosion surfaces

Most of southern Africa is characterised by a mature landscape that has various erosion surfaces that are separated by prominent geomorphic scarps. These erosion surfaces resulted from successive phases of erosion that were initiated by continental uplift at various times since the fragmentation of Gondwana.

Numerous erosion surfaces have been recognized on the African landscape. The oldest and most widespread is the Gondwana surface (Jurassic) and African surface (mid-Cretaceous) that are followed by the Post-African surface that is inland of the Great Escarpment. Seaward of the Great Escarpment, two surfaces of Post-African age have been recognized. They are referred to as Post-African I (Miocene), that is usually present as dissected tablelands and a younger Post-African II (Late Tertiary) surface that is expressed as recent incisions of coastal gorges.

Partridge and Maud (1987, 1998, 2000) have re-interpreted the macro-scale denudation history of the subcontinent and provided a complete literature summary on this topic.

The mid to late Cretaceous African erosion surface

Rifting, which separates Africa from South America and is associated with pre-existing Pan-African orogenic welts, occurred between 129 Ma and 121 Ma in the west (Partridge & Maud, 2000). Uplift along the rift shoulders resulted in a major marginal escarpment (the current Great Escarpment) that was driven inland by erosion during the early Cretaceous.

The Cretaceous period was characterised by warm, humid tropical climatic conditions (Tyson & Partridge, 2000) that resulted in accelerated weathering and fluvial erosion due to dense well-integrated drainage networks (Partridge & Maud, 2000). Vast erosional surfaces of late Cretaceous age were formed above and below the Great Escarpment (Partridge & Maud, 2000) and correctly termed much earlier as the African surface by King and King (1959). The warm and humid tropical climate of the Cretaceous period also resulted in the development of deep, koalinitised weathering mantles especially on susceptible lithologies (such as crystalline rocks that contain thermodynamically unstable alumino-silicate minerals). Towards the end of the Mesozoic (*i.e.* upper/late Cretaceous), the African surface was characterized by kaolinitised profiles to depths of 50 m or more beneath silicrete duricrusts (Partridge & Maud, 1987, 2000; Tyson & Partridge, 2000; Moon & Dardis, 1988).

Late Cretaceous and early Palaeocene pedocrete cappings (*i.e.* duricrusts) protected the African surface and its deeply kaolinitised saprolite from erosion processes in many localities (Partridge & Maud, 2000). The pedocrete cappings, which predominantly comprised silicrete and calcrete in the western and central parts of the southern African subcontinent, formed in response to the onset of drier climates towards the end of the Cretaceous period (Partridge & Maud, 2000; Tyson & Partridge, 2000). The Cretaceous-Tertiary boundary (K-T boundary) is characterised by significant cooling and aridification in southern Africa which is linked to major changes in atmospheric chemistry (Tyson & Partridge, 2000).

The African erosional phase was of long duration (>100 million years) and erosion proceeded to different base levels between the interior plateau and seaward of the Great Escarpment. According to Partridge (1988), peneplanation within the African cycle was complete before the end of the Cretaceous, while massive duricrust formation ended by the early Palaeocene. Huge thicknesses of material were removed during this period.

The African landscape was not subjected to significant regional tectonism during the Palaeogene (Partridge & Maud, 2000). In addition, arid conditions persisted into the early Eocene in the western parts of the African subcontinent, while more humid conditions prevailed in the east (Tyson & Partridge, 2000). Both factors contributed to slow landscape development during the Palaeogene (Partridge & Maud, 2000).

The Miocene Post-African I erosion surface

Moderate, but asymmetrical, early Miocene crustal uplift along several axes caused the westward tilting of the subcontinent and resulted in a slight steepening of the courses of westward flowing rivers (Partridge & Maud, 1987, 2000; King & King, 1959). The early Miocene crustal uplift and subsequent erosion resulted in the mid-Miocene Post-African I erosion surface (Partridge & Maud, 1987) which is dated at ages ranging from 12 Ma to 19 Ma (Pickford *et al.*, 1996). Early Miocene uplift is associated with limited incision of drainage channels of 100-200m below the African surface (Partridge & Maud, 2000; Pickford *et al.*, 1996). The Post-African I landscape development phase involved the removal of the deeply weathered mantles that underlay the African surface (Partridge & Maud, 2000). In areas (*i.e.* western

parts of southern Africa) that were subjected to minimal Miocene uplift, scattered residuals or reduced thicknesses of the weathered mantles remained. The Post-African I surface dominates the southern African landscape (Partridge & Maud, 2000).

The late Oligocene and early Miocene epochs are characterised by a period of global oceanic warming that had a regional influence on atmospheric circulation patterns (Tyson & Partridge, 2000). As a result thereof, rain-producing weather systems penetrated the arid western (*i.e.* Bushmanland and Gordonia) parts of southern Africa and resulted in a sub-tropical wet climate and a well-integrated drainage system (Tyson & Partridge, 2000). The wet interval of the early Miocene was brought to an end with the onset of cold upwelling in the Benguela current system on the west coast. The global effects of cooling and drying, especially during the mid-Miocene, have greatly impacted on the southern African environments with the onset of true coastal desert conditions (at approximately 15 Ma) along the west coast of southern Africa (Partridge & Maud, 2000; Tyson & Partridge, 2000).

The advent of warmer and more humid conditions during the early Pliocene resulted in a rejuvenation of major drainage systems in the semi-arid western interior. Massive and significantly asymmetrical late Pliocene uplift interrupted the Post-African I erosion phase and accentuated the westward tilting of the subcontinent. The results of the late Pliocene uplift in the western parts of southern Africa include; (a) further increases in the gradients of westward-flowing rivers with renewed incision within river valleys and (b) renewed movement along the Griqualand-Transvaal axis (Tyson & Partridge, 2000). The large-scale regional uplifts, within the south-eastern and eastern hinterland of the subcontinent, induced major influences on the regional climatic conditions. The east-west precipitation gradient is thus a result of the existence of contrasting current regimes along the east and west coasts as well as the enhanced regional uplift in the eastern parts of the African subcontinent. According to Partridge & Maud (2000), late Pliocene uplift resulted in a steepening of the east-west climatic gradient with the establishment or re-establishment of desert conditions in the western part of the African subcontinent. Furthermore, the initiation of the various phases of uplift coincided with the onset of an interval of global cooling at approximately 2.8 Ma (Tyson & Partridge, 2000). This resulted in the aridification of large tracts of sub-Saharan Africa and the development of extensive, but discontinuous, dune systems (such as the mega Kalahari) that extends into the Northern Cape Province of South Africa.

Namaqualand Weathering profile

Aggressive weathering processes and differential leaching has, through the downward movement of infiltrating waters, resulted in deep regolith profiles (**Figure 6**) (Taylor & Howard, 2000; Chilton & Foster, 1995; Gustafson & Krásný, 1994; Acworth, 1987). The regolith is a result of the infiltrating and acidic rainfall reacting with the host minerals that caused subsequent leaching of the more soluble and mobile elements (or compounds) and contemporary as well as subsequent re-precipitation of the less mobile elements or compounds (*i.e.* the formation of Al/Fe oxides and kaolinite as examples). The saprolite is characterised by massive accumulations of secondary clay minerals (especially kaolinite) that contain both primary minerals as well as intermediate weathering products.Figure 6: Typical weathered profile of Precambrian basement rocks (after Chilton & Foster, 1995; Taylor & Howard, 2000).
Chemistry, mineralogy, petrology, structure, the age of the land surfaces and, particularly, long-term climatic conditions influence the weathering process and therefore the development of the weathered overburden (Rebouças, 1993; Gustafson & Krásný, 1994).

Basement aquifers in arid regions are characterised by relatively thin regolith that is generally present above deeper groundwater levels (Chilton and Foster, 1995). The deeper groundwater levels and thin saturated regolith thickness in arid regions necessitates the drilling of deep boreholes to intercept structural features and contact zones at depth within the unweathered bedrock.

McFarlane (1987) proposes a general weathered profile for crystalline basement rocks in southern Africa. Detailed studies have been conducted on the textural and mineralogical content as well as on the hydrologic properties (the permeability and porosity) of the various zones within the weathered profile. These studies have concluded that the regolith is the main aquifer system and can attain a thickness of more than 80 m. Furthermore, local groundwater flow systems dominate and the water level seldom exceeds the depth of 15 m below the surface.

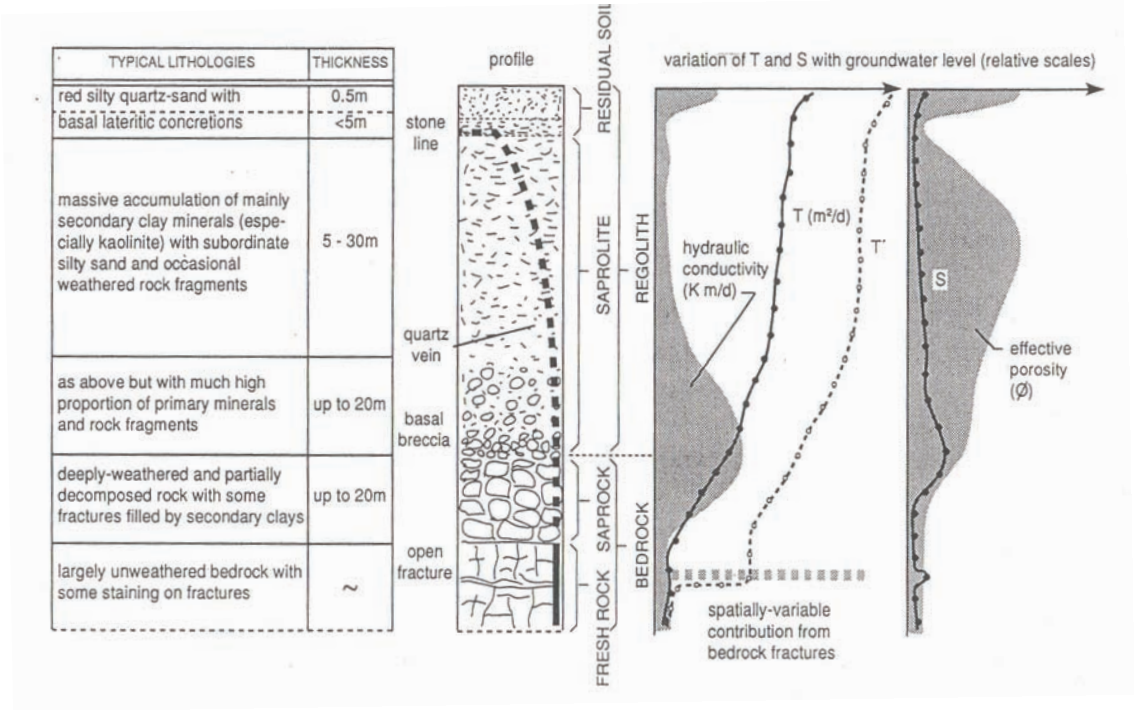

Figure 6: Typical weathered profile of Precambrian basement rocks (after Chilton & Foster, 1995; Taylor & Howard, 2000).

The aquifer systems that has been identified in Namaqualand includes both the lowermost parts of the weathered overburden (*i.e.* regolith) but also specifically the relatively weathered (*i.e.* saprock) and underlying fractured bedrock (*i.e.* fresh rock). The fracture systems have some degree of staining. Massive, but localised exploitable accumulations of secondary clay minerals (especially kaolinite) interspersed with both primary minerals as well as intermediate weathering products, are preserved in certain localities. Such localities do not coincide with the NNW-trending open valleys that are usually targeted for groundwater development.

An initial attempt to characterise the weathering profiles, which was based on limited borehole data obtained from the Komaggas reserve, was made for the crystalline aquifers in Namaqualand. Information was also gained from a number of related studies in Namaqualand. Detailed studies of the textural and mineralogical content as well as of the hydrologic properties of the weathered overburden in Namaqualand are required. The data represented below is based on information that was obtained from borehole logs and other studies:

- The depth of weathering (to different scales) in the Komaggas Rural Reserve is present to depths of 54-60 m below the surface for both the metasediments of the Khurisberg Subgroup and the granitic/gneissic rocks. In a few cases, the depth of weathering, especially for the metasediments of the Khurisberg Subgroup, extends to depths of 70-80 m below the surface or even deeper.
- Intense weathering of *in situ* material can occur to depths of 40-49 m below the surface for both metasediments of the Khurisberg Subgroup and for the granitic/gneissic rocks. In a few localities, which are associated with the metasediments of the Khurisberg Subgroup, intensely weathered, *in situ* material can occur up to depths greater than 80 m below the surface.
- Combinations of the differential weathering of rock types (*i.e.* contained primary minerals) together with localised weathering of fracture systems (*i.e.* joint systems, fault zones and fracturing associated with vein quartz) occur frequently. Furthermore, fractures (especially joints) that have an iron-oxide coating on the fracture walls also occur frequently in both the schist and the quartzite.

Conclusions

The nature and hydrogeological characteristics of the weathered crystalline rock derive from and are related to long-term, tectonically controlled geomorphic processes (Taylor & Howard, 2000). The present climatic conditions continue to drive, albeit at a much slower rate, the geomorphic processes in particular deep weathering and stripping that act on deeply weathered

basement rocks. In contrast, the character of the contained groundwater resources and its potential for the development are controlled by present climatic conditions.

The adopted model illustrates the dominance of fissure flow for the fractured, crystalline rocks of Namaqualand. Infiltration of water occurs along vertical to sub-vertical fractures with lateral flow along horizontal to sub-horizontal fracture systems. The water chemistry varies considerably among closely spaced fracture systems. The model displays a dominant vertical flow system (*i.e.* an infiltration phase) that is driven by local relief and an intermediate flow system that is driven by gradients along the valley systems.

Laterally extensive, linear and structurally controlled valley systems, which are especially associated with NNW-trending fault systems, are the usual targets for groundwater development within the Escarpment zone. The formation of the valleys is associated with the tectonic history and geomorphic development (*i.e.* bornhardt development) of the region. Wide, open valleys may result from the intersection of various sets of fracture systems. The saprock and top part of the underlying fractured rock (*i.e.* the bedrock) constitute the main aquifer system (**Figure 7**). The saprolite to saprock transition zone, with associated higher yielding boreholes, may be preserved in isolated locations.

Alternate periods of differing duration, of warmer humid atmospheric/climatic conditions followed by cooler and drier conditions resulted in repetitive cycles of accelerated weathering and erosional processes that were followed by periods of aridification. A course, but sequential, succession of tectonic and geomorphic events that resulted in the weathered aquifer systems of Namaqualand can be summarised as follow:

- Accelerated weathering and erosional processes, during the warm and humid tropical climate conditions of the Cretaceous period, resulted in the development of deep, kaolinitised weathering mantles to depths of 50 m or more especially on crystalline rocks that contain thermodynamically unstable minerals.
- Late Cretaceous and early Palaeocene pedocrete cappings (*i.e.* duricrusts) formed and protected the African surface, which has deeply kaolinitised saprolite, from erosion processes in many localities.
- Early Miocene crustal uplift and subsequent erosion involved the removal of the deeply weathered mantles that underlay the African surface. In some areas (i.e. western parts of southern Africa) that were subjected to minimal Miocene uplift, scattered residuals or reduced thicknesses of the weathered mantles remained.

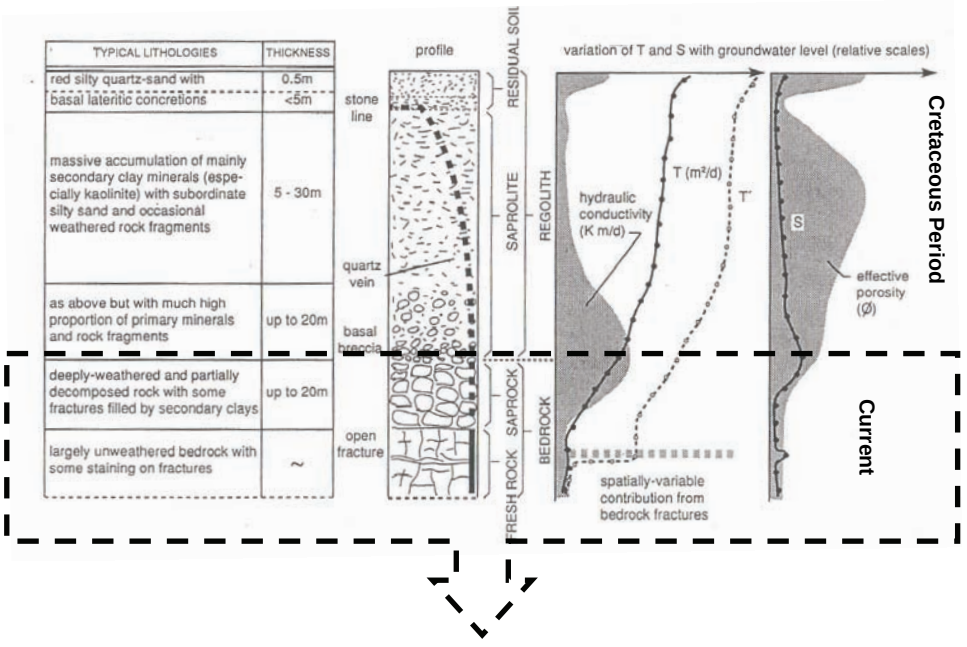

Figure 7: The bedrock (i.e. saprock to fractured rock) basement aquifer system of Namaqualand

- The aquifer systems were subjected to more recent alternating episodes of repetitive cycles of much shorter duration, and of probably less severe weathering and erosional processes, which were followed by periods of aridification

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Groundwater exploration and development

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Abstract

In southern Africa, some of the greatest groundwater needs occur in regions underlain by fractured basement aquifers with complex structurally controlled hydrogeology. The exploitation potential of these aquifers has been thought to be low due to historically low drilling success rates or to the high frequency of low-yielding boreholes. Using data from a case study in the Bushveld region of South Africa, it will be shown that low success rates can be attributed to inappropriate exploration or interpretation methods and an incomplete understanding of the tectonic and geological setting. A geological-based methodology to improve exploration success is described, demonstrating how significant savings in groundwater development costs, especially drilling costs, can be realised if success rates are improved.

Introduction

Basement aquifers are predominantly structurally controlled. The current paradigm of groundwater exploration in southern Africa is based on a geophysical approach, whereby most boreholes are sited by 'anomaly hunting' using magnetic, resistivity 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. This methodology has been and is currently used for the vast majority of rural water supply and private boreholes drilled in South Africa.

This approach can be considered to be water divining with the use of a variety of geophysical instrumentation. In many cases, due to the lack of geological and/or geophysical interpretation expertise of the operator, use of the instrument to detect anomalies on which to drill can be considered equivalent to the sticks, wires, bottles, clothes-hangers and pendulums of the diviner. Drilling on such anomalies is no guarantee of success. Many such anomalies have poor yields due to the presence of clay or secondary mineral infillings, or because they are lithological in nature. No geophysical technique can distinguish between such zones and transmissive ones therefore it is not surprising that in many areas of complex hydrogeology this approach has proved to be unsuccessful. Sami *et al*. (2002) demonstrated in 3 basement aquifer regions that the geophysical approach, used in isolation, only marginally improved success rates over random drilling and did not increase median yields. Failure should not be attributed to the geophysical methodology, but to the incompetence of the hydrogeologist who employs such an approach (if he is a hydrogeologist at all) for failing to realize the ambiguities.

Another approach has been 'remote sensing of anomalies', which is usually termed lineament mapping. This 'pseudo-geological' approach identifies 'target' features from lineaments (visual anomalies), using LANDSAT imagery or aerial photographs. Such lineaments are of variable or questionable hydrogeological significance, representing an amalgam of lithological contacts: dykes; ductile and brittle deformation zones; fences; non-geological features; figments of imagination; etc. Without a sound geological understanding of the region, it is usually not possible to distinguish between these features and therefore this approach should be treated with caution. This approach is an evolution of the 'anomaly hunting' principle under a high-tech disguise. The application of filters and digital enhancement techniques lends even more credo by 'high-lighting' the lineaments, implying that they are more hydrogeologically significant. This method is even more appealing to the non-geologist than geophysics. It generates pretty computer images to fool the unwary, utilises expensive software, does not require interpretation or understanding of geophysical curves, does not require you to get sweaty and dirty and it is non-discriminatory. The legions of chairborne commandos graduating without field geological experience or expertise can get involved from the comfort of their computers.

Although 'anomaly hunting' approaches continue to have a certain appeal to our primeval man's hunter instinct,

field hydrogeologists (usually reformed geologists) should remain sceptical of this approach. Success is still dependent on identifying 'the big five' (faults, shears, dykes, contacts, fracture zones) visually in the field. Exploration in fractured rock environments should be directed towards finding open fracture zones where permeability is enhanced, rather than blindly following the 'biggest anomaly is best' principle.

Fracture zones are primarily structurally controlled. Consequently an understanding of regional tectonics and its structural expression is essential to their characterisation. According to Coulomb's law of failure, tensional, compressional and shear stresses each leave a unique type of fracture pattern to be interpreted by the competent hydrogeologist with the use of geodynamic analysis. 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. Tensile fractures are commonly associated with dip-slip settings and normal faulting, which are characterised by conjugate joint sets and mode 1 tension joints.

Faults can be divided into normal or dip-slip (extensional), thrust-slip (compressional) and strike-slip categories depending on rock movement, which is dependent on prevailing stress conditions. Faults can be categorised by either field observations of rock movement and slickenline orientation or, alternatively, by their dip angle. Due to the stress conditions under which rocks break, strike-slip faults are predominantly vertical. Normal faults dip at ~60^0 and thrust slips at approximately 30^0. The dynamic analysis of faults and resulting conjugate fracture sets allows the stress conditions under which they formed to be predicted. Therefore the orientation of stresses can be predicted from the orientation of fractures and slip directions. By determining the age relationship of faults, variations in stress conditions over time can also be determined. For hydrogeological investigations, present-day stress conditions and their impact on existing structures are the most relevant.

Successful exploration consequently requires the development of a hydro-tectonic model that is based on observed fracture patterns and historic and current stress regimes from which tensional azimuths can be identified. If the orientation of fractures and slip directions are known, the orientation of principal stresses can be identified. Since stress forces can change several times over geological history, complex fracture patterns are often seen in terrains that have been subjected to several deformational episodes. This process can result in the reactivation of existing fracture systems under new stress conditions, which may change their compressive or tensile character. An understanding of the tectonic history of the region, and the accompanying stresses resulting in brittle deformation, can be considered to be the fundamental basis of deriving a hydro-tectonic model for assessing and classifying potential target features.

This paper describes a multidisciplinary approach by means of which promising hydrogeological target structures can be identified. These methods include:

1. geodynamic analysis on a regional scale to identify tectonic processes and their expression;
2. structural mapping of joints on an outcrop scale to identify compressional and extensional orientations through strain analysis;
3. the identification and categorisation of lineaments observed on LANDSAT that are based on identified stress orientations; and
4. geophysical exploration of identified potential water-bearing structures to pinpoint structures in the field.

Since data collection for exploration is costly and time consuming, a financial analysis of the proposed methodology is presented. It demonstrates that that exploration costs of the adopted approach are not higher than currently adopted methods. However, the ultimate establishment costs per successful water point and the costs of the water are dramatically reduced in comparison with conventional methods as a result of significantly higher yields. These results prove that it is cost effective to undertake groundwater exploration in a scientific manner, whether only successful points are required for hand pumps or high yields are required for motorised reticulated schemes.

From these results, a suggested method for exploration has been formulated to assist with the undertaking of regional exploration programmes (**see Figure 7**).

Investigation procedure

Geological literature review

The objective of a literature review is to obtain an understanding of the tectonic history of the region in order to understand the nature of observed structural features and to hypothesise as to the orientation of compressional and extensional forces. A hydrocensus of existing boreholes assists in identifying the relationship between high-yielding boreholes and structures of varying orientation and stress conditions when the location of boreholes is overlain on a structural map.

Geodynamic and strain analysis

Field and photogeological mapping may be required to identify faulting and fracturing as evidence of tectonic stresses. The geodynamic analysis of faulting is concerned with understanding how the tectonic and deformational history of the region is expressed in regional structures such as faults and the stress conditions under which rocks fracture. A strain ellipse is used to predict the extensional, compressional and shear stress origin of existing structures. The geodynamic analysis has the objective of identifying the orientation of structures and lineaments that are considered extensional in nature and are therefore preferred target features. Field structural mapping consists of mapping the strike and dip of observed faults and joint sets at an outcrop scale. These data sets are subsequently classified by setting and are interpreted with the use of stereonets to identify the principal orientation of extension.

LANDSAT image interpretation

LANDSAT TM imagery is used to map visible lineaments with the use of various enhancement techniques. Since the tectonic stresses on these lineaments is not known, they should not be used directly for borehole siting. Only once a structural interpretation has been undertaken can promising lineaments be identified.

Ground-based geophysics

Although the identification and selection of drilling sites should be based on structural geological criteria, geophysical exploration can form the basis of locating boreholes on these structures or of pinpointing identified structures in the field. Due regard should be given to factors such as access, topography, existing infrastructure, water rights, etc.

Study area

The study area is in the eastern limb of the Bushveld of South Africa. It occupies a 2-4 km wide N-S trending valley, arching around into an E-W trending valley as it follows the layering of the Bushveld. It covers the area from approximately 24°15´S to 24°37´S. The valley margins are bounded by steep terrain. Mean annual rainfall varies from 477 m in the north to 583 mm in the south.

The geology consists of the upper part of the Critical Zone and the lower part of the Main Zone of the Rustenburg Layered Suite of the Bushveld Complex and comprises alternating layers of pyroxenite, anorthosite and norite. The topographic highs that define the valley to the west and south and east and north respectively are underlain by rocks of the Main Zone Leolo Mountain gabbro-norites and the Wintersveld norite-anorthosite. The low-lying central valley is underlain by layered norite-anorthosite and pyroxenite of the Winaarshoek layer. Layering in the study area is generally NW-SE, dipping 20 degrees SW. Numerous dolerite dykes transect the area, generally trending NE.

The main aquifers in the region are structurally controlled and related to fault zones. The weathering susceptibility of the Bushveld Complex rocks generally increases with pyroxene content, which coincides with the valley floor areas. The valley floors are also covered with a thick deposit of clayey alluvium of between 20 and 30 m in thickness, which function as a source of storage.

Geodynamic analysis of faults

A structural interpretation of the region to delineate groundwater targets was undertaken by WSM. On the eastern limb, the emplacement of the Bushveld and post-emplacement isostatic adjustments caused E-W-oriented compression, followed by sagging and tensional conditions. Sagging structures commonly occur as normal faults, oriented in an arc that is parallel to the strike of the layering (N-S arching to E-W further north).

Differential sagging resulted in the development of strike-slip stresses and NNE wrenching, resulting in NNE wrench faults, such as the Wonderkop fault, which is located immediately west of the study area. NNE left-lateral wrenching would have introduced NNW-N oriented extensional stress (ENE-oriented extensional structures) and NE and ESE oriented shear structures (**Figure 1**). The NE trending Steelpoort fault to the south of the study area and several prominent ESE faults are such post-Bushveld age shear structures. Sagging structures of tensional origin and oriented NW parallel to layering would have come under compressional stress.

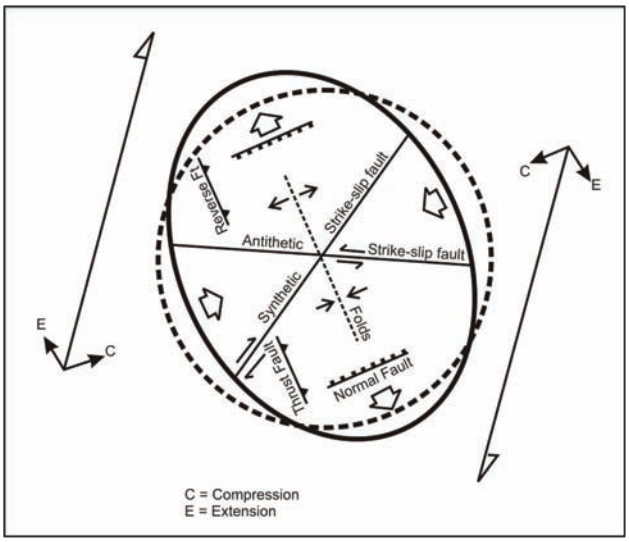

Figure 1: Theoretical fault pattern caused by strains related to wrench faulting

During post-Karoo times, stress due to downwarping on the Lebombo Moncline axis, following the rupture of Gondwanaland, would have resulted in E-W-oriented extension, with tension at its maximum on N-S structures. The existing NNE and NNW structures would have been re-activated under extensional stress.
Observed faults in the region (**Figure 2**) can be characterised as follows:

1. Primary N to NNW trend. This trend is sub-parallel to Bushveld layering and its origin can be attributed to sagging structures. This trend also cuts across Karoo strata, implying a post-Karoo re-activation by extension during Lebombo downwarping. This predominantly E-W extension has resulted in major rivers exploiting N-S structures, which is plainly evident on the topographic maps.

2. NNE and NE trend. These faults display left-lateral movement, which implies a shear stress origin that is related to NNE wrenching in post-Bushveld times. Faults also cut across Karoo strata and have therefore been re-activated during post-Karoo times. Post-Karoo re-activation of these faults can be attributed to the E-W extensional stress being taken up on pre-existing NNE structures. This trend was exploited by Karoo dykes, which intruded along the pre-existing vertical NNE and NE shear structures. However, the NNE and NE structures would not have been subject to maximum extension during post-Karoo times and are therefore less than ideal groundwater targets.

3. Secondary SE-SSE trend. These faults are non-linear and curve around the margins of the Nebo granites. They do not cut the Karoo and are therefore pre-Karoo in age. Their origin can therefore be attributed to sagging of the Bushveld and resulting normal faulting parallel to layering.

4. Secondary ESE trend. This orientation is consistent with shearing that resulted from NNE wrenching. It is also associated with the intrusion of diabase, which suggests a post-Bushveld vertical shear structure origin.

5. ENE trend. This orientation was subjected to extensional stresses due to NNE wrenching, which resulted in normal faulting, even along older ENE thrust faults such as the Zebediela fault. Evidence for the dip-slip setting is the presence of ENE oriented block faulting to the north and NW, into which Karoo sediments were deposited. Downthrows on these faults is 300 m to the south, which indicates that they are normal dip-slip faults that resulted from extension to the NNW-SSE during post-Bushveld times.

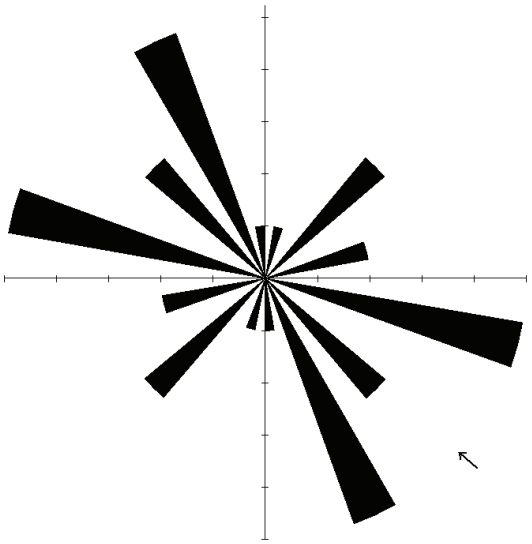

Figure 2: Rose diagram of observed faults

The fault pattern is consistent with post-Bushveld NNE wrenching (**Figure 2**), which would have resulted in the region being subjected to NNW trending extension and an associated ENE dip-slip setting. As a result, ENE-trending structures were subjected to extension and NE and ESE structures to shear. This fault pattern was subjected to post-Karoo extension, whereby the N-S sagging structures and NE and ESE shear structures would have been re-activated under extensional stress.

Dolerite dykes in the region exhibit NE, N to NNE and ESE trends and intruded along pre-existing sub-vertical fault zones. Several intrusive episodes have occurred that are related to post-Bushveld and post-Karoo tectonic stresses. The NNE direction is known as the Great Dyke direction. It represents an abyssal fracture zone along which mafic magmas were intruded into the crust, resulting in dyke swarms. This orientation is also the only prevalent orientation in Karoo age strata to the east, implying that N-NNE dykes are associated with E-W post-Karoo extensional stresses. The NE and ESE dykes intruded into vertical structures of shear origin.

Strain analysis of joint patterns

To ascertain whether predicted stress conditions from the geodynamic analysis could be verified, a total of 10 outcrops were mapped in the field and 93 joint orientation measurements were obtained. Several joint sets were observed (**Figure 3**), namely:

1. Sub-vertical N to NNE–SSW striking joints, dipping at 50-60^0 and at more than 80^0. These are interpreted as being dip-slip normal joints and associated mode 1 tension joints.
2. NNE-SSW steeply dipping joints. A vertical shear striking 200 with horizontal slickenlines was also noted, suggesting that this orientation has a strike-slip origin.
3. WNW-ESE steeply dipping joints. These are associated with the NNE joints and have a strike-slip origin.
4. SE striking shallow dipping joints. These are sub-parallel to layering and have a similar dip. Therefore they are attributable to the sagging of the Bushveld.
5. NNW-SSE striking moderately to steeply dipping joints. They are parallel to layering and probably have a dip-slip origin that is related to the sagging of the Bushveld.

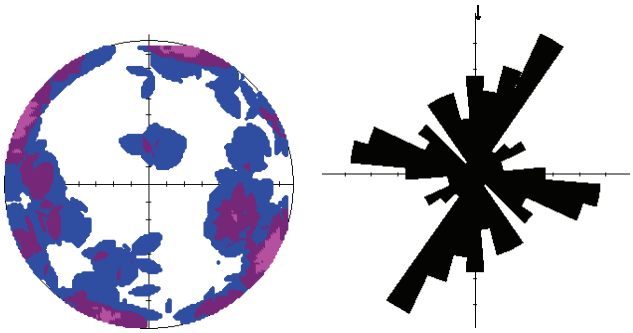

Figure 3: Equal area Stereonet and rose diagram of jointing

The pattern of faulting and jointing indicates both a dip-slip and strike-slip fault setting. To identify the different stress fields that are responsible for the observed fracture pattern, fractures were plotted into dip degree categories of 90-80, 80-50 and <50 degrees. The stresses responsible for the joint sets are shown in **Table 1**.

Fractures dipping 90-80^0

Several prominent joint sets are observed that are striking NNE, ESE, SSE and WNW (**Figure 3**). These joint sets are related to strike-slip faulting due to Post-Bushveld wrenching. Maximum extension would have been to the NNW, resulting in ENE-trending mode 1 tension joints (57/90 and 234/83 secondary poles).

Table 1: Orientation of stresses responsible for observed fracture sets

Dip	Setting	Orientation strike/dip	Compression	Neutral	Extension
80-90	Dip-slip	5/82	95/90	5/0	275/7
	Strike-slip	25/88 205/82 104/83 280/85	61/3	331/87	334/3
	Dip-slip	57/90 234/83	252/80	342/10	324/3
	Dip-slip	340/84	47/87	137/3	64/3
50-80	Dip-slip	3/63 192/55	98/77	8/13	284/22
	Dip-slip	337/59 160/62	67/86	337/4	66/6

A secondary pole can be observed that is trending N and dipping east. This can be attributed to mode 1 tension jointing due to E-W extension during post-Karoo times.

Another secondary pole trends NNW. This orientation is parallel to layering and could be related to tension that resulted from sagging. An associated joint set at a shallower dip suggests a dip-slip origin.

Orientation of stress fields

Maximum extension occurred to the W, NNW and ENE, implying that structures oriented to the N-S, ENE and NNW have a tensional origin. The NNW tensional orientation is of post-Bushveld origin and related to NNE wrench faulting. The ENE-oriented and W-oriented tension are related to post-Karoo lebombo downwarping and are therefore the most recent expression of structural stresses. N-S and NNW-SSE striking structures are therefore the most promising groundwater structures.

Post-Karoo dykes could have intruded in the NE orientation due to the existence of vertical shear structures. However, this orientation is not the most promising from a stress-orientation perspective.

Fractures dipping between 80-50^0

These fracture sets are considered to be related to dip-slip stresses. Prominent sets strike N-S and NNW-SSE. These sets are related to E-W extension that resulted from Lebombo downwarping.

The predominant orientation is to the NE in terms of frequency. This orientation is associated with Karoo-age dolerite (evident in the Karoo lithologies west of the Oliphants River), diabase dykes and strike-slip faults of post-Bushveld origin. However, these lineaments are relatively short and do not exceed 10 km in length. This orientation is not associated with extensional stress and therefore these lineaments do not represent favourable groundwater targets.

The longest lineaments are oriented NNW and N. However, very few lineaments with these orientations were observed. These orientations represent predicted tensional structures that are due to dip-slip related faulting and are the preferred groundwater targets. Major regional rivers, such as the Olifants River, Dwars River and Watervals River, can also be observed to have major N-S oriented segments.

Interpretation of lineaments

Figure 4 shows the orientation of LANDSAT lineaments in the region. These lineaments were identified independently by another geologist in order to avoid bias.

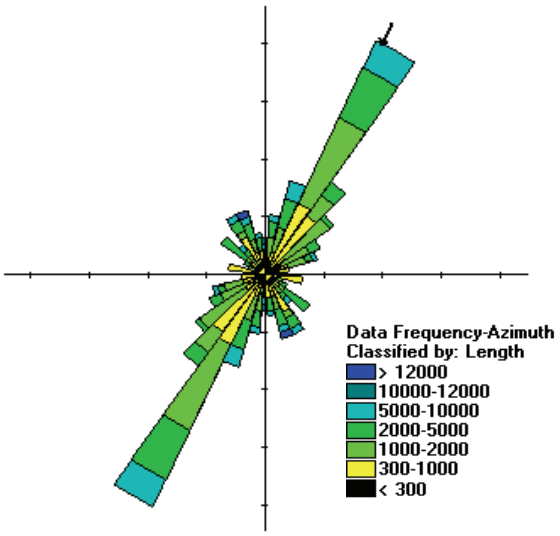

Figure 4: Frequency-length (m) Rose diagram of lineaments.

Drilling results

Results obtained from 3 exploration strategies are shown in **Figure 5:**

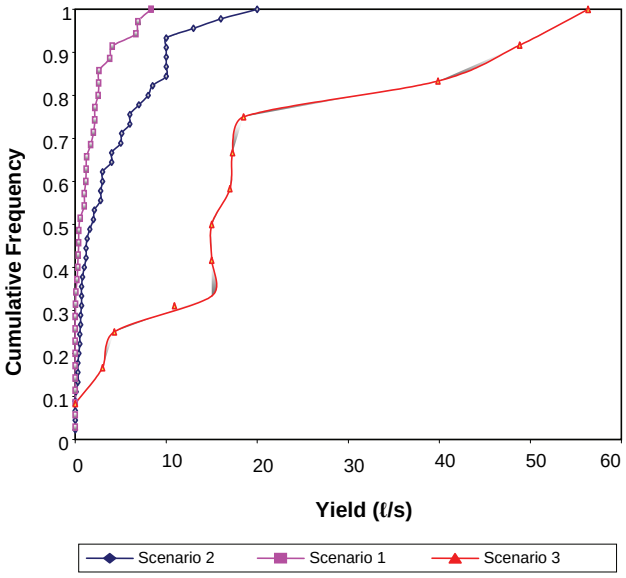

Figure 5: Drilling results

1. **No structured exploration or drilling randomly or by visual observation:**
   Scenario 1 represents historical results that are recorded in the National Groundwater Database on the farms on which the investigation was conducted. This scenario is based on historic drilling records, which are assumed to represent borehole siting without scientific exploration methods.

2. **Exploration based on a hydrocensus, EM-34 and magnetometer traverses undertaken over LANDSAT-identified lineaments, VES confirmation and a desk study of existing maps**
   This scenario is based on the historic success rates achieved by consultants who worked in the area. The depth of investigation shows that the methodology is more intensive than the current practice in the hydrogeological industry of anomaly hunting and only used the EM-34 and magnetometer investigations after a brief (if at all) desktop study.

3. **Full exploration based on the proposed methodology**
   This scenario is based on the use of a MAX-MIN system that was used to investigate LANDSAT lineaments that were considered to be tectonically significant by geodynamic and strain analysis.

The median yield achieved in scenario 1 was 0.5 ℓl/s. The success rate (defined as boreholes that yield > 0.1 ℓ/s) was 66%. Only 21% of boreholes would have been successful if motorized pumps were to be installed (yield > 2 ℓ/s).

Scenario 2 selected mapped structures as lineament targets. The primary targets selected were NE faults and dolerite dykes, which are the most prevalent target in the study area. These targets were subjected to magnetometer, electromagnetic (EM-34) and resistivity (VES) investigations to identify drilling sites. The median yield achieved was 2 ℓ/s and the success rate was 91%. A total of 50% of the boreholes could be equipped with motorised pumps.

Scenario 3 represents the boreholes drilled during this investigation. Drilling sites were almost exclusively N-S, NNE and NNW structures, predicted to be extensional in nature and identified in the field. One borehole was drilled on an E-W structure, which proved to be dry. The median yield achieved was 15 ℓ/s and the success rate was 92%. A total of 85% of the boreholes could be equipped with motorized pumps.

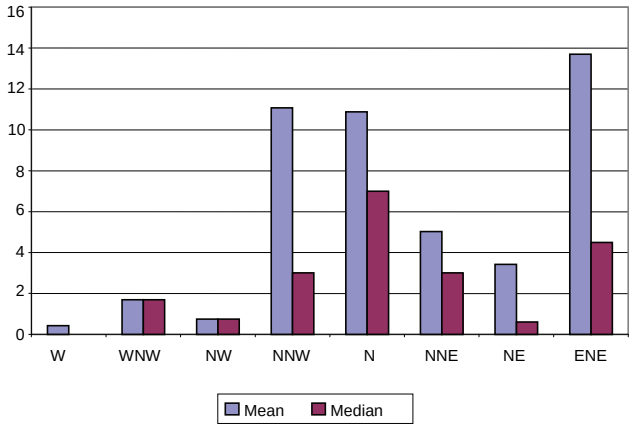

Figure 6: Borehole yield versus the orientation of drilled targets.

Figure 6 shows a target analysis that was undertaken by overlaying all the boreholes with adequate co-ordinate data on a structural geology map in order to identify the orientation of their targets. Only boreholes that lay on an identifiable structure were included. The results show that boreholes that lie on N-S structures have the highest median yield. High yields were also achieved from boreholes on ENE and NNW targets. These are the orientations that were predicted to be under maximum extension by the geodynamic and strain analyses. The NE and W orientations, predicted to be under shear, generally have poor yields, in spite of dolerite dykes being targeted.

Financial analysis

The financial analyses was used to evaluate the extent to which the proposed exploration strategy is financially viable in terms of reduction in overall borehole establishment costs (average cost for each successful borehole) and the cost of the yield obtained (average cost per litre per second borehole yield). The costs associated with exploration work include a desk study, LANDSAT and aerial photo interpretation, geophysical surveys, structural mapping and community liaison. The costs were based on standard South African rates in 2004 and the standard number of man-hours per activity envisaged during groundwater exploration investigations.

Table 2: Assumed costs to establish 10 boreholes based on achieved success rates and approximate quantities

ITEM		Units	Rate	Scenario 1		Scenario 2		Scenario 3	
				Qty	Cost	Qty	Cost	Qty	Cost
Desk Study[1]	E	Day	3 500			1	R 3 500	5	R 17 500
EM34 survey[3]	X	Day	3 500			3.7	R 12 950		
Max Min survey[4]	P	Day	4 000					3.6	R 14 400
Resistivity survey[5]	L	Day	3 000			5.5	R 16 500		
Geophysical interp.	O	Line	500			22	R 11 000	11	R 5 500
Subsistence	R	Day	300			10	R 3 000	6	R 1 800
Landsat image[6]	A	Each	3 000			1	R 3 000	1	R 3 000
Landsat interp.	T	Day	3 500			3	R 10 500	3	R 10 500
Structural mapping[7]	I	Day	3 500					3	R 10 500
Subtotal - Exploration	O				R 0		R 60,450		R 63 200
Community liaison[2]	N	Hr	250	16	R 4 000	11	R 2 750	11	R 2 750
Drilling[8]		Hole	15 000	16	R 240 000	11	R 165 000	11	R 165 000
Drill supervision		Day	2 000	20	R 40 000	11	R 22 000	11	R 22 000
TOTAL					R 284 000		R 250 200		R 252 950
Per successful site					R 17 750		R 22 745		R 22 995
Median yield		ℓ/s			0.5		2		15
R/ℓ/s		R/ℓ/s			R 568 000		R 125 100		R 16 863

Groundwater development costs to establish 10 successful boreholes, excluding testing and equipment, are shown in **Table 2**. Exploration that uses the proposed approach has a similar cost implication to conventional exploration. However, the geophysical component is reduced in favour of structural mapping and the development of a geodynamic model.

1. Review of topographical and geological maps and geological reports.
2. At 1h per drilling site.
3. At 1 technician and 1 labourer and 3 boreholes sited per day including magnetometer surveys.
4. At 2 technicians and 2 boreholes sited per day including magnetometer surveys.
5. At 2 technicians and 2 boreholes sited per day.
6. At 22% recovery per usage of R 10,000 per 180 x 180 km image and R 1,200 in man-hours for co-ordinate registration.
7. Field mapping of outcrops and aerial photo interpretation.
8. Casing costs are not considered as it is assumed that only successful boreholes would be cased, which would result in similar casing costs for all scenarios.
9. According to the success rate of 67% as determined from the drilling records in the NGDB.
10. According to the success rate of 91% as determined from the drilling records.
11. According to the success rate of 92% achieved during this investigation.

The results suggest that a geological approach to exploration that is oriented to the identification of targets on a regional scale could in the long-term result in significant cost savings, especially when the costs of regional geological exploration are spread over many boreholes. In such cases, dedicating a larger proportion of the budget to structural mapping may result in more efficient drilling and a net reduction in establishment costs, especially when motorised pump systems are planned. For such an exploration programme to be successful, it should incorporate field geological mapping; remote sensing and appropriate geophysical exploration; and the development of a hydro-tectonic model.

Groundwater exploration is significantly more cost effective when structural controls on groundwater occurrence are considered so that only potentially significant targets are considered for field investigation.

The proposed approach to groundwater exploration exhibits a significant economy of scale and unit costs per borehole decrease with the number of boreholes drilled. Consequently, such an approach is warranted only when the exploration costs can be distributed over several boreholes. Based on a financial analyses for the establishment of ten boreholes, the proposed methodology proved to be cost-effective, in terms of both successful boreholes established and the cost per ℓ/s of water delivered.

Recommendations for groundwater exploration in fractured terrain

Hydrocensus

The objective of a hydrocensus is to hydrogeologically characterise a region in terms of the physical and economic feasibility of meeting water demands through groundwater by quantifying the expected borehole yields and their variability by geological domain; historic drilling success rates and probabilities of exceeding specific yields; and the proximity of boreholes to geological structures and their yield. The identification of high-yielding boreholes may also assist in identifying targets that are potentially high yielding.

These investigations should attempt to determine the number of boreholes that would be required to meet water demands, the role of geological structures on yield, the depth to which boreholes should be drilled and the suitability of water quality for the desired usage.

Tectonics and geodynamics

Geodynamic investigations require that the tectonic history of the region be unravelled so that mapped, identified or presumed structures and lineaments can be explained in terms of historic and present-day geological strain. Depending on the age of the rocks and the structural complexity, this process could involve an extensive literature review of the crustal evolution of the region. Since these processes are of a large scale, investigations are often much broader than the study area.

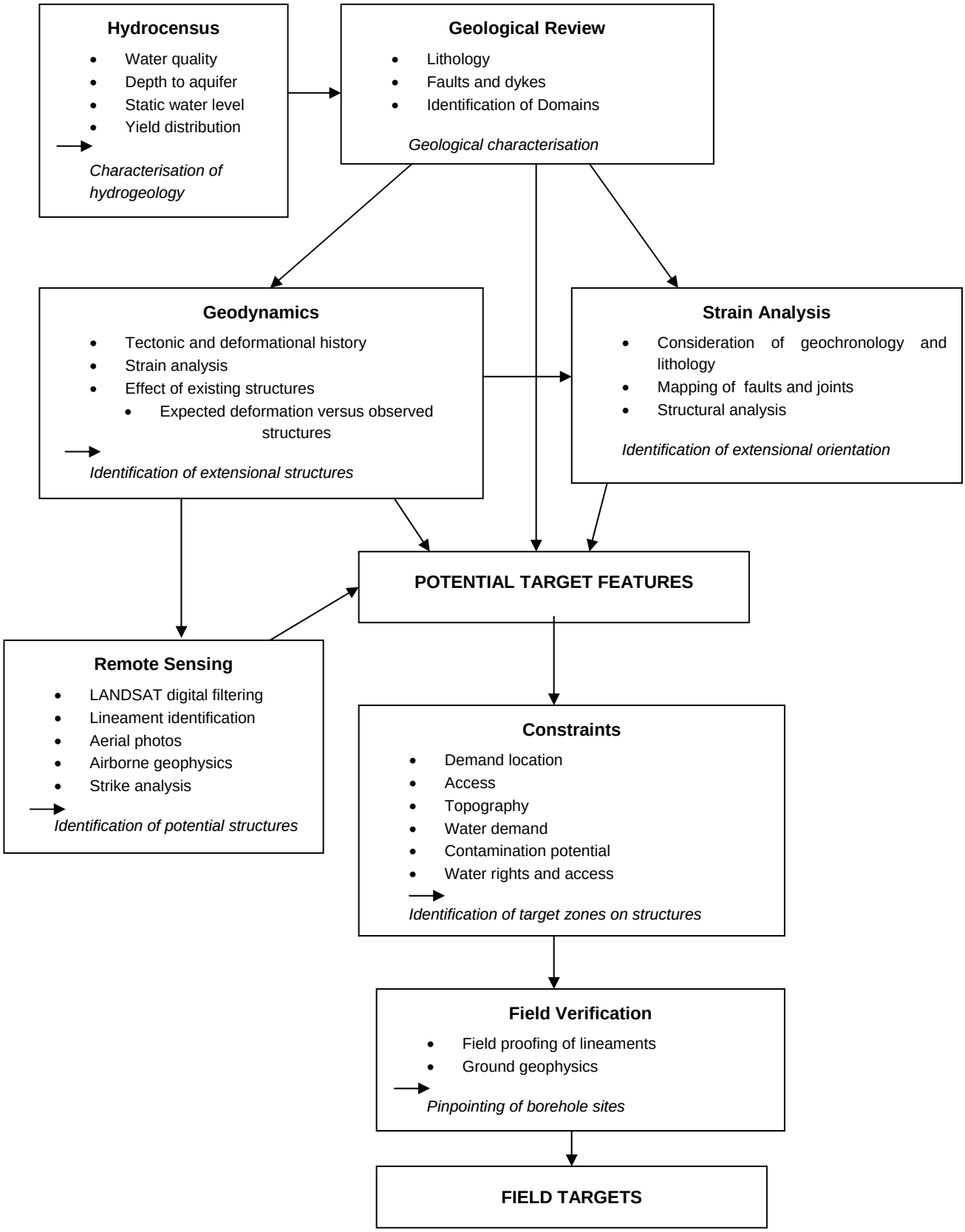

Figure 7: Flow chart of the recommended groundwater exploration process

Geodynamic investigations aim to obtain a conceptual model of pre-, post- and syntectonic geological evolution that describes historical extension, compression and shear orientations in geological time that is based on the observed pattern of faulting. A geodynamic interpretation permits an understanding and classification of observed lineaments and joint patterns in terms of their origin and present strain conditions, thereby enabling the identification of preferred structures.

Strain analysis

A strain analysis attempts to identify strain conditions in rocks by identifying compressional and tensional orientations from the observed strike and dip of joints with the use of stereonets. The objective is to identify the orientation of tensional and compressional forces that resulted in the observed fracture patterns. The risk of using this methodology is that in many cases rocks have been exposed to several tectonic events, perhaps with different stress orientations, and therefore jointing from several generations may be superimposed. Consequently, subsets of joints have to be related to a specific tectonic event. The identification of joint patterns that are related to specific events requires the geodynamic analysis to identify stresses that occurred at various periods in time. For this reason it is also often necessary to conduct joint mapping in the most recent lithological formation that is present, even if it is external to the study area, in order to identify stresses that originated from the most recent tectonic event. This process enables relative dating of joint sets.

Remote sensing and geophysical survey

The objective of using remote sensing methods is to identify structures of promising orientation and of hydrogeological significance that are not noticeable in the field or that have not already been mapped. The usefulness of remote sensing is hindered when the disturbance of the land surface hinders lineament identification; surface cover, such as sands, prevents identification of subsurface structures; lineaments are related to non-structural features, such as lithological variations of non-hydrogeological significance; or features are too narrow to be delineated at the scale of the image. Remote sensing that is used in isolation poses the risk of succumbing to the largest or most frequent anomaly syndrome, rather than identifying that which is the most hydrogeolgically significant.

Field proofing investigations are required to identify the nature of target lineaments to determine their nature and origin and to pinpoint the lineaments in the field with the use of observation or geophysics, with due consideration being given to constraints on siting (topography and access; water-demand location and quantity; reticulation or distribution systems; access to properties; water rights; contamination potential and vulnerability; and acceptance of drilling site by the stakeholders).

Conclusions and recommendations

Cost-effective groundwater exploration in fractured environments should:

- **Have a regional focus and be based on the identification of structurally significant target features for a region rather than be driven by local demand.**

  In which case a large number of structures can be identified with the use of a geodynamic methodology. Subsequent pinpointing of boreholes and drilling of targets can be driven by local demand in accordance with priorities.

- **Consider the expertise required rather than the expertise locally available.**

  Borehole siting is commonly undertaken by local consultants with the use of tools and skills that they have available. This approach often results in the repetition of poor practice and the use of instrumentation or methodologies that cannot achieve the required results. The consequence is much wasted time and money and little water. Structural geological understanding is essential to successful exploration.

- **Be guided by an understanding of the geodynamics, together with the water-bearing properties of identified targets, rather than be restricted to 'divining' with the use of a variety of instrumentation.**

  Only in this way can a conceptual model of groundwater occurrence be developed and refined so that an improved understanding of groundwater is achieved.

- **Consider the geological nature of targets prior to geophysical investigation.**

  Some high-yielding targets may not exhibit any geophysical anomalies with the use of magnetics or electromagnetics, yet they can be of structural significance. Conversely, some promising geophysical anomalies may yield dry boreholes if drilled on targets that are not structurally relevant (compressional lineaments, compressional dykes, lithlological variations etc.).

- **Groundwater exploration should be tendered on a per successful site or R/ℓ/s basis, i.e.** ***define outputs rather than inputs***.

  The current practice of subcontracting borehole siting to geohydrological consultants purely on the basis of cost or a per borehole sited basis does not promote the incentive to increase success rates. In fact, the opposite may be the case as the consultants' income increases with the number of boreholes sited and the number of boreholes at which drilling supervision is provided, regardless of the success rate. The subcontracting of borehole siting independent of the successful establishment of a borehole also shifts the responsibility of the implementing agent who controls the drilling budget. An incentive to increase success rates could be achieved by tendering groundwater exploration on a per successful site or a per R/ℓ/s basis (independent of drilling costs), thereby creating a motivating factor for increasing the success rates. This approach is adopted in Mozambique, which encourages consultants to use the most appropriate methodology for exploration and discourages incompetent hydrogeologists and diviners.

The above exposition suggest that there is a significant need for a fundamental paradigm shift in groundwater exploration in southern Africa. All of the above lessons can be considered to be opposed or contradictory to the current practice of groundwater exploration for rural water supply.

The hydrogeological community has paid scant, if any, attention to the importance of geodynamics and structural analysis in groundwater exploration. Consequently, exploration has been relegated to an exercise in geophysical anomaly hunting that adds little to the identification of future targets. A structural understanding of the aquifer is rarely built up and mistakes are commonly repeated. This shortcoming may reflect a lack of training in structural geology in South Africa, which is fundamental to groundwater exploration in fractured aquifers.

The losers in this regard have been the implementing and funding agencies as well as the communities who end up with much less water for their money than could have been achieved. The winners have been the hydrogeolgical community who have increased revenue by increasing the number of boreholes sited per day and the number of holes sited, while avoiding responsibility for their failures or incompetence, as well as the water diviners who can point out that they are usually as successful as hydrogeologists.

Groundwater exploration and development of basement aquifers in Botswana

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Abstract

Basement aquifers cover only 10% of Botswana, but form an important groundwater resource as some of the most densely populated portions of the country are underlain by crystalline basement. Groundwater exploration and assessment of basement aquifers has been undertaken as part of large-scale resource assessment projects as well as at the local scale as part of village water supply development. Case studies that illustrate both scales of investigation and development are presented from different areas of the country. Sufficient borehole yields, acceptable quality and reasonable drilling success rates were obtained in all areas through the implementation of comprehensive and integrated siting programmes that involve airborne geophysics; remote sensing analysis; mapping and ground truthing; and ground geophysical surveys with the use of multiple methods. In areas with high population densities, integrated supply strategies that are based on basement aquifers as well as water transferred from external sedimentary aquifers are being implemented. The primary issues concerning basement aquifers in Botswana are quality (both natural quality and anthropogenic contamination), the heterogeneity in rates of recharge and the complexities of fractured aquifer assessment. Although moderate borehole yields are often obtained, the long-term sustainability of groundwater abstraction is often problematic.

Introduction

Botswana is an arid to semi-arid country, centrally located within southern Africa (**Figure 1**), with limited surface water resources and hence a significant reliance on groundwater. It shares borders with South Africa, Namibia, Zambia and Zimbabwe and has a total land area of 582 000 km^2. The majority of the country is characterised by flat savannah and, although devoid of major mountains, more hilly country is present along the eastern margin. The major physiographic features in the country include the Okavango Delta, Makgadikgadi Pans, Tsodilo/Aha Hills and the Kalahari.

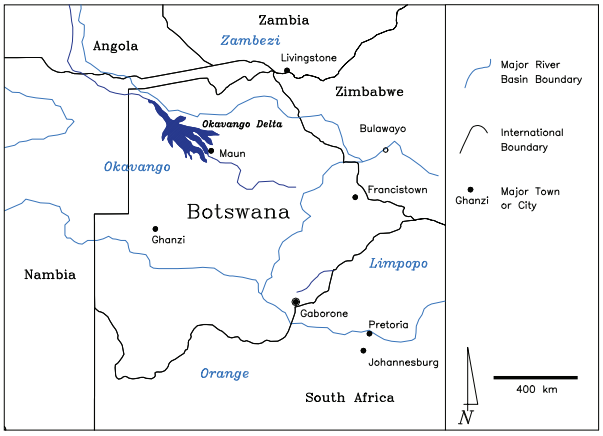

Figure 1: Botswana location map.

Climate

The climate of Botswana is primarily semi-arid with rainfall ranging from approximately 250 mm/yr in the southwest to 550 mm/yr in the east and up to a maximum of 690 mm/yr at Kasane (extreme north). Annual open water evaporation is in the order of 2 000 mm and exceeds average rainfall in all months of the year. The mean annual precipitation is approximately 550 mm, with 80-95% of the rainfall occurring during the summer months when evaporation is highest. Average temperatures are also high with a mean annual temperature in Gaborone of 28.4^{o}C and in Maun (northwest) of 30.3^{o}C.

Water resources

Two active river systems form borders with adjacent countries (Limpopo and Linyati/Chobe), while the Zambezi River, which forms a border with Zambia, extends only 200 meters. Only three major river systems are perennial (Okavango, Linyati/Chobe and Limpopo) with the remainder generally experiencing annual periods of no flow. The total estimated runoff for the country is 705 MCM or 1.2 mm (National Water Master Plan, 1991), which is extremely small in comparison with other similar countries (i.e. Australia) and emphasises the meagre surface water resources of Botswana.

As a result of climate and the limited distribution and extent of surface water resources, groundwater has and continues to be an extremely important resource in the development of the country.

Nearly half of the drinking water demand for the country is provided by groundwater with more than 90% of villages in Botswana supplied by groundwater (NWMP, 1991). Many of the major towns, such as Molepolole, Kanye, Serowe, Maun and Ghanzi are supplied by groundwater, while many other towns use groundwater and surface water or have wellfields as backup capacity to surface water sources. A major pipeline, the North-South Carrier, connects reservoirs in the north with the capital, Gaborone, as well as with a series of major towns and villages on the eastern margin of the country. There are several major wellfields that offer emergency backup capacity in periods of drought.

Basement aquifers in Botswana

Approximately 10% of the country is underlain by Archean basement that consists of metamorphic and plutonic bedrock. Basement formations are present primarily in the east of the country, but also include areas of the north-west where Kalahari Beds cover is often thick. The basement regions of the east tend to be found in regions of relatively high population density (**Figure 2**).

Extent of basement rocks

The most extensive areas of basement outcrop/subcrop in Botswana are present in the north-east of the country, near the city of Francistown (**Figure 2**). However, recent high resolution aeromagnetic surveys (DGS, 1997) carried out in the Okavango region in the north-west of the country have led to the revision of the national geologic map and a significant increase in the area of basement interpreted to be present beneath thick Kalahari cover in this region.

Crystalline basement lithologies include granitoids, gneisses, granites, migmatites and meta-plutonic rocks in the north-east and granite, gneisses and granitoids in the south-east (Carney *et al.*, 1994). The north-east region is primarily interpreted to be gneiss and banded gneiss (DGS, 1997).

Structural environment

In the north-east of Botswana, crystalline basement is complexly folded and faulted and is grouped within five major tectonic terrains, the Francistown Complex, Mosetse Complex, Motluotse Complex, Limpopo Belt and Mahalapye Complex. The south-eastern basement terrain is much less structurally complex with structures consisting primarily of NW-SE trending faulting and E-W and NW-SE trending antiforms and synforms. The basement terrains of Botswana tend to be structurally complex and often faulted although the major regional faults and structural zones in Botswana (**Figure 2**) are present outside of the basement terrains.

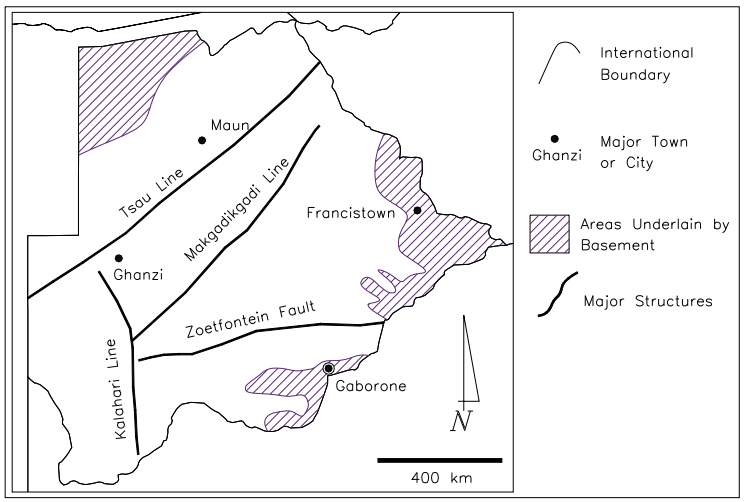

Figure 2: Distribution of Basement and Major Structures in Botswana.

Groundwater development in basement aquifers in Botswana

To highlight the challenges and evolving approach of groundwater exploration and development in basement aquifers in Botswana, three case studies are presented, namely one that involves a large-scale regional exploration and assessment project and two that consider typical village water supply projects. The case studies illustrate the strategies and methodologies that are being employed in Botswana to address the complexities and difficulties inherent in groundwater development in basement aquifers in a semi-arid environment. They also underscore the important potential that is associated with basement aquifers in the region.

Major development projects

A major groundwater exploration and development project, which is focussed on basement aquifers as well as on Karoo formations was completed in the north-east of Botswana. It is the Groundwater Investigation for Rural Water Supply in the Northeastern District and Parts of the Neighbouring Central District (DWA, 2001). The goal of the project was to explore and assess the groundwater potential in the north-eastern district (north of Francistown, **Figure 1**) which has a high population density, is underlain by basement complex and has had a history of water supply shortage.

The exploration phase of the project included extensive use of airborne and ground geophysics (AEM, airborne radiometric survey and ground HLEM, VES and electromagnetic methods); detailed structural and geologic mapping; recharge assessment; and the drilling and construction of exploration and test-production boreholes. A total of eight successful boreholes were completed in crystalline basement aquifers that have yields ranging from 0.5-15 ℓ/s. Water quality in all boreholes was within Botswana's drinking water standards (TDS 270-630 mg/ℓ).

Although the basement aquifers in the north-east district were considered to have significant potential, due to the relatively high demand in the concentration of villages and the considerable expected population growth, the final recommended strategy for long-term water supply was to use a range of sources that include basement aquifers, a major wellfield developed in Karoo sandstones and abstraction from alluvial sand aquifers along rivers. This involves local sources (basement and sand river) as well as water transfers (from the distant Karoo wellfield) to provide a reliable and sufficient water supply solution in this basement area of Botswana.

Village-scale development projects

Many groundwater exploration and development projects have been completed in basement aquifers for village water supply in Botswana. In isolated villages in much of the west of the country, where even intermittent surface water resources are absent, groundwater offers the only viable option for water supply. Therefore successful identification of sufficient groundwater resources for village water supply is a requirement of these projects. No alternatives are readily available. The groundwater exploration and development for the village of Qangwa in northwestern Botswana provides an example of groundwater exploration in this environment.

In the east of the country, some perennial rivers are present, one being the Limpopo River. Many villages have developed along the course of the Limpopo, which forms the border with South Africa. Although surface water would appear to be a logical source for some of the relatively large villages in basement terrains, significant groundwater potential has been identified in shallow basement aquifers that are hydraulically connected with the river system in the villages of Mabalane, Sikwane and Mathudubudukwane (the 'river villages').

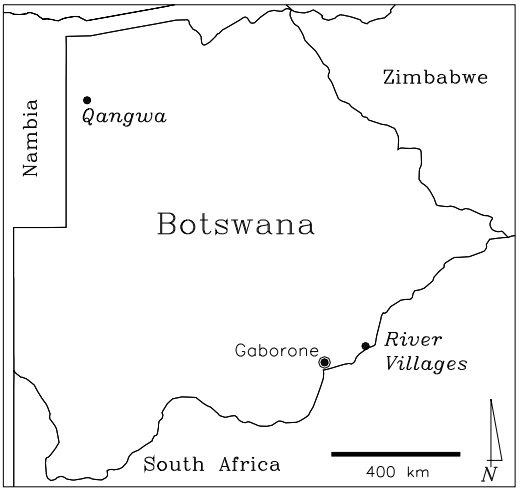

Figure 3: Village Project Locations.

Groundwater development in Qangwa, Ngamiland district

The village of Qangwa is located in north-western Botswana, near the border with Namibia (**Figure 3**). Population density in most of western Botswana is extremely low, less than 1 person per km^2 and villages are small and far apart. As such, water demand is low (16 m^3/d for Qangwa), but the requirement for reliability and sustainability is very high due to the isolated nature of villages in this area. Additionally, the vulnerability of shallow basement aquifers to contamination is illustrated by the deteriorating water quality of the existing supply borehole that is located within the village with nitrate levels recently reaching 139 mg/ℓ. Additionally, naturally occurring fluoride (2.93 mg/ℓ) and manganese (125 mg/ℓ) that exceed Botswana's drinking standards were identified in the existing production borehole.

To address the water quality problems as well as to cater for future demand growth, a groundwater development project was implemented (DWA, 2004).

The Qangwa area is underlain by the Qangwadum Basement Complex of Upper Proterozoic Age (1200-570 million years), which is covered by variably thick sands of the Kalahari Beds. The Qangwadum Complex mainly comprises granitic gneisses and augen gneisses with minor developments of medium grained biotite-muscovite granite. Aquifers tend to be developed at shallow depths (<50 m), primarily in the upper weathered mantle of the basement. Drilling success rates for the area are extremely poor, with only one in five boreholes near Qangwa encountering groundwater (existing supply borehole: 0.6 l/s) and similar success rates observed across this area.

Exploration Methods

Considering the 20% drilling success rate in this area, a comprehensive siting programme was implemented. Initial assessment included the interpretation of existing airborne magnetic survey (AEM) data in conjunction with satellite imagery and a site reconnaissance/borehole census. A series of north-west to south-east trending faults were identified near Qangwa and are clearly depicted in the AEM image. Parallel and cross-cutting lineaments were also observed in the satellite imagery. Areas of the most prominent development of these interpreted structures and their intersections were targeted for ground geophysical surveys, with the focus on dry river channels (enhanced recharge potential) away from the village and cattle posts in order to avoid contamination threats.

The ground geophysical surveys selected, were integrated magnetic and horizontal loop electro-magnetic (HLEM) profiling, followed by vertical electrical soundings (VES) in areas of interest. A key component of the survey was calibration at boreholes with existing hydrogeologic data. An example of an interpreted data set at a calibration borehole is provided in **Figure 4**. HLEM was found to be effective in identifying fracture/fault zones in the basement where weathering/fracturing would be expected to be most developed, while VES provided quantification of the anticipated depth of fracturing.

Results

A prioritised set of nine drilling sites in two target areas were selected on the basis of the interpretation of the ground geophysical surveys. Drilling at the first site encountered a significant fracture zone to 38 meters with an estimated yield of more than 14 ℓ/s. The second site encountered less extensive fracturing, but still had an estimated yield of 3 ℓ/s. These yields were subsequently confirmed during test pumping. Laboratory analyses of water samples from both boreholes indicated that all parameters were within Botswana's drinking water standards.

The good success rate and high yields obtained in this project in a difficult basement environment is attributed to the integrated siting investigation, which included AEM and remote-sensing interpretation, multiple ground geophysical survey methods and, most importantly, overall co-operative interpretation and site selection by the hydrogeologist and geophysicist involved in the project.

Groundwater development in the river villages, Kgatleng District

The adjacent villages of Mabalane, Sikwane, Mathudubudukwane and Malowane are located along an approximately 10 kilometer stretch of the Limpopo River, 50 kilometers from the capital, Gaborone. The villages have experienced rapid growth due to their proximity to the capital and the presence of a border post with South Africa, which resulted in demand rapidly outpacing several existing low-yielding supply boreholes. Consideration was given to connect the villages to the North–South Carrier water pipeline, but a decision to explore the basement aquifers in the area (DWA, 1999) was taken prior to committing to this large capital investment.

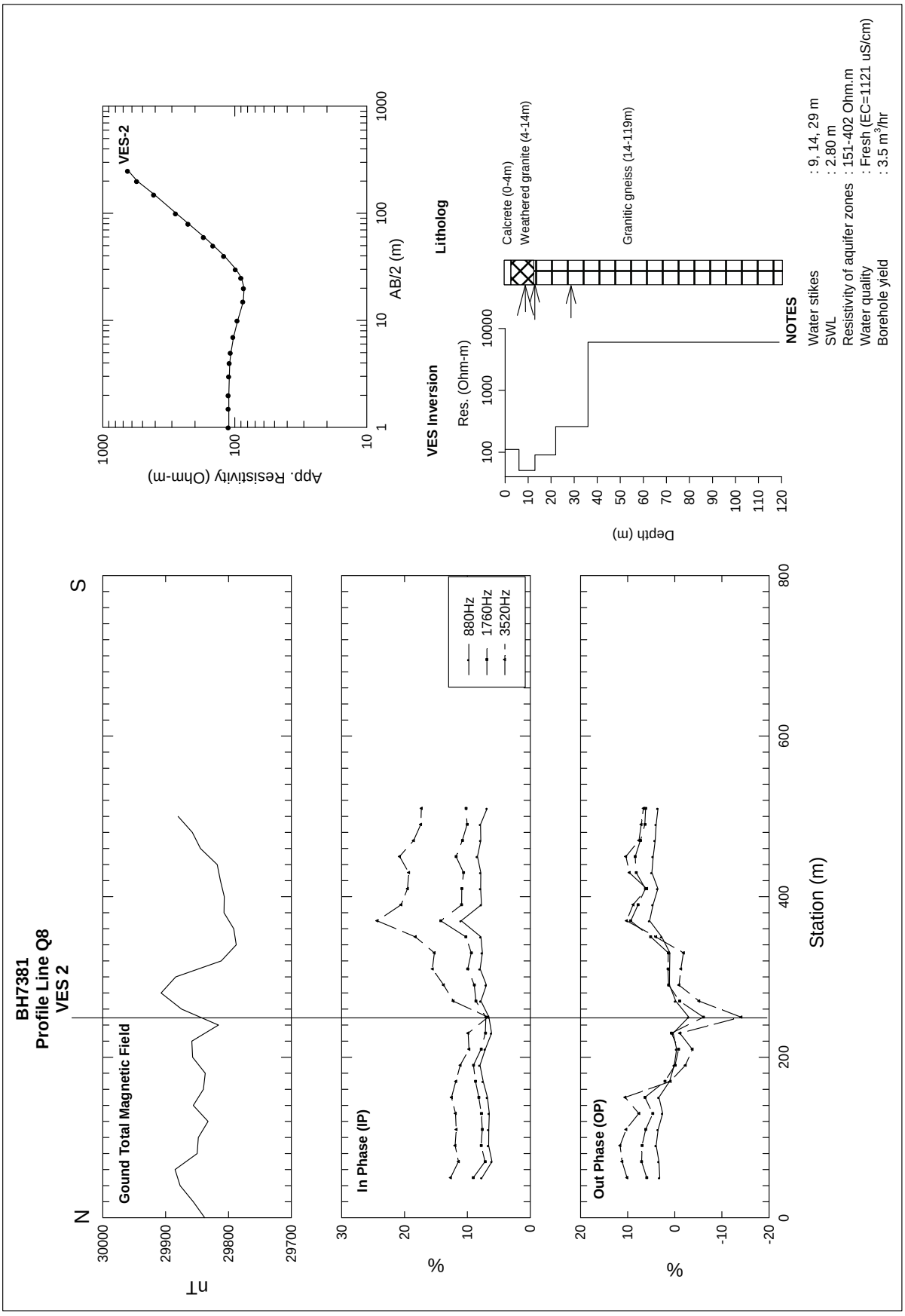

Figure 4: Integrated Interpretation of Geophysical Data Sets: Calibration Borehole.

The river villages area is underlain by gneisses and granitoids of the Archean Olifant's Drift Formation. Foliation trends in the Olifant's Drift gneisses and granitoids are generally west-north-west, parallel to the major structures of the area and crossing the Limpopo River.

Given the rapid growth of the villages, there was significant concern that basement aquifers would provide insufficient yields and unreliable supply over time. Existing production boreholes in the vicinity of Mabalane had shown yield reductions in the order of 50 percent since commissioning less than 10 years earlier, primarily due to lower water tables and aquifer depletion. However, some boreholes close to the Limpopo River were found to have been in operation for periods of 20 to 30 years and more, with no observed yield reductions.

Based on a review of existing data, a two-pronged groundwater exploration and development strategy was developed, including re-testing of the existing production boreholes to evaluate the causes of the yield decline and the exploration of areas adjacent to the Limpopo River to assess the potential of aquifers that are recharged by the river.

Re-testing existing production boreholes

The primary existing production boreholes are present along a small intermittent stream that is approximately five kilometers from its confluence with the Limpopo in an area that is underlain by granitic basement. Although a major source for the supply of the river villages, a persistent yield decline was observed in all the boreholes by operations staff, which created serious shortfalls.

To assess whether yield reductions were the result of borehole damage (encrustation, biofouling or collapse) or aquifer depletion, a re-testing programme was implemented. Each borehole was taken off line individually to avoid significant supply disruption, the production pump removed and examined and a step test and 72 hour constant-rate test implemented prior to re-commissioning the borehole. The inspection of pumps and rising mains provided an indication of the potential of biofouling or encrustation. Observation of water levels in adjacent production boreholes during testing was used to evaluate the presence of interference.

The results of the re-testing programme clearly indicated that the major cause of yield decline was primarily overexploitation of the aquifer, which resulted in significant water level declines (up to 40 m). This was further aggravated by borehole interference that is associated with boreholes that are sited along the same structure. As such, the groundwater exploration programme went ahead to replace these existing boreholes and develop sufficient additional capacity for future demand.

Exploration methods

Given the moderate topography of the area and generally thin cover, aerial photograph interpretation was a critical first step in the exploration activity. The focus of air photo interpretation was the identification of lineaments associated with structures, emphasising those that cross the Limpopo River. Fieldwork was then carried out to provide detailed geologic and structural data, particularly along the river margins where bedrock was well exposed.

Similar to Qangwa, an integrated geophysical survey comprising magnetic and HLEM profiling with VES in selected locations, was conducted in the study area. A series of prioritised sites were selected for drilling with eight boreholes eventually drilled. Five were successful with tested yields ranging from 1 to 15 ℓ/s. During borehole test pumping, extremely heavy rainfalls were experienced (resulting from the 2000 cyclone) and three boreholes showed significant response to recharge (up to 5 m water level rise) with one borehole showing full recovery during test pumping due to the recharge event.

The water supply from the new project boreholes provides for the present demand and ten year estimated demand, allowing decommissioning of the existing and low-yielding boreholes and avoiding the necessity of connecting the villages to the North-South Carrier pipeline. The completion of boreholes proximal to the Limpopo River, where aquifers are interpreted to be in hydraulic connection is expected to address the problems of limited sustainability of the basement aquifers that are dependent on rainfall recharge in this environment. The observed recharge effects during an unusual rainfall event supports the conclusion that the new production boreholes are in active aquifer systems.

Basement aquifers in Botswana: challenges and potential

The above case studies provide an overview of the nature of challenges that are associated with groundwater development in basement aquifers in Botswana as well as their potential and important future role in water supply at many levels. The significant experience in basement aquifer exploration and assessment in Botswana provides important insights for the region in terms of strategies for basement aquifer development and the constraints and potential that these groundwater resources represent.

The key issues that arise from the Botswana experience in basement aquifers are described below.

Storage and recharge

In a semi-arid to arid environment such as Botswana, with a common occurrence of drought, aquifer storage characteristics are a crucial aspect of the sustainability of groundwater abstraction. As a result of the commonly limited extent of basement aquifers that is associated with fracture zones and some weathered profiles, basement aquifer storage often has poor characteristics and results in borehole yield decline over time and in many cases, eventual abandonment of boreholes. The river villages production boreholes provide a typical example of the limited sustainability of some basement aquifers in this environment.

However, there are indications that many basement aquifers in Botswana are actively recharged, even in areas of Kalahari Beds sand cover. Where recharge is reasonably regular and of sufficient magnitude, even basement aquifers of limited storage characteristics can be sustainable. Basement aquifers that underlay and are in hydraulic connection to perennial or intermittent streams clearly have greater recharge potential as well as provide potential for induced recharge under abstraction conditions.

Recharge assessment in basement aquifers is a critical challenge for improving the reliability and sustainability of abstraction. The identification of fresh groundwater in shallow basement aquifers in arid to semi-arid areas of Botswana, where Kalahari Beds unconsolidated cover is ubiquitous, suggests that active recharge occurs. However, due to the intermittent nature of recharge in these areas, direct methods, such as the monitoring of water levels, may not show a recharge event over the period of study. Therefore more innovative methods for recharge assessment in these aquifers, such as CFC sampling, will be crucial to effectively evaluate sustainable resources from these aquifers. CFC analysis has been increasingly used in Botswana to evaluate the potential of active recharge in the recent period and thereby enable assessment of the sustainability of groundwater supply from these aquifers. CFC testing was used to evaluate recent recharge to high-yielding aquifers in fractured basement in the Tsabong Area of Botswana as part of the assessment of sustainability of these aquifers for town water supply (DWA, 2002).

Exploration methods

In Botswana, groundwater exploration has increasingly focussed on integrated and comprehensive siting programmes that involve remote sensing imagery, regional airborne geophysical data sets and multiple ground geophysical survey methods, even for small rural village projects. This strategy is considered to be particularly vital for groundwater exploration and development in basement aquifers.

Implementation of comprehensive siting methods has shown the potential not only to increase drilling success rates in basement aquifers, but also to result in borehole yields that are well beyond existing averages. Relatively high borehole yields (>14 ℓ/s), which are confirmed through quantitative analysis over 72 hours, in basement aquifers have been achieved across Botswana when integrated siting methods have been employed.

Vulnerability

The vulnerability of basement aquifers to contamination has been well documented throughout the region. In Botswana, the primary anthropogenic threat to shallow basement aquifers is nitrate, which often can result in local aquifer contamination beyond acceptable drinking standards in periods of the order of ten years. The primary strategy to address this issue in Botswana has been the siting of supply boreholes well away from human and livestock areas. Since rural water supply is based strictly on mechanised pumped boreholes and not handpumps or open wells, this does not impose a significant constraint on the exploitation of basement aquifers for rural water supply.

Potential

When comprehensive and integrated siting methods are employed, including remote sensing interpretation,

airborne geophysics, ground geophysics and geologic/structural mapping, basement aquifers have been found to provide moderate yields (5 – 15 ℓ/s) with acceptable drilling success rates (>75%). Sustainability is the crucial issue with the geometry/extent of basement aquifers as well as their storage characteristics often very difficult to assess accurately. In Botswana, sustainable development levels from basement aquifers is presently based primarily on regular monitoring and the adjustment of abstraction rates, as required, if persistent water level declines are observed.

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Groundwater chemistry of basement aquifers: A case study of Malawi

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Abstract

This is a review of groundwater chemistry in Malawi. In spite of their low water-yielding capacity of between 0.15 to 5 ℓ/s, basement aquifers are the source of water supply for about 60% of the rural population in Malawi. Most of boreholes and wells are in the basement aquifers, which covers approximately 70% of the land surface. They also contribute between 10-30% of the total annual stream and river flow. Fractures, weathered zones and intrusions control the occurrence of basement aquifers leading to the inherent heterogeneity of basement aquifers in terms of hydraulic characteristics and lithology. While ground water is generally of acceptable quality, sporadic cases of high concentration of iron, fluoride and salinity have been reported which may underscore a widespread problem being masked by limited data. On the other hand, the occurrence of electrical conductivity values of over 4000 µs/cm and 1000 µs/cm of two bores in the same village in Dowa West is indicative that large communities in Malawi might be consuming ground water of unacceptable qualities that poses a potential health risk. The mixing of groundwater with surface water on the valley lower slopes of Bua River provide a case of a common route for microbial contamination of boreholes and poses a health hazard to some communities. Insufficient sampling, analysis of potential toxic compounds, research on groundwater quality and dissemination of research findings could be responsible for creating inadequate public awareness of the potential health risks that rural people, who depend on groundwater sources, are facing.

Introduction

Malawi has about 12 000 boreholes and 5 600 wells (Kalua *et al.*, 1997) and these sources supply water to about 60% of the national population (National Statistical Office, 2002). Most boreholes and wells are in basement aquifers, which cover approximately 70% of the land surface area, (**Figure 1**). Aquifers contribute between 10-30% of the total annual stream and river flow in Malawi and are the main source of stream and river flows during the dry season (Malawi Government-UNDP, 1986). Most of the groundwater is used for domestic purposes with limited amounts being used for small-scale irrigation (National Statistical Office, 2000). In recent years, groundwater demand is on the increase as evidenced by the number of boreholes drilled between 1992 and 1996 (**Figure 2**).

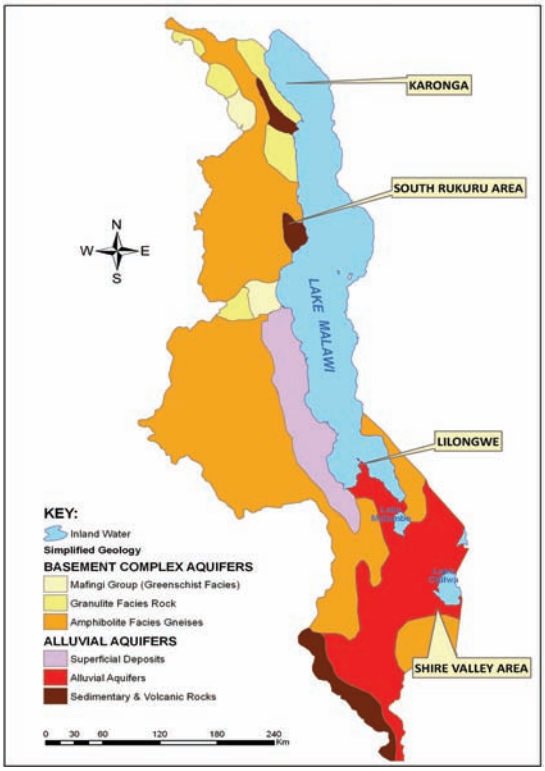

Figure 1: Malawi's Hydrolithological Units (Source: Government of Malawi-UNDP, 1985)

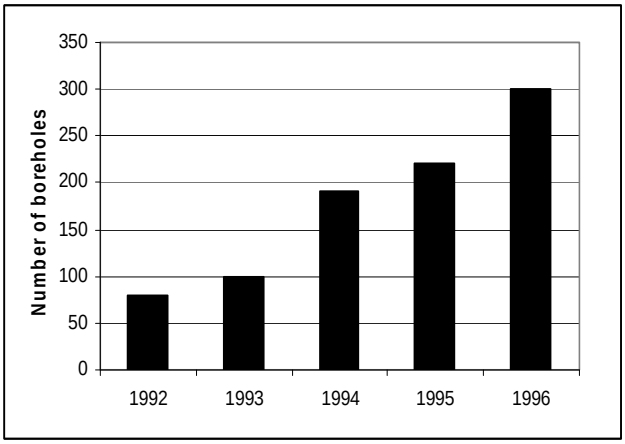

Figure 2: Number of boreholes drilled in Malawi from 1992 to 1996 (Source: Malawi State of Environment Report, 1998).Major aquifer systems

According to Malawi Government-UNDP (1986), there are two main types of aquifers in Malawi. The extensive, but relatively low-yielding, basement aquifers and the high-yielding alluvial aquifers (**Figure 1**).

Basement complex aquifers

Basement complex refers to crystalline metamorphic and igneous rocks of Precambrian to Lower Paleozoic age (Carter and Bennett, 1973). The major lithological units of the basement complex are syenitic granites, charnocktic and ultra-basic gneisses, schists, granulalites and quartzites.

Basement complex aquifers are of two types and their occurrence is associated with physiographic units (**Figure 3**). The first type is characterized by the prolonged *in situ* weathering of basement complex rocks, which produces a layer of unconsolidated saprolite material that constitutes the aquifer system. The second type is characterised by largely fractured unweathered basement complex rocks (Malawi Government-UNDP, 1986). These commonly occur in plateau areas (**Figure 3**) where saprolite thickness generally ranges from 15m to 30m. These basement aquifers can be found in the areas around Zomba and the Mulanje Mountains (**Figure 3**), upper Shire River Valley, Lilongwe-Kasungu Plain and South Rukuru River catchment (**Figure 3**).The average yield in the weathered zone of the basement complex is in the range of 1-2 litres per second (Stanley International, 1983).

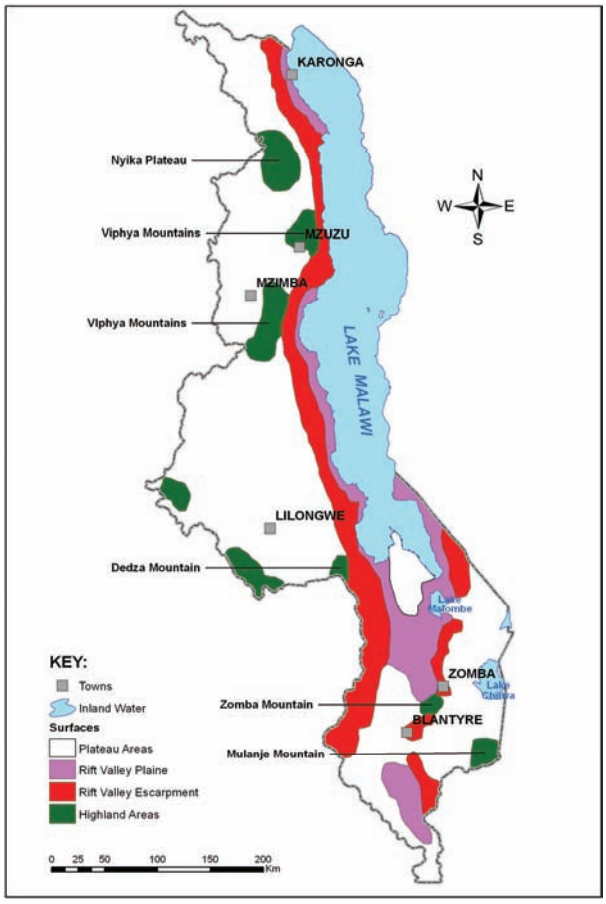

Figure 3: Major physiographic zones of Malawi

In the plateau areas in which basement rocks predominate, groundwater occurrence is mainly dependent on secondary porosity derived from fractured rock. Aquifer yields for the weathered fractured crystalline basement rocks are in the range of 2-4 litres per second. Yields from groundwater in the basement complexes are generally only sufficient for rural water supplies by hand pumping (Stanley International, 1983).

In the Upper Shire River Valley (**Figure 3**), basement complex rocks form the main source of the valley-fill deposits. Sandy clays cover the northern part of this area to a depth of up to 60 m while arenaceous deposits of deltaic origin underlie the southern part of the aquifer. Aquifer yields range from 0.15 to 1 litre per second (Stanley International, 1983).

In the Lilongwe area (**Figure 3**), the aquifers are part of the extensive Central Region Plateau, which is at an altitude of 1 100 m above mean sea level. The Plateau is underlain by basement complex gneiss and granulites of which the buried surface slopes towards Lake Malawi and are intersected by faults associated with the development of the Rift Valley (Carter and Bennett, 1973).

The lakeshore rift valley plain (**Figure 3**) covers an area of about 1 400 km^2 and is generally bounded to the west by the Rift Valley Fault Scarp. About 50% of the boreholes in this area derive water from fractured crystalline and weathered rocks, which produce very low water yields with a maximum yield of 0.2 litres per second (Stanley International, 1983).

The South Rukuru River catchment (**Figure 1**) drains an extensive area of about 12 200 km^2 in the northern region of Malawi. Igneous and metamorphic rocks of the basement complex underlie this catchment and the aquifer yield range is 0.75 litres per second to 3 litres per second (Malawi Government-UNDP, 1986).

Some of the basement aquifer systems in Malawi have also been affected by intense lifting that is associated with the Great East African Rift system. Dolozi *et al*. (in press) note the presence of major geological lineaments and faults in most crystalline aquifers in the Zomba area including the Zomba Plateau. Northeast trending faults that are associated with the East African Lift Valley marks the Zomba Mountain's western border. These major faults and lineaments, together with the weathered portions of the crystalline basement rocks, constitute the aquifer system of the mountain. These geological features, coupled with high rainfall in areas like the Zomba and Mulanje Plateaus, are favourable for recharge.

From the preceding discussion it is evident that fractures, weathered zones and intrusions control groundwater occurrence in crystalline basement rocks with generally low yields, rarely exceeding 3 to 4 litres per second. The challenges in such hydrogeological environments are mostly two-fold: quality and quantity**.**

Alluvial aquifers

Alluvial aquifers are fluvial and lacustrine sediment successions with variations in both vertical and lateral extent. These aquifers are relatively high yielding in comparison with the basement complex aquifers with recorded yields in excess of 10 litres per second. They are mostly located in the rift valley floor areas along the shore of Lake Malawi on the western side of the Shire River Valley, which includes the Salima-Nkhotakota-Karonga area; the Bwanje Valley; the Upper and Lower Shire Valley; and Lake Chilwa basin on the outer slopes of the Zomba Plateau (GOM-UNDP, 1986; Stanley International, 1983) as shown in **Figure 1** and **Figure 3**.
The main lithological component of the alluvial aquifers is clay with significant occurrences of poorly sorted sands in some localities. Most of the alluvium aquifers are unconfined although most thick clay sequences are semi-confined. In the Lake Chilwa Basin, which is perched on the eastern side of the rift valley, most of the alluvium aquifers are clayey with the highest yields obtained from sand and gravel aquifers that are found in buried river channels (GOM-UNDP, 1986).

Hydrochemistry of basement aquifers in Malawi

The quality of groundwater in Malawi is generally acceptable for domestic use. Some problem areas are identified in which a high concentration of individual ions may render the water unacceptable for human consumption. Malawi adopted the more realistic drinking water standards of the Government of Malawi-UNDP (1986), which are shown in **Table 1**, because the World Health Organisation's (1993) standards were considered to be too strict.

Most of the hydrochemical studies of basement aquifers in Malawi were carried out in the 1970s and early 1980s by the Malawi Geological Survey Department and are contained in Geological Bulletins and various geological reports (Bradford, 1973; Chapusa 1977; Pascal, 1973; and Wilderspin, 1973; Bath, 1980; Malawi Government-UNDP, 1986). Although this information is valuable, the results of groundwater analyses may reveal imbalances between cations and anions and thus should therefore be used with caution. Water samples have been collected without filtration and acidification (for cation analysis) and unstable parameters such as pH and alkalinity have not always been measured in the field (Bath, 1980). Analyses for groundwater chemistry are presently carried out by the Ministry of Water Development's Central Water Laboratory, which was established in Lilongwe in 1982/83.

The water quality in the basement complex aquifers is characterised by the dominance of alkaline earths in the cation group and carbonates in the anionic group. Groundwater in the basement complex aquifers shows low total mineralisation, indicating that most of the water is derived from recent recharge. The chemical, physical and biologic parameters that are being monitored include those mentioned in **Table 1** as well as fluoride, sulphate, nitrate, iron, total hardness (manganese and magnesium), electrical conductivity (for total dissolved solids), tubidity, total Coliform and pH (GOM-UNDP, 1986). Iron is being monitored in Lilongwe, Dowa and Karonga. Manganese and magnesium are being monitored in the Chikwawa and Nsanje districts and sulphates are being monitored in Dowa. **Table 2** shows the most common ranges for various parameters that are associated with groundwater resources in the basement complex and alluvial aquifers.

Table 1: Standards for drinking water in arid regions adopted in Malawi (Government of Malawi-UNDP, 1986)

Parameter	Suitability for permanent supply			
	Good	Fair	Moderate	Poor
Electrical conductivity S/cm	0-750	750-1 500	1 500-3 000	3 000-6 000
Na (mg/ℓ)	0-115	115-230	230-460	460-920
Mg (mg/ℓ)	0-30	30-60	60-120	60-120
Hardness (mg $CaCO_3$/ℓ)	0-250	250-500	500-1 000	1 000-2 000
Cl (mg/ℓ)	0-180	180-360	360-710	710-1 150
SO_4 (mg/ℓ)	0-145	145-290	290-580	580-1 150

Table 2: Common range in the quality of groundwater (Government of Malawi, 1986).

Parameter	Unit	Weathered basement	Alluvial aquifers
Electrical conductivity	ℓs/cm	100-1 000	500-3 000
Total dissolved solids	mg/ℓ	60-600	300-1 800
Calcium	mg/ℓ	10-100	50-150
Magnesium	mg/ℓ	5-50	20-100
Sodium	mg/ℓ	5-70	20-1 500
Potassium	mg/ℓ	1-6	1-6
Total Iron	mg/ℓ	1-5	1-5
Bicarbonate	mg/ℓ	100-500	200-1 000
Sulphate	mg/ℓ	5-1 000	20-2 000
Chloride	mg/ℓ	Less than 20	20-2 000
Nitrate	mg/ℓ	Less than 5	Less than 5
Fluoride	mg/ℓ	Less than 1	2-10

Suitability and salinity

Groundwater quality is generally acceptable for domestic use despite widespread occurrence of high iron concentration (Malawi Government-UNPD, 1986). There are, however, some problem areas where groundwater quality is not suitable for human consumption and most of these areas are still to be delineated in greater detail.

Electrical conductivity (EC), which is indicative of the total amount of dissolved solids and salinity, has been used to assess groundwater quality in Malawi (Bath, 1980). The upper limit of groundwater quality, expressed as EC, that is suitable for human consumption in Malawi has been set at 3 000 µS/cm (Malawi Government-UNDP, 1986). In general, groundwater from basement aquifers within the plateau areas has a lower EC (750 to 1 500 µS/cm). Boreholes located in escarp zones have EC values greater than 3 000 µS/cm (Bath, 1980).
The groundwater quality can vary greatly even over short distances. This is indicative of the heterogeneity of basement aquifers, both in terms of hydraulic characteristics and lithology. For example, several boreholes in the Dowa West Integrated Project area had EC values close to 4 000 µS/cm while those nearby, some even in the same villages, have recorded EC values of less than 1000 µS/cm (Malawi Government-UNDP, 1986).

This implies that people of the same village could be consuming groundwater of different qualities when it is derived from different boreholes. The increasing number of NGO's that are providing boreholes to rural communities at a time when there is decreasing capacity for the monitoring and control of groundwater quality (by the Ministry of Water Development) poses a potential risk in this regard.

In the Dowa West Integrated Project area, high levels of EC are mainly attributed to high levels of sulphates, as shown in **Figure 4** (Malawi Government-UNPD, 1986). There is therefore a need in Malawi to verify the source of high levels of EC and to accurately delineate the

source of sulphates and assess its linkage to the distribution of groundwater quality. This requirement is imperative, because there have been few reliable field measurements of groundwater quality elsewhere in Malawi apart from the area under the Dowa West Integrated Project (**Figure 4**). Logic therefore suggests, and indeed experience bears out, that this scenario of the Dowa West Project area is more likely to be widespread across Malawi rather than being an isolated case.

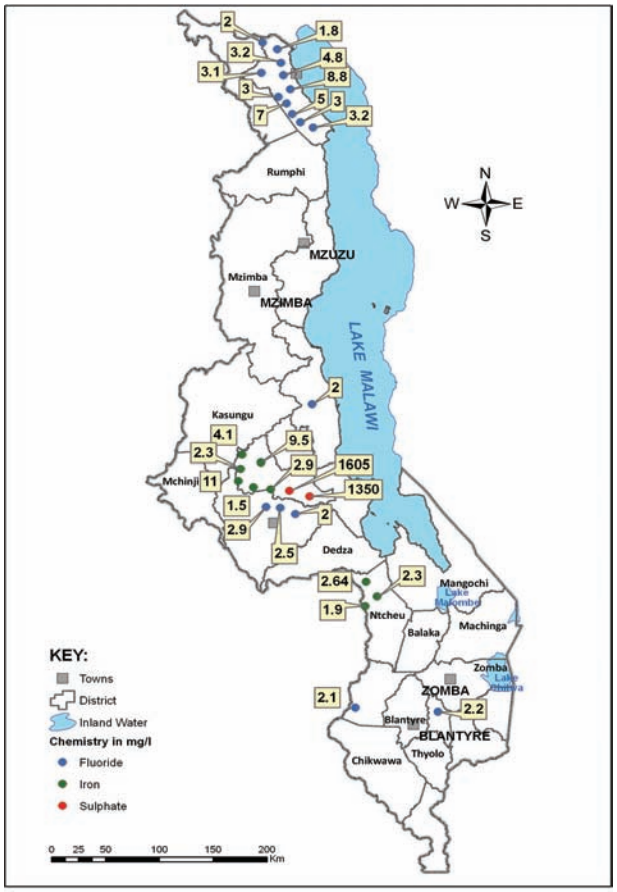

Figure 4: Levels of fluoride, iron and sulphate in groundwater

Stratification of groundwater quality is also possible for basement aquifers (Malawi Government-UNDP, 1986). For example, conductivity logging and analyses of groundwater samples from different depths for several boreholes in the Lilongwe area revealed vertical and horizontal changes in hydrochemistry (Smith-Carrington, 1983).

Fluoride, iron and sulphate

Figure 4 shows the spatial distribution of fluoride, iron and sulphate concentrations for groundwater that is based on data of the Ministry of Water Development (1997). It is clear from the figure that there are a number of areas in Malawi for which information is scarce or not available. For example, information on fluoride is restricted to the Karonga Lakeshore Lilongwe, Nkhotakota, Mwanza and Chiradzulu areas. Similarly, analyses of sulphate and iron concentrations have mostly been carried out for groundwater in the Dowa District. There is therefore a clear need for further research in other parts of the country where basement aquifers occur.

The available data indicate that the fluoride concentration of groundwater is generally above the recommendations of the Ministry of Health of 0.6-0.8 mg/ℓ (Malawi Government, 1998) for human consumption. Consumption of water with a high level of fluoride could lead to fluorosis, i.e. bone diseases and mottling of teeth (Malawi Government, 1998). Thus far there have been few studies that link the concentration of fluoride with these known diseases in Malawi (Malawi Government-UNDP, 1986).

Groundwater contamination and toxicity

Palamuleni (2002) states that the lack of reporting of incidences of groundwater contamination is one of the most important water-related health problems that Malawi is facing. This arises from a number of factors such as the lack of public awareness; insufficient sampling and analyses of potentially toxic compounds; and limited research on groundwater contamination.

Two boreholes in the weathered basement aquifers on the lower valley slopes of the Bua catchment provide a good example of the latter. At this site, groundwater rises to the surface and mixes with the surface water of a nearby wetland (Malawi Government-UNDP, 1986). The mixing of groundwater and surface water could also provide a common route through which microbial contamination of groundwater could take place. Palamuleni (2002) observed that groundwater quality in the Lunzu Township of Blantyre in Southern Malawi was threatened by the poor sitting of sanitary and waste disposal facilities that resulted in microbiological pollution. This observation is supported by Dolozi *et al*. (in press, Malawi Journal of Science and Technology) who report a number of high levels of faecal coliforms in wells and boreholes in the municipal area of Zomba. There is a need for research into the mixing of groundwater and surface water and the evaluation of its impact on health.

Conclusions

This review indicates that there is insufficient sampling and monitoring of groundwater, analyses of potential toxic compounds and research on groundwater quality in Malawi. This scenario could be responsible for inadequate public awareness, and the resultant masking, of the potential health risks that are faced by rural people who are dependent on groundwater. There is therefore a need to conduct further studies in the following areas:

- Identification and delineation of areas with unacceptably high concentrations of iron, fluorine, salinity and sulphates
- Determination of the causes of salinity to enable appropriate mitigatory measures to be instituted
- Evaluation of the extent to which the mixing of surface water with groundwater leads to the contamination of groundwater.
- Assessment of the possibility that the stratification within basement aquifers leads to adjacent boreholes yielding groundwater of significantly different qualities.

Malawi should develop a strategy for creating public awareness of the potential health risks that are faced by people who depend on groundwater sources. At present, most Malawians take it for granted that borehole water is safe and only associate health hazards with microbial contamination. The general public is therefore inadequately informed about the issues of groundwater toxicity. The implementation of the above-mentioned proposed research could significantly contribute to creating an informed Malawian public.

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A methodological approach to recharge estimation of semi-arid basement aquifers – the central Namaqualand case

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Abstract

Recharge is important for quantifying available water resources and to identify areas that are vulnerable to pollution. Recharge is difficult to estimate reliably and the application of more than one method is usually recommended. In semi-arid basement aquifers there is generally a dearth of data, making the estimation of recharge difficult. The choice of methods will depend on the availability of data, conceptualisation of the aquifer system and the study objectives. In this paper a simple approach is followed to identify quantitative recharge estimation methods that are applicable to a particular area. In the case study three methods were identified and applied to estimate recharge. The methods are the chloride mass balance, cumulative rainfall departures and saturated volume fluctuation methods. Recharge estimates varied between <1 – 11 mm/yr. Several data sets were used to develop a conceptual understanding of regional groundwater recharge patterns through factor analysis and GIS modelling.

Introduction

The quantification of the rate of groundwater recharge is important for the optimum management of groundwater, especially in basement aquifers in semi-arid and arid regions in which the storage potential is relatively low. To meet the increasing human, agricultural and ecosystem demands on these basement aquifers, best estimates of groundwater recharge is required. Basement aquifers are used here to describe both the weathered zone and fractured rock aquifers. A systematic approach was developed to quantify natural recharge in an area considered representative of arid to semi-arid conditions: Namaqualand in South Africa. Recharge assessment approaches include both quantitative estimates and qualitative assessments. Quantitative estimates are important for the optimum managment of well fields and aquifers. The pattern of recharge is defined by, among others things, the distribution of precipitation, topography, geology, hydrogeology and land-use patterns at a given location. In the assessment undertaken for the Central Namaqualand region, recharge was estimated with the use of the chloride mass balance (CMB), Cumulative rainfall departures (CRD) and saturated volume fluctuation (SVF) methods and integrated qualitative approaches (i.e. statistical and geographical information systems).

The use of quantitative and qualitative approaches are important as the uncertainty associated with recharge estimates is dependent on the level of understanding of recharge processes, spatial density, time frequency and length of data records (Church *et al*., 2003).

Concepts and variability of recharge

Recharge concepts

Recharge is defined as that portion of precipitation that reaches the water table, either by direct contact in the riparian zone or by downward percolation through the unsaturated zone. Other sources of recharge include irrigation return flow and artificial recharge. Groundwater recharge is dependent on factors such as climate, geology (lithology and structures), geomorphology, vegetation, soil conditions and antecedent soil moisture.

Lerner *et al*. (1990) defines three principle mechanisms for aquifer recharge, namely:

- Direct recharge – the addition of water to the aquifer in excess of soil moisture deficits and evapotranspiration by vertical percolation through the unsaturated zone;
- Indirect recharge – the percolation of water through the beds of surface water bodies or ephemeral streambeds; and
- Localised recharge – this entails recharge from localised water ponding directly overlying the aquifer and percolating through the unsaturated zone.

The scale of recharge assessments is usually determined by the objectives of a study. At smaller scales, recharge estimates are important to manage localised groundwater abstraction or determine aquifer vulnerability. At larger scales, recharge estimates are important for catchment management. Groundwater recharge estimation is prone to errors due to the application of techniques that average values over time and space (Gee and Hillel, 1988).

Spatial and temporal variability of recharge

Temporal variability

Recharge in arid and semi-arid areas is primarily driven by the occurrence of periods of above-normal rainfall. The climate of southern Africa is inherently variable in time and space and changes through seasonal, annual, decadal, millennial and even longer variations (Meadows, 2001). Recharge will also be influenced by this variability. The temporal variability of recharge is a result of the incidences of rainy days as well as the intensity and duration of the rainfall events. Rainfall in dry areas is usually in the form of short intense rainstorms. It is generally documented that rainfall below a certain value, usually 400 mm, will not result in any, or insignificant, recharge (e.g. Gustafson and Krasny, 1995; Singhal 2003). This assumption is often not valid due to the fact that arid regions receive occassional intense rainspells, which generate infiltration, percolation and eventually recharge under favourable conditions. Recharge in arid and semi-arid areas is mainly indirect. In semi-arid regions, recharge may be direct if favourable conditions exist. Conditions that are favourable for recharge in turn determine the spatial extent of recharge.

Spatial variability

Geomorphic features favourable for recharge in semi-arid areas underlain by basement aquifers are indicated in **Table 1**. The alluvium (or soil cover) and weathered zones are important in that they store infiltrating water and may, under favourable conditions, transmit the stored water to the fractured aquifer. Localised recharge areas are related to the type of aquifer. The alluvial aquifers are easily recharged due to their favourable hydraulic characteristics and their position within the landscape. The structural control on the drainage systems is evident in their alignment along fracture systems associated with the underlying bedrock. The alluvial systems are major pathways for groundwater recharge to the weathered and bedrock aquifers. The distribution of rainfall over an area is determined by the movement of the frontal systems and the effects of topography (i.e. orographic rain).

Table 1: Geomorphic features that influences recharge.

Terrain	Conditions	Recharge probability
Granitic domes	Fractured	Low - Moderate
Fractured bedrock	Little soil cover	Moderate - High
Foothills/ Mountain fronts	Contact zones	High
Valleys	Fractured/ weathered	High
Rivers/streams	Significant soil cover	High
Plains	Thick soils/ Xeric shrubs	Low

Estimating recharge

Commonly used methods to estimate recharge in southern Africa

Several methods have been developed over the past few decades to determine recharge. Publications that deal exclusively with recharge and the various methods include, among others, 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). Estimation techniques are divided into physical techniques, tracer techniques and numerical models. Different techniques estimate recharge over different spatial and temporal scales (e.g. Scanlon *et al*., 2002; Beekman and Xu, 2003).

A summary of the principle approaches applicable in arid and semi-arid areas are presented in **Table 2**.

The applicability of any recharge estimate depends on the availability of data and the potential to obtain data, the characteristics of the area and, importantly, the cost of obtaining data. Recharge estimation methods and case studies are well documented. It is beyond the scope of this paper to describe all the techniques.

Bredenkamp *et al*. (1995) and Beekman and Xu (2003) provide a comparison of methods that are used in estimating recharge.

It should be noted that the accuracy and cost of a particular method are relative and depend on factors such as:

- The proximity of the study area to the research institution;
- The availability of laboratories (in-house versus commercial);
- The availability of specialised equipment (in-house versus commercial or acquisition);
- The availability of skilled human resources (in-house versus consultants); and
- The level of accuracy and quality assurance required.

Table 2: Comparison of methods for estimation of recharge (Beekman and Xu, 2003).

Zone	Method	Limitations	Applicability[2]			Rating[3]		
			Flux (mm/a)	Area (km2)	Time (yrs)	Acc.	Ease	Cost
SW	HS	Ephemeral rivers	400 - 4 000 (0.1 - 1 000)	10^{-4} – 1 300 (10 – 1 000)	0.3 - 50 (1 - 100)	2-3	1-2	1-2
	CWB	Inaccurate flow measurements	100 - 5 000	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 run-off	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 – 10 000	2	1	1
	Historical	Poorly known porosity; present ^3H 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 - 1 000)	(1 – 1 000)	(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->10 000	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)	(0.1 – 1 000)	(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, $^3H/^3He$, CFC: poorly known porosity / correction for dead carbon contribution	^{14}C: 1 - 100 $^3H/^3He$, CFC: 30 -1 000	^{14}C, $^3H/^3He$, CFC: $2*10^{-6}$->10^{-3}	^{14}C: 200 – 200 000 $^3H/^3He$, CFC: 2 - 40	3	2-3	3

[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/year; other data represent global values and are from Scanlon *et al*. (2002).

[3] Ratings for methods applied to semi-arid southern Africa (1 is cheap and 3 expensive).

Selection of appropriate recharge estimation method(s) – A decision support framework

Groundwater recharge assessments can be divided into qualitative and quantitative approaches. The type of data available will determine the recharge estimation methods that can be applied. Both qualitative data (i.e. geomorphological and hydrogeological maps, etc.) and quantitative data (i.e. water levels, rainfall, chemistry, etc.) can be used to develop conceptual models and to determine recharge rates. Recharge assessments should follow the general approach outlined in **Figure 1**.

In order to find methods that may be applicable for estimating recharge, an Excel spreadsheet was programmed to determine the suitability of various methods, based on the availability of data and the potential to gather the required data. A suitability assessment index was created to determine whether available data for a specific area are sufficient to perform a detailed recharge assessment.

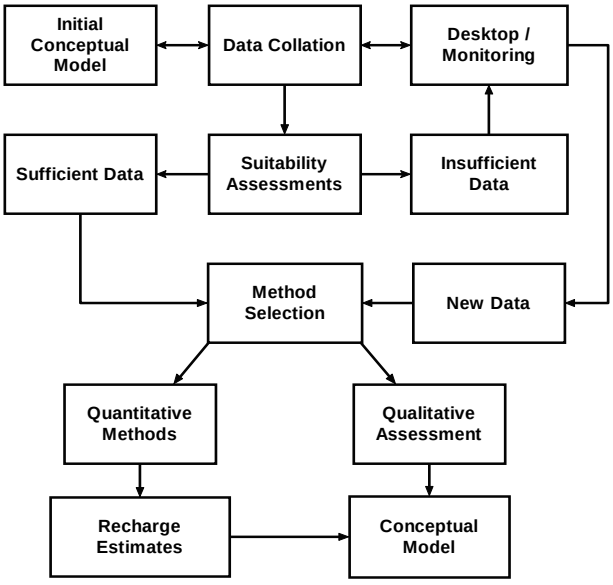


Figure 1: Generalised approach for conducting recharge assessments.

The suitability assessment is based on a simple approach whereby various data sources/types are listed. Based on the availability and the type of data, a score is given. If a particular dataset is available, it scores 0.5 and if not, 0; and if the data are quantitative, it scores 0.5 whilst qualitative data score 0. Qualitative data are important for the development of conceptual models, but cannot be used to estimate recharge. The approach is subjective and requires that it be evaluated against the objectives of the study. If insufficient data are available, the recharge study will become complex and expensive. Based on the total score of the avialable data, a recommendation is made whether recharge could be reliably estimated or whether additional data should be collected.

If sufficient quantitative and qualitative data are available, the user can proceed to the various recharge estimation methods. Different methods are listed and each method is preprogrammed with the minimum data required. The user can input the type of quantitative data available or data that will be collected within a specific project. The minimum requirements of each method are assigned a value of 1. If all the data for a specific method are available, the column is totaled and if the total equals the preprogrammed value, the applicable cell will return a "yes" or "no" that indicates whether a specific method could be used to estimate recharge.

Recharge estimation in central Namaqualand

Approach

Based on the above approach, four methods for estimating recharge (including the GIS assessment) and two for a qualitative assessment method of recharge (including the GIS assessment without recharge estimates) were identified that could be applied in the central Namaqualand area. These methods are the CMB, CRD and the SVF methods. Data that were available or collected, included water levels, rainfall, abstraction, water chemistry and position. The qualitative assessments of recharge, using statistical analysis and the GIS assessment techniques, identify areas that are, respectively, receiving recharge and are favourable for potential recharge. The National Water Archive contains data on hundreds of boreholes with water chemistry for the area. This data and data collected during an extensive hydrocensus in the area (Titus *et al.*, 2002) was analysed statistically with the use of factor analysis. A recharge potential map was produced by integrating various spatial data sets. The semi-quantitaive GIS assessment was used to produce a regional map with the use of a weighting and rating approach within ArcView™.

Physiography of the study area

The study area is located in the Northern Cape Province of South Africa and is situated in an area called Namaqualand (**Figure 2**). The area is well known for its copper and diamond mining activities as well as for its annual mass flowering after the first significant rainfall. The central Namaqualand area comprises coastal, intermediate and mountainous zones. The area has several rural and mining villages that are dependent on groundwater resources, except for the larger towns, such as Springbok, that are supplied with water via a pipeline from the Orange River.

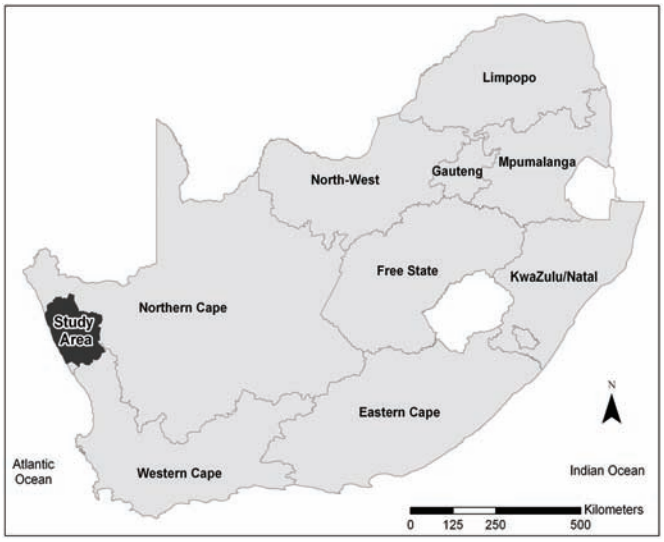
The climate of the study area is controlled by altitude, topography and distance from the sea. The region can be classified as arid to semi-arid, with rainfall occurring mostly during winter.

The mean annual precipitation (MAP) varies from 44 mm in the coastal zone area to 480 mm in the Kamies Mountains.

Higher rainfall in the higher lying areas is the result of orographic rainfall. High incidences of fog days on the West Coast contribute significant moisture to the coastal areas of Namaqualand (Olivier and Van Heerden, 1999).

Namaqualand can be subdivided into three major geological provinces (Tankard *et al*., 1982). These provinces are the basement rocks of the Namaqua Province, the volcano-sedimentary rocks of the Gariep Complex in the north-west and a Phanerozoic cratonic cover. The geology of the area has been discussed in detail by Titus *et al*. (2002) and Titus (2003).

Groundwater occurs 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. The fractured bedrock and weathered zone aquifers are hydraulically linked; the weathered zone acts as a reservoir that is able to recharge the bedrock aquifers. This process may be minimal where extensive clay layers exist between the two aquifers. The weathered zone aquifers are generally considered to be the most productive groundwater zones (e.g. Tindimugaya, 1995; Acworth, 1997). Superimposed on the basement aquifers are the alluvial aquifers that are associated with the ephemeral rivers, paleochannels and the coastal plain. Alluvial aquifers associated with the river systems are usually very shallow, namely 1 – 15 m, and in the coastal areas, tens of metres.



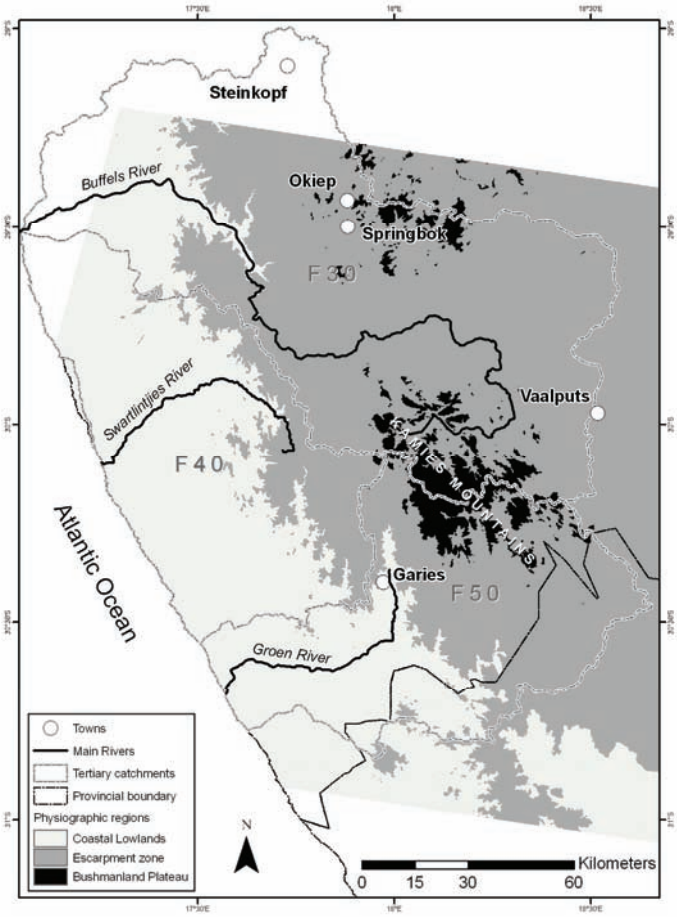


Figure 2: The study area

Tracer balance approaches

Chloride mass balance (CMB)

The fundamental basis of the CMB method is that the water mass flux crossing the plane of the water table can be calculated if most of the assumptions outlined in **Table 3** are met (Bazuhair and Wood, 1996; Wood, 1999). Because these conditions are not all met, the method does not permit accurate quantification of recharge rates. However, it is still a suitable method for a first approximation of recharge. Cook (2003) also 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, but also states that the method can provide better estimates of recharge to fractured rock aquifers than most other methods.

Table 3: Assumptions when using the CMB method and the situation in Namaqualand.

Assumption	
Chloride in groundwater originates only from precipitation (no unmeasured chloride mass from overlying, underlying or adjacent aquifers and no unmeasured run-on occur).	×
Chloride is conservative in the system.	✓
The chloride mass flux has not changed over time.	?
There is no recycling or concentration of chloride within the aquifer.	×
No evaporation of groundwater occurs upgradient from the groundwater sampling points.	?
The adsorption of chloride in soils and the vegetation uptake is considered negligible.	✓

× = not met; ✓ = met; ? = uncertain

The method is attractive to obtain a first estimate of total recharge if saturated zone samples are used. The chloride concentration in rainfall measured over the Springbok area is highly variable. Most of the rainfall that occurred in 2001 over the area was collected for chloride analysis. The values ranged from 0.17–8.59 mg/ℓ with a volume weighted concentration of 2.42 mg/ℓ. Because chloride in rainfall was only monitored at one site the results had to be extrapolated to the whole area. Chloride concentrations increase with increasing rainfall. This is based on available chloride data for the near coastal areas of South Africa (**Figure 3**). Based on a linear regression, the relationship between chloride and the amount of rainfall occurring near the coastal sites of southern Africa at a distance >15km away from the coastline, the chloride in precipitation can be estimated by (Adams *et al.*, 2004):

$$Cl_P = 0.0043(P) + 1.1214$$

Where Cl_P (mg/ℓ) is the chloride concentration of the rainfall and P is the precipitation in mm. The relationship provides a best estimate of chloride in rainfall in the absence of data. The chloride concentration of the rainfall in the study area, excluding the coastal strip and the area behind the escarpment ranges between 2 and 3 mg/ℓ. The area also falls in relatively large homogenous rainfall regions as defined by Dent *et al.* (1990). More data on chloride deposition will further reduce uncertainties.

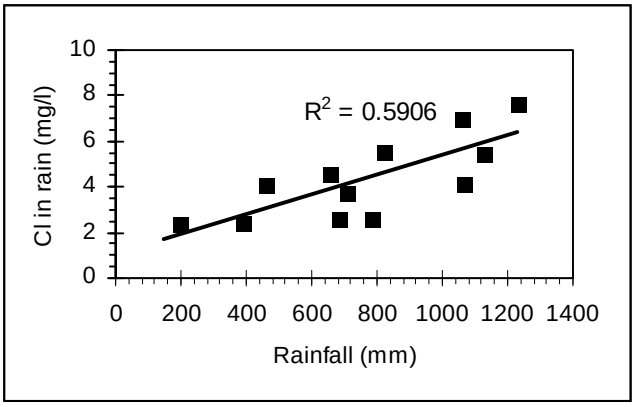


Figure 3: Relationship of chloride vs. rainfall amount for the coastal areas of South Africa (Adams *et al.*, 2004)

The results are shown in **Table 4**. The average, maximum and minimum chloride concentrations of the groundwater at the specific localities were used to determine the average, minimum and maximum rate of recharge. In the hard rock areas, higher chloride values may indicate very old water and in the alluvial aquifers high chloride values may indicate leaching of evaporitic salts during infiltration and leakage of groundwater from the adjacent hard rock aquifers. However, low chloride groundwater is also associated with the higher lying areas and alluvial zones receiving active recharge. Higher lying areas have higher recharge rates (10.6 mm/yr) compared to the low-lying areas where recharge is generally less than 1 mm/yr. There is considerable evidence that shows that groundwater recharge is significant in upland semi-arid environments (Seyfried *et al.*, 2005). The CMB method gives incorrect results for alluvial zones due to the presence of chloride that is not derived from rainfall. Excess chloride comes from infiltrated runoff.

Table 4: Recharge estimation using the CMB method.

Site	Cl_{gw} (mg/ℓ)		MAP (mm)	^1Cl_P (mg/ℓ)	Re (mm/yr)			^{2}Re (%)
	Max.	Min.			Mean	Min	Max	Mean
Buffels River	747.9	369.6	188	1.93	0.7	0.5	1.0	0.4
Bulletrap	283.7	279	172	1.86	1.1	1.1	1.1	0.7
Kamieskroon	2 229.2	99.1	212	2.03	0.7	0.2	4.4	0.3
Klipfontein	1 859	1 393	196	1.96	0.2	0.2	0.3	0.1
Komaggas	1 481.3	186.4	229	2.11	1.0	0.3	2.6	0.4
Leliefontein	209	34.8	395	2.82	10.6	5.3	32.0	2.7
Rooifontein	1 907.5	54	138	1.71	0.4	0.1	4.4	0.3
Spoeg River	1 970.8	1 575.1	200	1.98	0.2	0.2	0.2	0.1

[1]Extrapolated values. [2]Average value as a percentage of the mean annual rainfall.

Physical approaches

Cumulative rainfall departures (CRD)

Estimating recharge by correlating water levels, rainfall and aquifer storage was identified as the most promising method for application in the study area. The response of an aquifer to recharge can be assessed quantitatively and qualitatively. A qualitative approach would involve examining water level hydrographs for periods of recharge (Adams *et al*., 2004). The quantitative methods that involve water levels require a good knowledge of the storage coefficients (S-values) of the aquifers (Bredenkamp *et al*., 1995). These methods do not yield absolute values for recharge because of the interdependence between recharge and the S-value of an aquifer. Hydrographs are used to determine the spatial and temporal changes in water levels and to apply these changes, whether they are anthropogenic and/or naturally induced changes, to estimate aquifer storativity and then recharge. Conversely, if recharge is known, the S-value of an aquifer can be determined. Water levels in the study area, extracted from the Namaqualand hydrocensus database, reveal that most of the water levels occur between 5-20 mbgl. Methods that involve the use of water levels are sensitive to the depth to water level. As the water level becomes deeper, the relationship between rainfall and recharge becomes weaker. The area of influence is also an important parameter to determine. The area of influence is generally considered to coincide with areas that contribute to recharge.

Several methods exist in determining aquifer storage. These methods include the interpretation of hydraulic tests (e.g. aquifer test data), volume balance methods (e.g. saturated volume fluctuation (SVF) method),water budget methods, geophysical methods and field capacity tests (Healy and Cook, 2002). Storativity values were calculated for the study area with the use of aquifer test data and values obtained by the SVF method. S-values calculated during periods of no recharge, using the saturated volume fluctuation method (Van Tonder and Kirchner, 1990), are expressed as:

$$S = \frac{(I - O - Q)}{\frac{\Delta V}{\Delta t}} \qquad (2)$$

where: I = inflow; O = outflow; Q = abstraction; ΔV = change in saturated volume aquifer and Δt = time increment.

The SVF and CRD methods were programmed in Microsoft Excel (Visual Basic for Applications™) and include additional tools to estimate S-values (SVF and recession period methods) and recharge (SVF and equal volumes) that are used in **Table 5**. The S-values obtained by pumping test analyses are also included for comparison. Recharge estimates from the SVF and equal volume methods are in close agreement. The S-values obtained from the SVF method are an order of magnitude lower than that obtained from pumping test data. Bredenkamp *et al*. (1995) and Van Tonder *et al*. (2005) caution against the use of S-values that are obtained from pumping test data because the results can be unreliable in fractured rock environments. Recharge estimates are higher in aquifers that are associated with the alluvial and weathered zones.

Table 5: S-values calculated for the study area compared to the pumping test results.

Site	$S_{(SVF)}$	$S_{(PT)}$	$R_{SVF\ (\%)}$	$R_{Equal\ volume\ (\%)}$	$R_{SVF\ (mm)}$	$R_{Equal\ volume\ (mm)}$
Buffels River	5×10^{-3}	1.0×10^{-2}	2.8	2.5	5.3	4.7
Bulletrap	5.43×10^{-5}		0.2	0.2	0.3	0.3
Klipfontein	3.86×10^{-5}	9.5×10^{-4}	0.1	0.1	0.3	0.1
Komaggas	7.83×10^{-4}	6.6×10^{-3}	1.9	2	4.4	4.6
Rooifontein	8.5×10^{-4}		1.9	1.9	2.6	2.6
Spoeg River	1.47×10^{-4}	1.4×10^{-4}	0.1	0.1	0.2	0.2

S-values calculated from the aquifer test data in crystalline basement aquifers are usually highly erroneous due to problems of non-uniqueness, the spacing of the observation boreholes and the hydraulic connectivity of the observation boreholes with the pumping borehole. The S-values obtained from the SVF method may also be subject to the same errors as that of the pumping test data. The SVF value is probably closer to the true value because it integrates the S-value over a larger area. The values obtained with the use of the two methods give a range in which simulations, using the cumulative rainfall departure (CRD) method, can be performed. The S-values can be ascertained, relatively, on the responses of the water level fluctuations. Rapid water level rises/drops indicate that the S-value is mainly associated with the fractures, indicating lower S-values. Slow water level rises/drops may indicate storage in the fractures and matrix, indicating higher S-values. In the Buffels River area recharge is estimated to be 5 mm and in the Spoeg River less than 1 mm of MAP contributes to the groundwater resources (**Table 5**).

The CRD method uses the same data as the SVF method. The main advantages of using the CRD method in central Namaqualand are: (1) the method can accommodate variable pumping rates; and (2) the method can incorporate a lag time if water levels are deep and recharge is not immediate after a rainfall event. As the depth to the water table increases the correlation between rainfall infiltration and recharge decreases (Wu *et al*., 1996). Wu *et al*. (1996) also state that for groundwater at intermediate depth the recharge events produced by individual rainfall events merge into one single annual event although a few peaks of recharge correspond to large rainfall events or concentrated rainfall clusters. Two versions of the CRD method are available, namely the Bredenkamp *et al*. (1995) and the Xu and Van Tonder (2001) methods.

The approach was as follows:

- To calculate recharge by using the S-values derived from both the SVF and the aquifer test; and
- To calculate recharge by using both the Bredenkamp *et al*. (CRD 1995) and the Xu and Van Tonder (CRD 2001) formulas.

In most cases the two CRD versions give different results. Xu and Van Tonder (2001) found similar variations when they applied both methods to the Grootfontein dolomitic aquifer. Recharge values range from 0.1 mm to 6.4 mm of MAP (**Table 6**). Recharge to aquifers associated with the alluvial zones, like the Buffels River aquifer, receive more recharge than aquifers associated with the crystalline rocks.

The results of the revised CRD (2001) are favoured because of the following (Xu and Van Tonder, 2001):

- The revised CRD method produces a better fit between the observed and the simulated water levels;
- The method can account for variable pumping and outflow rates;
- It can account for trends in data; and
- The method does not require a large set of spatial data.

The disadvantages of the method are:

- The approach does not address parameter variations spatially; and
- Recharge is averaged over the simulated period and may be significantly higher than the average during periods of peak rainfall. It is well recognised that recharge in drier climates is associated with short periods of intense rainfall (i.e. episodic recharge).

Table 6: Recharge estimations using the two CRD methods and different S-values.

Site	Method	$Re_{SVF}(S)$ (%)	$Re_{PT}(S)$ (%)	Area (km2)	$Re_{SVF}(S)$ (mm)	$Re_{PT}(S)$ (mm)
Buffels River	CRD (2001)	3.43	6.87	12	6.4	12.9
	CRD (1995)	6.56	13.11		12.3	24.6
Bulletrap	CRD (2001)	0.06		20	0.1	
	CRD (1995)	0.12			0.2	
Klipfontein	CRD (2001)	0.04	0.92	15	0.1	1.8
	CRD (1995)	0.07	1.78		0.1	3.5
Komaggas	CRD (2001)	0.29	1.64	25	0.7	3.8
	CRD (1995)	0.58	4.92		1.3	11.3
Rooifontein	CRD (2001)	0.54	3.06	8	0.7	4.2
	CRD (1995)	0.87	5.12		1.2	7.1
Spoeg River	CRD (2001)	0.04	0.04	25	0.1	0.1
	CRD (1995)	0.1	0.1		0.2	0.2

All concentrations are in mg/ℓ unless indicated otherwise

Integrated approaches

Factor analyses

The statistical approach involves the use of groundwater chemistry and isotope data to delineate areas of recharge and discharge. This approach can also indicate regions in which direct recharge occurs (Lawrence and Upchurch, 1982). The basic assumption is that in areas that receive direct recharge the water chemistry would not show large deviations from the rainfall chemistry as opposed to water that has undergone significant chemical changes as a result of evapotranspiration prior to infiltration and long residence times that results in "old" and stagnant water with no "refreshening" from recharging rainwater.

Table 7: Factor loadings for the 12 variables selected.

Variable	Factor 1	Factor 2	Factor 3	Factor 4
Altitude (m)	-0.35	-0.51		
pH		0.38	0.50	
HCO_3	0.30		0.56	0.43
Na	0.87			
Cl	0.94			
Ca	0.91			
K	0.58			
Mg	0.89			
SO_4	0.76			
NO_3				0.88
F			0.88	
Sr		-0.87		
^{18}O (‰)		-0.86		
Eigenvalues	4.76	2.13	1.19	1.07
Cumulative % variance	36.62	53.02	62.21	70.41

Only the R-mode intrepretations are discussed here. The Q-mode interpretations appear in Adams *et al*. (2004). Four factors account for 70.4 % of the variance in the data set (**Table 7**). Factor 1 has a high loading of variables that contribute to the salinity of the groundwater in the area. Included in this factor is the altitude of the sampling point.

The altitude load is weakly negative, indicating that salinity generally increases with decreasing altitude. Groundwater flow in topographically steep areas is dynamic resulting in water with low salinity. The factors that influence factor 1 include the aquifer as well as topographical, climatological and geological characteristics. It is assumed that areas with very high salinities occur in discharge zones and the fresher water in recharge areas or close to these areas.

However, the formation of saline soils as a result of high evaporation, discharge and, to a lesser extent, irrigation return flow may, during periods of high infiltration and subsequent recharge, add to the salinity of the groundwater in recharge areas. Areas are also indicated where over-abstraction leads to the upconing of poorer quality water.

Factor 2 includes pH, strontium, oxygen-18 and altitude (**Table 7**). The grouping has high negative loadings for strontium and oxygen-18. The exact explanation for this loading is not known. The crystalline basement rocks have naturally high strontium concentrations. The presence of altitude within this factor indicates that the pH is controlled by the altitude and is a result of more acidic direct recharging precipitation. Factor 3 includes pH, bicarbonate and fluoride (**Table 7**). The fluoride in the groundwater is generally high in the central

Namaqualand area due to the influence of the geology. Elevated fluoride concentrations in the groundwater occur sporadically. The fluoride in the groundwater is mainly controlled by the pH of the groundwater. The presence of bicarbonate in this factor indicates localised recharge as HCO_3 is primarily derived from the dissolution of carbonate minerals by slightly acidic rainwater. At higher altitudes or topographically steep zones fluoride concentrations are generally low. Areas that receive direct recharge seem to be unaffected but some distance away the process becomes significant. This is an indication of residence times and flow regimes.

Factor 4 is characterised by a high nitrate and moderate bicarbonate loadings (**Table 7**). This factor is associated with pollution from agricultural activities. This factor indicates localised point recharge by nitrogen-rich water that results from animal drinking stations and possibly pit latrines. Livestock farming and the planting of livestock feed are the dominant agricultural activity.

Geographical information systems (GIS)

The GIS approach involves the evaluation of different surface and subsurface features and its influence on natural groundwater recharge. The approach is mainly of a subjective nature in which probability weights are assigned to features that may have a positive or negative effect on groundwater recharge.

By incorporating the rainfall distribution and amounts, a map of recharge from direct rainfall is produced (**Figure 4**). The method is demonstrated in Conrad and Adams (2007). Eleven data sets were collated that could be used in defining a recharge potential map. They are:

1. Lineaments + flow potential (confirmed by NDVI / SAVI)
2. Lineament density
3. Lineament intersections
4. Drainage density
5. Land cover
6. Soil type (clay content)
7. Soil thickness
8. Soil texture (% rock vs % soil)
9. Slope (degrees)
10. Depth to groundwater
11. Lithology (geology)

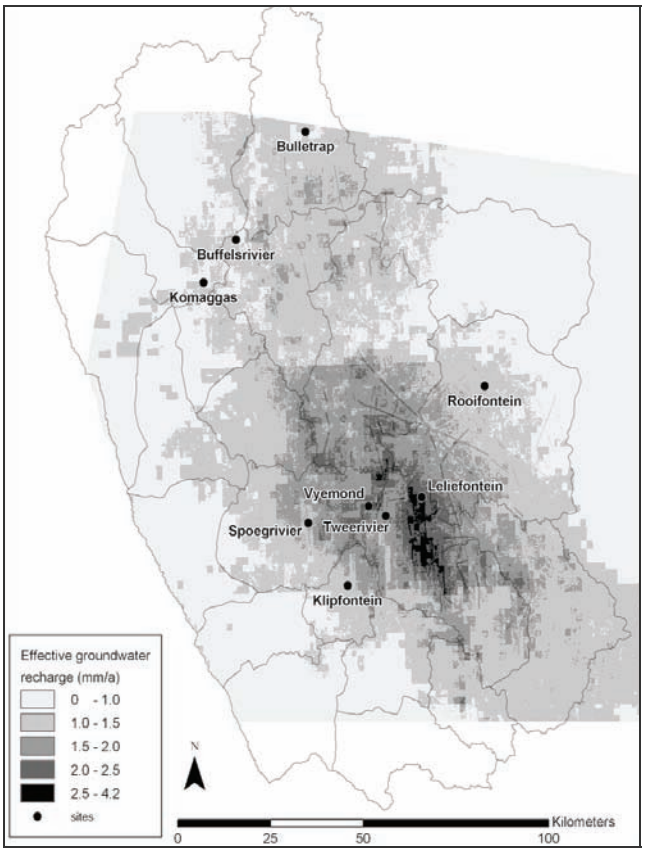


Figure 4 Recharge potential map for the central Namaqualand region.

Recharge is higher in the high-lying areas where rainfall is significantly higher as a result of orographic rains. Recharge is also higher along major linear structures that are exposed on the outcrops or that underlie the structurally controlled valleys and riverbeds. The GIS-generated results compare well with point estimates, with the use of several different methods for calculating groundwater recharge. The GIS approach is an excellent tool for visualisation and spatial analysis. However, the method is more descriptive and subjective and less quantitative than rigorous analytical approaches to recharge calculations.

The main shortcoming of the approach is that it only assumes direct vertical infiltration. Therefore a number of assumptions are needed to arrive at a groundwater recharge probability map.

Discussion and conclusions

Assessing recharge to any aquifer depends on the type of area under investigation as well as the availability and spatial distribution of good quality data. The assessment of groundwater resources is inherently complex in arid

to semi-arid crystalline terrain due to the complex geological and hydro(geo)logical conditions as well as the variability of the climate. Groundwater recharge rates over large areas are difficult to estimate due to problems associated with upscaling and data distribution.

Two approaches have been followed in this study whereby recharge was quantitatively and qualitatively assessed. Applying the CMB method and water level to rainfall relationships (SVF and CRD) gave quantitative estimates of recharge. The qualitative assessment involved the use of existing data from the area and the application of statistical and spatial techniques to assess recharge processes and patterns. The results of the quantitative analysis are shown in **Table 8**. Recharge was calculated as the average annual recharge. However, it is well recognized that only certain rainfall events during the wet winter season will contribute to meaningful recharge (episodic recharge). The aquifers associated with some of the alluvial systems of the Buffels River are being actively recharged. This is also corroborated by tritium and CFC measurements in the Buffels River (Wachtler, 2006).

Table 8: Comparison of results between the CMB, SVF and CRD methods.

Site	MAP	CMB	SVF	CRD	GIS	MRT	Aquifer
	(mm/yr)					(yrs)	
Buffels River Town	188	0.7	5.3	6.4	1.2	Modern	Alluvial/Basement
Bulletrap	172	1.1	0.3	0.1	1.0		Basement
Klipfontein	196	0.2	0.3	0.1	1.2	>30 000	Basement
Komaggas	229	1.0	4.4	0.7	1.1	Modern	Alluvial/Basement
Leliefontein	395	10.6	-	-	2.8	> 5 000	Basement
Rooifontein	138	0.4	2.6	3.06	1.3		Alluvial/Basement
Spoeg River	200	0.2	0.2	0.1	1.3	>2 000	Basement
Tweerivier	296	3.5	0.6	1.8	1.6		Basement
Vyemond	239	-	0.05	0.09	2.3		Basement

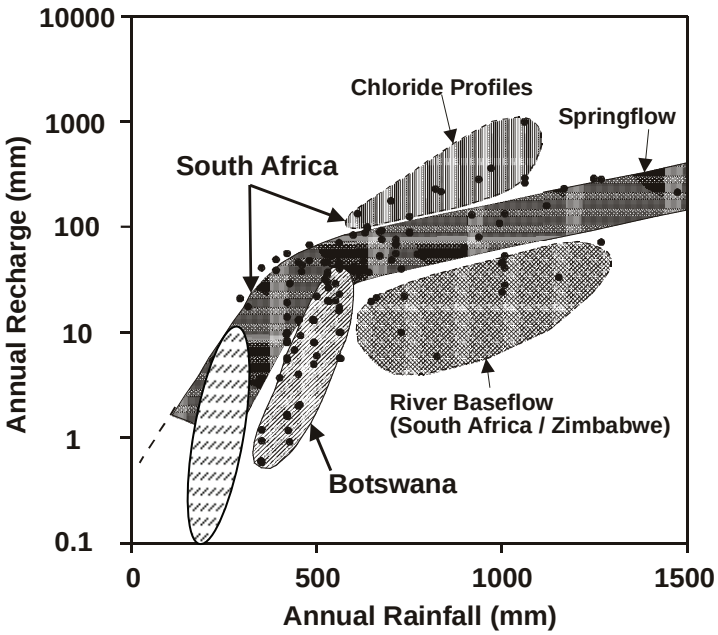


Figure 5: Recharge estimates for Southern Africa (after Beekman *et al.*, 1996; Beekman and Xu, 2003) integrating the Namaqualand estimates from the CRD method.

Regional and national estimates of groundwater recharge are important for a first overview of recharge, but more detailed information on a local or sub-regional scale is necessary for best management practices. Regionally, recharge generally increases with the amount of rainfall. The Namaqualand estimates fit well into the recharge trends for southern Africa that were identified by Beekman *et al*. (1996) and Beekman and Xu (2003) (**Figure 5**).

The approach followed in this study can easily be replicated in areas where the required data are available.

The CMB method is the most widely used approach for the estimation of recharge in arid and semi-arid regions (Scanlon *et al*., 2006). The CMB method is ideally suited for semi-arid environments and an effort should be made to develop long-term records of wet and dry chloride deposition.

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Basement aquifers Groundwater recharge, storage and flow

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Abstract

The characteristics of secondary aquifers vary widely, but more often than not the values for basement aquifers tend to be on the low side. Smaller communities that cannot afford expensive schemes often rely on them, but borehole siting, resource evaluation; and aquifer management are difficult while the vulnerability may be high. Aspects of siting and ways to improve recharge are discussed.

Introduction

What have (metamorphic) basement aquifers in common with other aquifers and what is specific to them? What is common is the dependency of recharge on rainfall and - given climate, rock type and some other variables - equilibrium between average rainfall and vegetation cover that transpires the available water. During droughts, plants perish while during high rainfall periods the main groundwater recharge takes place. What they have in common with other non-sedimentary aquifers is also the secondary porosity that is due to jointing and fracturing.

What is specific to basement aquifers is old age, generally high grades of metamorphism and a long tectonic history. In southern Africa, basement is comparatively seldom exposed as it is often covered by younger formations. Where there are no surface water supplies, the rural population has to rely on groundwater resources. In basement rocks, groundwater resources are often limited in size and/or difficult to explore.

For the last two or three decades, investigations have focussed on basement aquifers in tropical Africa. Following Wright (1992), as cited in Chilton and Foster (1995), these often low-productivity aquifers have: (i) widespread occurrence in areas of relatively high rural population density and (ii) often shallow water levels that allow low-cost exploitation (cf. also Zoppis and Zoppis, 1989).

Basement aquifers tend to have low storativity values and, if larger supplies are sought, there have to be saturated higher porosity reservoirs that can feed the basement joints and fractures, such as weathered bedrock (Detay and Poyet, 1990) or alluvial sediments. They tend to mask the underlying bedrock structures. Consequently, geophysical exploration methods and remote sensing are gaining in importance.

Recent hydrogeological research in South Africa has dealt with basement in the less densely populated arid Namaqualand (Bertram and Vandoolaeghe, 1981; Titus, Pietersen *et al.*, 2002) and in the Northern Province (Geophysical exploration: Botha, Combrinck *et al.*, 2001 and Hydrogeology of Groundwater Series: Vegter, 2001; Vegter, 2001; Vegter, 2003; Vegter, 2003b). The Windhoek aquifer (and the adjoining Khomas Hochland) of the Damara Sequence and Namibian Erathem will also be discussed because it has similar aquifer properties and is well researched.

The status quo

Borehole yields and aquifer properties

Reported yields from boreholes in basement aquifers vary widely. For instance, the transmissivities for tested Zimbabwean boreholes range between 0.5 and 100 m^2/d (Chilton and Foster, 1995).

According to Vegter (2001a, b and 2003a, b), between ⅓ and ¾ of the recorded boreholes in Regions 1 (Makoppa Dome), 3 (Limpopo Granulite-Gneiss Belt), 7 (Pietersburg Plateau) and 19 (Lowveld) in north-east South Africa were unsuccessful, i.e. with a yield of less than 0.1 ℓ/s (**Table 1**).

Table 1: Percentage of yield ranges of boreholes in Regions 1, 3, 7 and 19

	<0.1 ℓ/s	0.1 – 0.9 ℓ/s	1 - 5 ℓ/s	5>Yield<10 ℓ/s	>10 ℓ/s
Region 1	64 - 74%	20%	6 - 15%	<2%	<1%
Region 3	34 - 67%	21%	15 - 30%	1 - 3%	
Region 7	48%	21%	24%	4.5%	2.2%
Region 19	40 - 55%	38 - 50%	18 - 28%	5%	2 - 3%

Under the favourable conditions of the Dendron area (in Region 7), however, groundwater irrigation schemes abstract 8.6 Mm^3 per annum. Toens *et al*., as quoted by Titus, Pietersen *et al*. (2002), report that 37% of boreholes in Namaqualand yield 0.1 to 0.5 ℓ/s and only 5.5% produce more than 10 ℓ/s.

Borehole yields depend on the permeability of the targeted structure and the transmissivity of the rock in the area affected by pumping. In addition, the size of the reservoir (saturated pore volume), the interval between recharge events and the recharge amounts determine the long-term productivity of the aquifer (after the losses have been taken care of).

Although faults, fracture zones and dykes may reach greater depth as evidenced by hot springs, e.g. in the Lowveld in South Africa or in Windhoek, the best supplies are generally struck at depths varying between 10 – 15 m below the water table in the Lowveld and 10 to 40 m below the water table in Region 7 (Pietersburg) or in Namibia (see **Figure 1**).

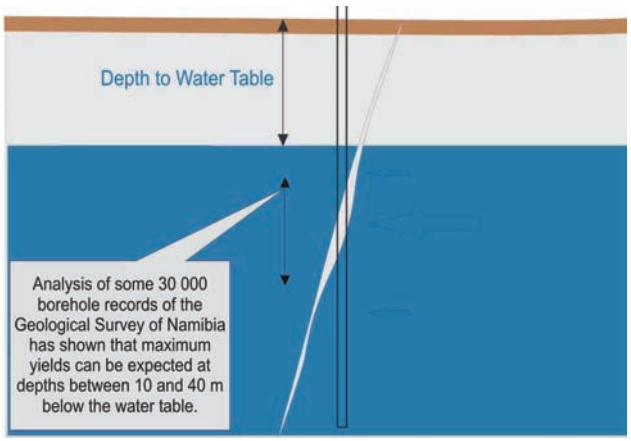

Figure 1: Depth to drilling target – at 10 to 40 m below the water table the fault/fracture permeability is the highest.

At greater depth, the walls of a fault are not yet weathered by the circulating groundwater while near the water table, at reduced hydrostatic pressure, dissolved CO_2 escapes and calcium carbonate may precipitate. Statistical analysis of some 30 000 Namibian borehole records reveal that only about 1% of boreholes in fractured rock had their main water strike deeper than 40 m below the water table (S.Z.E. Dippenaar, pers. comm.).

Site selection

Most faults and fractures are of tectonic origin. Knowledge of the stress field may help to identify the direction of tensional structures that tend to have higher permeability. Local circumstances may determine whether openings are blocked by weathering products or whether flow paths in a down-gradient direction have a greater permeability as a result of the preferred groundwater flow direction.

Rock outcrops are often covered by soil, alluvial deposits or weathering products, especially in more humid regions where it may be difficult to geologically pinpoint the targeted structure. Remote sensing, geophysical exploration methods and GIS therefore become increasingly important (Kruck, 1979; Boeckh, 1992; Greenbaum, 1992; Gustafsson, 1994; Sander, Chesley *et al*., 1996).

In South Africa, Botha, Combrinck *et al*. (2001) successfully used airborne geophysical data as an aid to identify and map regional structures in the Nebo Granite, south-east of Pietersburg in the Northern Province.

The electromagnetic technique was then used to determine whether there was weathering that was associated with the target structure. Subsequently, the average yield of the sites was 5.8 ℓ/s with only 7.6% of the sites unsuccessful. This result proves the usefulness of applying appropriate exploration methods.

The most economic option to supplement Windhoek's water demand is to artificially recharge the Windhoek aquifer when the dams have sufficient water and this requires an upgraded infrastructure to infiltrate and abstract the additional water. Amongst other things,

helicopter-borne geophysical surveys were carried out to help identify covered faults and fracture zones. The system includes geophysical sensors for collecting five-frequency electromagnetic, magnetic and gamma-ray spectrometry data as well as altimeters and positioning systems. **Figure 2** shows resistivity raw data together with existing boreholes and geologically mapped structures while **Figure 3** depicts the total gamma count. With the help of the geophysical data, target structures can be better and more comprehensively located and their relative importance can be better assessed.

An aspect that deserves more attention in southern Africa is the choice of the optimum drilling technique as well as proper cleaning and development after drilling. Cleaning is particularly important when holes are drilled in low permeability fractured rock where down-the-hole hammer drilling often blocks smaller joints and fractures.

In the beginning of the 1990s, Less and Andersen (1994) carried out hydrofracturing for the South African Department of Water Affairs and Forestry and showed the potential of improving yields of weak boreholes. Vegter (2001) summarised hydrofracturing results in Region 3. On average the improvement of 16 boreholes was 0.74 m^3/h.

Twelve successfully hydrofractured holes improved on average by 1.22 m^3/h, and the four unsuccessful ones decreased by 0.68 m^3/h. The mean yield of the 16 holes before hydrofracturing was 1.32 m^3/h with individual yields ranging between 0 and 5.9 m^3/h.

Recharge

The amount of recharge depends on a considerable number of factors that have an influence on it. Bredenkamp and Xu (2003) have listed them as follows:

- Rainfall *f*(intensity, frequency, variability and spatial distribution);
- Evapotranspiration losses *f*(temperature, wind, humidity and phreatophytes);
- Discharge losses *f*(interflow, springs, base flow, lateral flow and artificial discharge);
- Catchment *f*(soil type, thickness, spatial distribution, topographical features, vegetation); and;
- Geology *f*(rock type, fracture network and dyke occurrence).

Whether mankind is responsible for the changing climate is still being debated, but we can at least influence those factors that relate to land use.

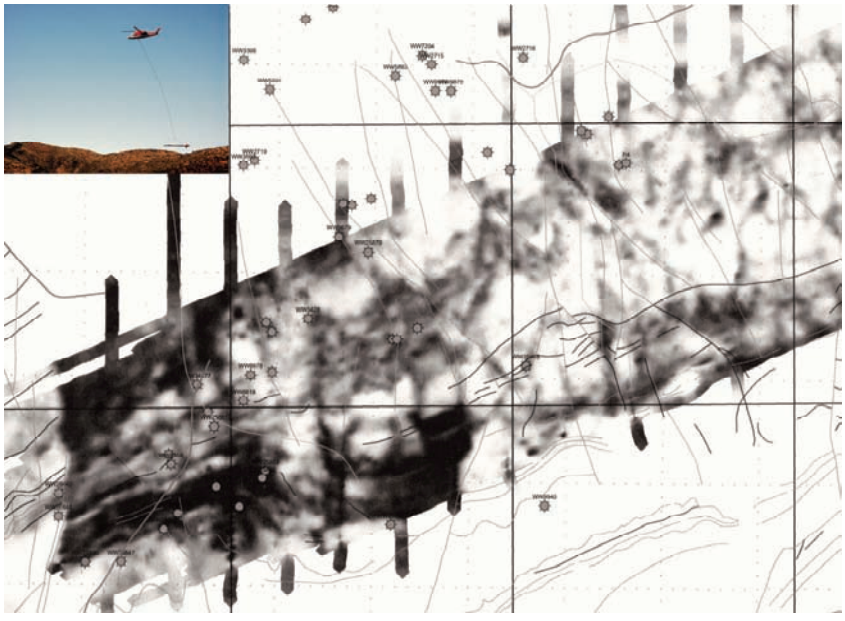

Figure 2: Helicopter-borne geophysics over the southern Windhoek Townlands (apparent resistivity raw data).

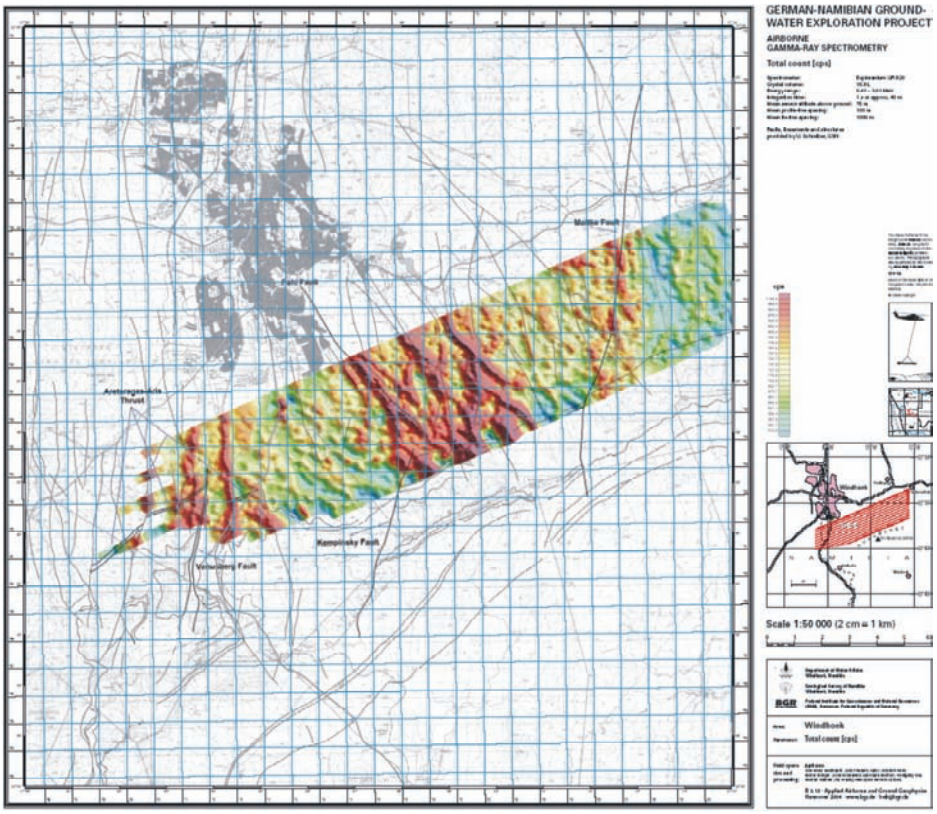

Figure 3: BGR helicopter survey: Total gamma count with overlain geologically mapped structures.

Climatic influences

Rainfall, as a source of groundwater recharge, is the most important of these factors. That we are experiencing a rapid climate change (which obviously affects rainfall) is hardly being debated amongst scientists. Since industrialisation began (implying that manmade CO_2 output might be a major reason), the sea temperature in the Arctic has risen by 3°C and the forecast is that by the year 2100 there will be an additional rise of 7°C, resulting in an ice-free Arctic during the summer months. Alpine glaciers have been receding since 1856 (Kirchner, 2003) and "Snow on the Kilimanjaro" will also be a thing of the past in the not too distant future. Hansen, Ruedy *et al*. (1996) of NASA and NOOA have observed the worldwide temperature change between 1965 and 1995 (see **Figure 4**) and for us it is of particular interest that on their maps there is a "hot spot" over southern Africa during all four seasons.

Alexander (2004) is of the opinion that "there is no evidence to support the view that climate change could cause appreciable environmental damage or increase the frequency and magnitude of floods and drought in southern Africa within the foreseeable future" and he expects "on the contrary beneficial consequences of increased global warming". The analysis of Namibian rainfall over the past decades by Hutchinson (1998) in the report by Seely, Crerar *et al*. (1998, see **Figure** 5) as well as approximately 20% reduced runoff of Okavango and Cunene Rivers in the 1990s may, however, indicate a trend towards drier conditions over the subcontinent.

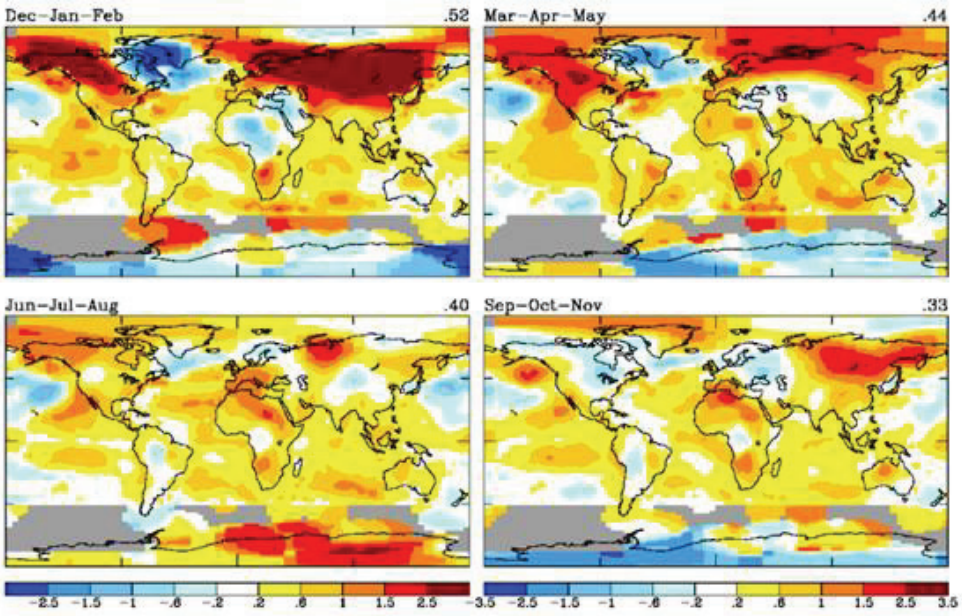

Figure 4: Seasonal mean change of the land-ocean temperature index based on the linear trend for the period 1965-1995 (Hansen, Ruedy *et al.*, 1996).

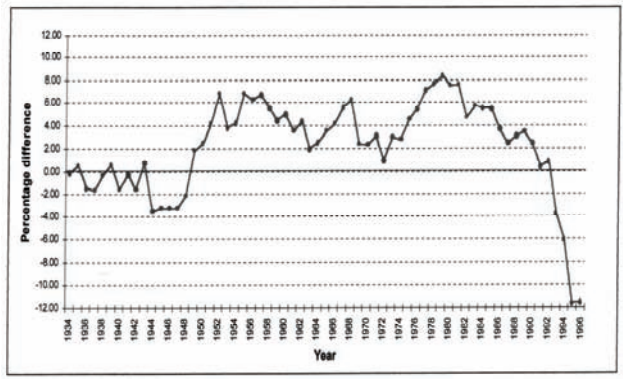

Figure 5: '20-year' running mean as percentage of long-term mean (Seely, Crerar *et al.*, 1998)

Land use

Plant water demand can be considerable. De Klerk (2004) showed in a recent study that, during the growing season, bush encroachment could abstract up to a few hundred cubic meter of water per day from a one hectare surface area. In Namibia, there is a drive to inform the population about the threats of a deteriorating environment. Scientists in South Africa (and elsewhere) are also aware of the effects of bush encroachment, alien plants and water demand of forest plantations (Kok, 1976; Vegter, 1985; Vegter, 1993; Vegter, 1995; Scott and Le Maitre, 1998; Toens & Partners, 1998; Winter, Harvey *et al.*, 1999; Parsons, 2004)

Aquifer management

If we want to manage basement aquifers properly, we should have a sufficient knowledge of:

- The amount of the mean recharge, which is variable;
- The reservoir size and characteristics; and
- The time span for which the stored water has to last.

This is also difficult to establish. However, the larger the reservoir and the more frequent (some) recharge is occurring and the smaller the water demand, the easier the management task is. In a wider sense, management includes measures that enhance the utilisation potential.

Storage

The porosity of fractured crystalline aquifers is comparatively low (**Table 2**). For the Windhoek Aquifer, Carr and Barbour (1999) give the following storativity values that were derived from pumping tests:

- Test pumping in 8 boreholes, 1989: 0.22%
- Test pumping in 11 boreholes, 1995 to 1998: 0.29%
- Drawdown-production, period 7/66 to 9/69: 0.17%

Kirchner (1976) obtained a storativity value of 0.5% during an 18 month pumping test of a production borehole (Bh 9/14). Therefore, if larger abstraction rates are to be maintained for prolonged periods, there should be either a very sizable aquifer or the aquifer should be hydraulically connected to saturated high porosity formations such as a thick regolith or alluvium that can feed the fractured aquifer for a longer period than just the short rainfall events in arid and semi-arid areas. The graben part of the Windhoek Aquifer is partly fed by the higher lying alluvium of the Usib River that collects the runoff from the southern slopes of the Auas Mountains. In more humid regions, a thick saturated regolith can often develop that recharges basement aquifers.

Table 2: Porosity values of crystalline rocks (after Titus, Pietersen *et al.*, 2002)

Crystalline rocks	Porosity [%]
Fractured crystalline rocks	< 10
Dense crystalline rocks	< 5
Basalt crystalline rocks	3 - 35
Weathered granite	34 - 57
Weathered gabbro	42 - 45

Recharge enhancement

Indirect recharge can be enhanced if the runoff is retarded. The building of a "Grundschwelle" in the alluvium of smaller rivers can do this. A "Grundschwelle" is a concrete structure that rests on the bedrock and goes up to the surface of the alluvium, blocking the base flow in the alluvium and feeding faults and fractures that follow or cross the riverbed. Alternatively, smaller or larger (earth) dam walls can create small impoundments. This method improves the yield of boreholes that are drilled in the Damara mica schist of the Khomas Hochland. While water is in the dam and a few weeks afterwards, average borehole yields are up to 10 m^3/h. Because of the generally small storage capacity of the targeted en echelon structures, yields recede to 0.5 m^3/h or less within a few weeks after the dams have dried up.

The City of Windhoek plans for similar structures at the foot of the Auas Mountains where faults or fracture zones intersect rivers so that runoff can be retarded and the recharge period prolonged.Another structure outside of Namibia, that is not well known, is the Sand Storage Dam. It was originally designed by Wipplinger (1958) and can support smaller communities. A sand storage dam can be built in catchments with predominantly arenaceous weathering products. It is constructed as a concrete wall in stages of about 1 m in height with a v-notch opening in the middle (see **Figure 6**). During floods coarser sediment is retained while the suspended silt and clay is carried away with the overflowing and outflowing water. Once the sand has reached the height of the wall, a new section is built. In this way dams of several metres in height with a considerable storage capacity are built where the water is largely protected from evaporation. Water is abstracted either through an outlet at the foot of the wall, a well in the retained sediment or in a borehole nearby that is fed through fractures that are recharged by the dam.

Artificial recharge

If there is a periodic surplus of surface water or if reclaimed water of suitable quality is available, artificial recharge provides a further possibility to enhance the aquifer utilisation potential (Murray and Tredoux, 2002). Depending on the availability and cost of alternate resource development, this may be a feasible option. In developing countries, the scarcity of capital does not permit transportation of water from distant sources (WMO, 1979).

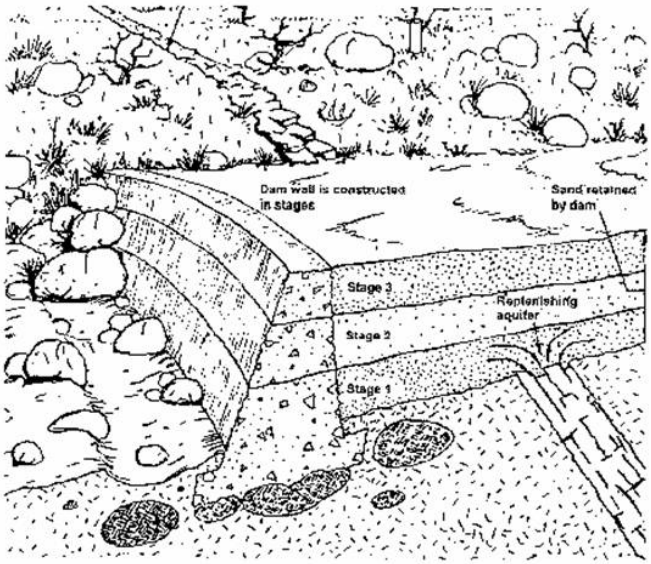

Figure 6: Sand storage dam (Seely, Crerar *et al.*,1998)

In the case of Windhoek (see the most recent reports by WCE, 2003; Windhoek Aquifer Consultants, 2004; and Murray, 2002, for further reference), artificial recharge is the most economical option to increase the supply capacity to the city, amongst other things because the

scheme will be an "add-on" system that can be extended as the need arises. More than 20 Mm^3 can be stored in a water-level depression some 30 to 50 m deep, about 4 km wide and 8 km long, which has been created through the abstraction of more than 100 Mm^3 since the beginning of the 1950s.

Flow

It is essential for detailed exploration of these aquifers to understand how water flows in fractured rock aquifers (and how pollutants spread). In his Darcy Lecture, (Shapiro, 2004) showed that, at metre scale, permeabilities vary from as little as 10^{-10} m/s to highly conductive fractures with K-values in the 10^{-4} range (see **Figure 7**). Bulk rock permeability determinations over larger distances yielded values in the order of 10^{-7} m/s.

In fractured rock aquifers there is hardly ever piston flow and individual solutes will move in varying direction with varying velocity from higher head to lower head. In **Figure 8** water can flow directly from A to B, follow the longer path via C at a correspondingly lesser gradient or stay unmoved in blocked opening D.

In Windhoek, Van Wyk, Murray *et al*. (2000) did tracer and dilution tests during a borehole injection test in a borehole that is sited on a fault in fractured quartzite aquifer. The injection test formed the basis of a study into the artificial recharge to the Windhoek aquifer. After 187 days of injecting water at a rate of 17 ℓ/s, the tracer Fluorescein was added to the injection water and monitored in a borehole 786 m away. After 216 minutes, the tracer arrived at the observation borehole, giving a flow velocity of 3.6 m/min.

^{14}C age determinations of samples from the Windhoek Aquifer yielded apparent ages between about 6 800 years at the foot of the Auas Mountains near the catchment boundary and 21 800 years at the site of the former hot springs some 10 km NNW. This corresponds to equilibrium Darcy flow velocity of about 0.7 m/a and is in good agreement with the values cited by Shapiro above.

Highly permeable structures, such as the one investigated by Van Wyk, Murray *et al*. (2000), can yield permeability values that are even 2 orders larger than the range given in **Figure 7**. This is good news if one is looking for high-yielding boreholes. At the same time it increases the vulnerability threat in terms of both over-abstraction and potential pollution.

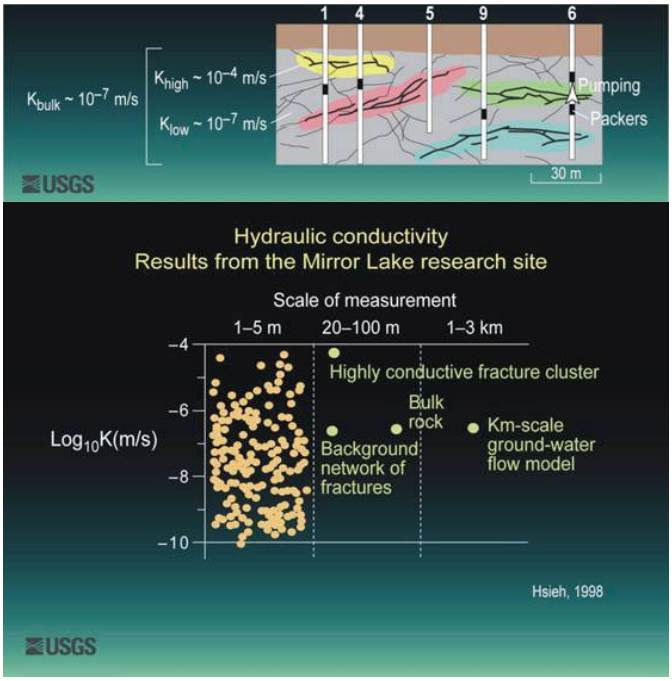

Figure 7: Flow paths and permeability determination in fractured rock at the Mirror Lake research site (top) and effective permeability over larger distances (bottom) (source: Allan Shapiro, USGS).

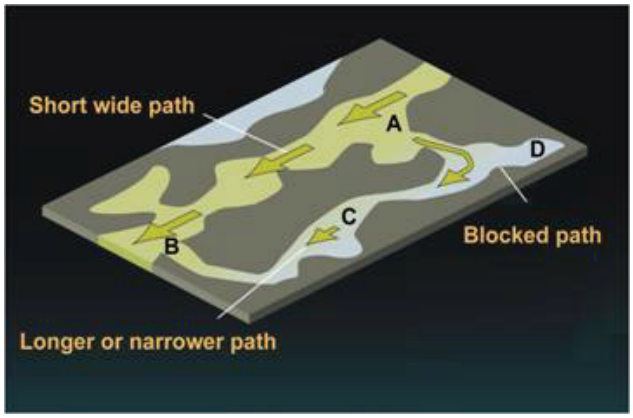

Figure 8: Flow in fractured rock aquifers

Conclusions

Basement aquifers are especially important for the rural population, which cannot afford expensive water supply systems.

More sophisticated geophysical and remote sensing techniques are required to locate promising target structures under overburden. Regional stress analysis may help to identify more favourable (tensional) fault/fracture directions. The yield of basement aquifers is often limited because of comparatively low permeability and storativity although they occasionally support larger irrigation schemes.

Recharge is ideally from saturated porous regolith or alluvium. Global warming may have a serious impact on recharge rates in southern Africa. Water conservation and better use of the resources is therefore advocated while pollution should be guarded against. Bush clearance, natural indirect recharge enhancement and artificial recharge are some of the options that can be considered in order to improve water supplies.

Considering that with an increasing population and the improved living conditions of rural communities, the water demand will rise, water reclamation could significantly contribute to meeting water needs (Clayton, Van Vuuren *et al.*, 1982). In Windhoek, for example, water reclamation accounts for one-third, which is up to 7.5 Mm^3/a, of the present water demand.

Improved (geophysical) siting techniques; recharge enhancement measures; aquifer protection; and resource evaluation and management are the topics that need most attention and – together with public awareness and demand management - promise the highest returns.

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Factors that control sustainable yields in the Archean basement rock aquifers of the Limpopo Province

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Abstract

One of the challenges of a conceptual model for basement aquifers and a precursor for sustainable aquifer management is to understand the factors that control high borehole yields in the crystalline terrain. The basement rocks of the Limpopo Province are geologically and structurally complex, shaped by multiple tectono-metamorphic events that span at least 600 million years (Kramers *et al.*, 2006). Therefore the groundwater flow and the hydraulic properties of the basement aquifer depends on a number of factors such as weathering; climate; lithology; geological structures, including neo-tectonic stresses, presence and thickness of Quaternary or alluvial sediments; depth of weathering; age of landforms (erosion surfaces); and relief. This study indicates a number of control factors that influence the productivity of boreholes within the basement rocks of the Limpopo Province. Knowledge of the dominant factors in each area or groundwater zone is useful for groundwater exploration projects. Despite the similarities in some of the investigated control factors that influence borehole productivity on a regional scale (e.g. rivers and lineaments), the heterogeneity of the aquifers suggest an overriding influence of local features such as small-scale structures.

Introduction

The Department of Water Affairs and Forestry (DWAF) has proposed sustainability as a concept that will resolve water-use issues. Together with equitable access to water, sustainability is one of the main principles of the National Water Act of 1998. However, the meaning of the word 'sustainability' is often contested and it is operationally and conceptually one of the most complex concepts that modern science has faced (Cabezas and Fath, 2002). Early efforts to define sustainable yield brought forth certain considerations and determining factors that limit the definition to specific environments and associated acceptable changes over time. When considering, for example, the spatial scale of an aquifer system, it is important to understand the associated scale of influence. Withdrawals from an aquifer might have a severe impact on individual ecosystems locally, but might be considered minor in terms of recharge and discharge for the catchment as a whole (Maimone, 2004). Thus the position, spacing and depth of boreholes strongly influence the possible sustainable borehole yield (Seward *et al.*, 2006). Understanding the behaviour of groundwater and the varying factors that control borehole productivity can be regarded as a first step in determining any form of sustainability, whether it is on the catchment, basin or borehole scale.

The variability of borehole yields in Archean crystalline basement rocks is usually dependent on one factor or a set of controlling factors (Wright, 1992; Neves and Morales, 2007). Regolith thickness, lithology, climate (past and present), age of land surface, relief, tectonics and structural geology are a complex pattern of factors that are responsible for determining borehole yields. The common viewpoint (e.g. Chilton and Smith-Carington, 1984; Wright, 1992) of crystalline aquifers is that long-term borehole productivity relies on the presence of a weathered material that overlays the fractured rock. Even where the basement is fractured, if weathering is thin or absent, the available groundwater resource is likely to be small and unreliable unless an alternative source of indirect recharge to the fractured basement, such as a river or associated alluvium, is present. The relationship of the weathering process to permeability is complex and variable and often more advanced weathering products are found in regolith that overlays older erosion surfaces (e.g. African). However, the significant differences of weathering thickness and borehole productivity on the erosion surfaces suggest overriding influences of other factors (e.g. tectonics and structural geology). Highly fractured zones, which act as regional hydraulic conductors, may be ideal target areas for productive boreholes if clay has not filled the discontinuities due to more recent weathering or the

fractures are not being closed up due to the influence of neo-tectonic stress fields and their preferred orientation. The influence of topography on borehole productivity on a regional scale may be attributed to plains that develop superficial coverings that allow for higher recharge as well as to the thickness of the unsaturated zone. In basement rocks, shallow water levels generally reflect a subdued surface topography, implying aquifer recharge on the broad interfluves and groundwater discharge in surface depressions. Therefore boreholes located on slopes and hill tops are often much less productive than boreholes located in valleys. It is apparent that the productivity of boreholes, and therefore their sustainable yield, depends on a complex combination of factors, in addition to the particular characteristics of an area.

Despite the fact that a great portion of the population of the Limpopo Province of South Africa depends on water supply from basement rock aquifers, few studies have been done on the behaviour and factors controlling the yields of boreholes. In the current study, an attempt is made to identify the most common factors that influence the yields and transmissivities of boreholes within the Limpopo Province.

The study uses a dataset that was established as part of the Limpopo Groundwater Information Project (GRIP), which was initiated by the Department of Water Affairs and Forestry. Under the GRIP framework, single-well pumping tests were primarily conducted to recommend sustainable abstraction rates for rural water supply boreholes. The determined 'sustainable abstraction rates' are based on the FC programme (Van Tonder *et al*., 2002), which typically addresses the long-term assurance of water supply from a borehole that is based on available drawdown figures and abstraction rates for a single borehole and by no means on the sustainable borehole or aquifer yield as described by, for example, Kalf and Woolley (2005).

An initial assessment of the dataset within the study area was limited to one thousand boreholes, but has since been increased to over two thousand boreholes that are distributed over an aerial extent of approximately 16,000 square kilometres. The compiled dataset consists of the following hydrogeological parameters: static water level, *SWL*; transmissivity, *T*; sustainable yield, *sust Q*; and borehole depth (*BH depth)*. In order to identify factors that influence the hydrogeological parameter, the dataset was spatially subdivided with the use of available GIS layers. Selection criteria included lithology, erosion surfaces, topographical setting as well as proximity to rivers, structures, lineaments and faults. The (arithmetic) mean values of the selected subsets were compared to the corresponding population mean and a one-sided Student *t*-test was used to determine the level of confidence that the specific value is larger or smaller than the population mean. This approach ensures an unbiased assessment of a large number of influencing factors. An inherent flaw is that the assessed boreholes were not drilled randomly (statistically), but after preliminary site investigations. In this regard the dataset is biased towards one or the other anomaly and higher yields are to be expected due to the "pre-selection" of samples from a theoretical population of boreholes in basement aquifers. However, the large number of assessed boreholes of varying success compensates partially for this statistical bias.

Description of study area

Physiography

The study area falls within the Pietersburg Plateau and Lowveld groundwater regions as defined by Vegter (2001). The boundaries of these two regions coincide roughly with the watershed (escarpment) of two surface water management areas in the middle of the focal area (**Figure 1**), the Limpopo (WMA1) and the Levuvhu/Letaba (WMA2) water management areas. The Pietersburg Plateau, east of the watershed, is flat and almost featureless with the Blouberge towards the west and the Soutpansberg towards the north-east forming topographic highs. Partridge and Maud (1987) described the southern third of the plateau as a dissected African surface with mountainous ground above the African surface found in the extreme south-western and south-eastern corners of the region. The northern two-thirds is classified as undifferentiated post-African surface. The climate of the plateau is characterised as semi-arid with a mean annual rainfall that ranges from of 300 mm to 700 mm per annum.

The Lowveld region to the west of the watershed is characterised as a plain that undulates moderately with highly irregular, almost hilly, surfaces. The transition from the Plateau to the Lowveld is a sloping, strongly undulating surface in the upper catchment of the Levuvhu/Letaba WMA.

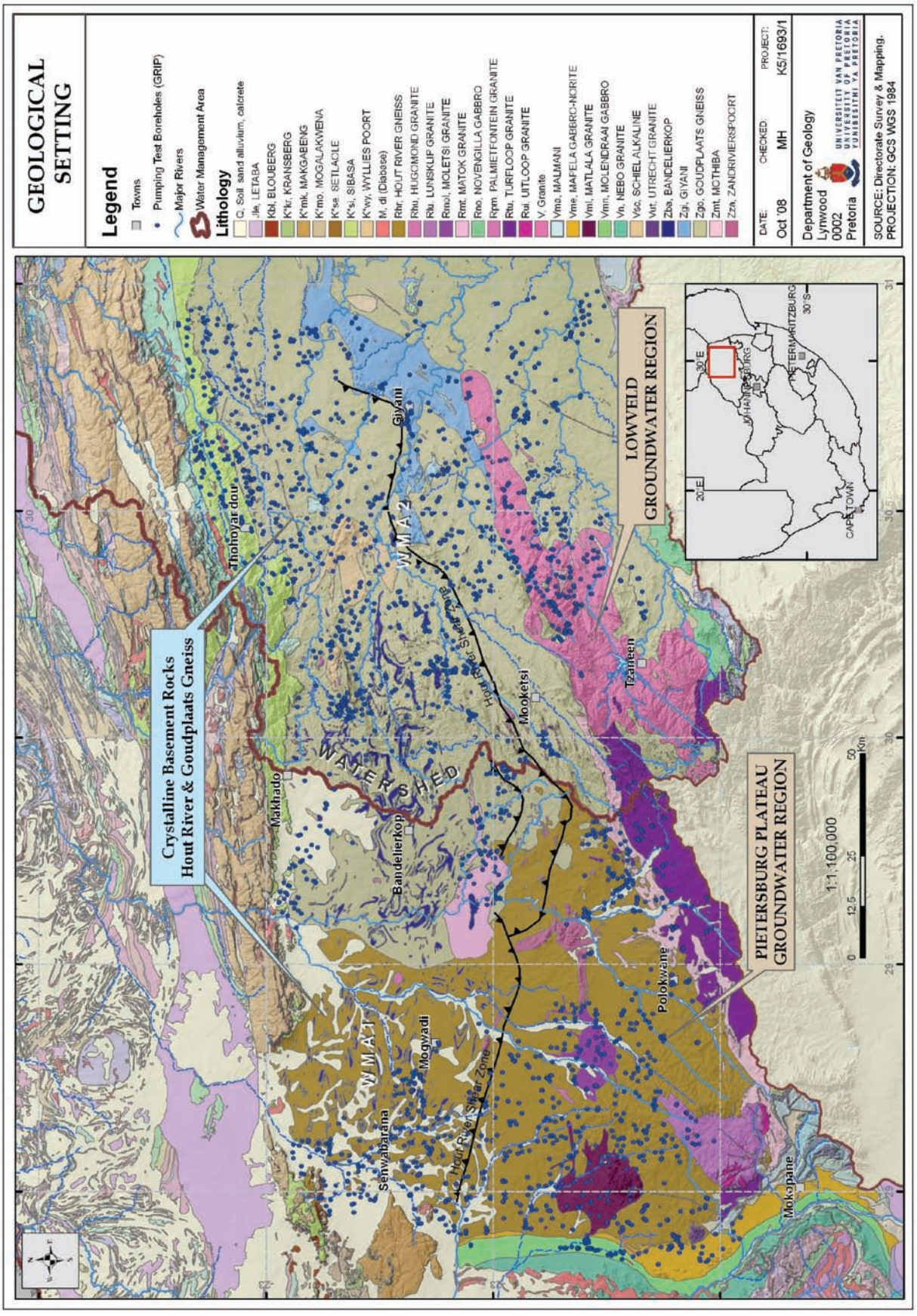

Figure 1: Location of the study area, displaying geology and borehole distribution

The Lowveld is characterised by subtropic temperatures and is semi-arid with a fairly high humidity. Against the escarpment, orographic rain occurs frequently and the mean annual rainfall varies from 650 mm in the north to over 1000 mm in the south. The land surfaces of the Lowveld include the dissected Africa surface, that is directly east of the central escarpment, and a dissected post-African surface further east. Rivers in both regions have water throughout the wet season, but are otherwise dry.

Geological setting

The rectangular study area covers the crystalline basement rocks between the Pietersburg Greenstone Belt in the south to the Soutpansberg basaltic lavas in the north. The western margin is delineated by intrusive rocks of the northern lobe of the Bushveld Complex and the eastern margin by the Giyani Greenstone Belt (**Figure 1**). The geology of the project area entails almost entirely Archaean basement lithologies, dominated by two lithostratigaphical units in the basement complex, namely the Hout River Gneiss, which underlays the larger part of the Pietersburg Plateau, and the Goudplaas Gneiss which underlays the larger part of the Lowveld groundwater region. Other younger granitic intrusions occur as scattered bodies and batholiths (**Figure 1**).

Structurally, the study area is located in the north-eastern part of the Kaapvaal craton and the southern marginal shear zone (SMZ) of the Limpopo Mobile Belt. This northward dipping zone is referred to as the Hout River Shear Zone (**Figure 1**). The Hout River Shear Zone incorporates the ortho-amphibole isograd in its hanging wall so that relatively low-grade basement rocks to the south are separated from higher (amphibole and granulite) grade rocks in the SMZ hanging wall. Diabase dykes occur throughout the region and form dyke swarms where they outcrop more densely in the north-eastern part of the study area. The dykes show a dominant north-east trend in the study area (**Figure 4**). and are associated with 2.7 Ga Ventersdorp Supergroup trends (Uken & Watkeys, 1997), which formed either in response to the Limpopo orogeny (Burke & Dewey, 1973) or by crustal extension due to mantle plume activity (Hatton, 1995). Later Karoo dolerites sporadically cut through the older dykes, but usually follow the same intrusion paths as their Archaean predecessors. The Hout River Shear Zone was probably one of the controls of the dyke emplacement in the study area with more dykes observed north of the HSZ (in the SMZ) than to the south of it. Alluvial deposits are present along the lower reaches of the major rivers.

Structural and tectonic context

The dominant NE-SW extensional neo-tectonic regime in the study area resulted from the unbroken lithosphere's resistance to relative rotation between the Somalia Plate and the Africa Plate (Bird *et al.*, in 2005). Normal faults and open joints were formed mainly in the NW-SE direction, and therefore structures inherited from the Precambrian tend to be open under the current neotectonic stress regime (**Table 1**). Shallow-dipping joints (those inclined from zero to forty-five degrees) are well spread out over the entire study area (**Figure 2**). Whereas some of these joints could have formed due to dilatation (i.e. pressure release as a result of erosion or plutonism), it is believed that many of these joints are actually tectonically induced, suggesting that the study area was at one stage subjected to compression. Such regime would favour the formation of open discontinuities 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. Joints striking NE-SW were probably reactivated during successive tectonic events (for example the N-S extension during later Karoo times) and lie parallel to one of two strong preferred lineament orientations (NE-SW and NNE-SSW) as displayed by the dolerite dykes in the study area.

As geological time passed, the extensional tectonic stresses were continuously alleviated along the structures, which began to act as crustal weakness zones. In some areas, tectonism and metamorphism were both so intense that they cannot be unraveled. Due to the shearing complexity and extent of these zones (e.g. Hout River Shear Zone), it is difficult to assess their influence on well productivity, but the mylonitic rocks, which occupy the shear zones, are likely to be highly brittle, weathered and more fractured than the surrounding gneiss and granites, providing obvious targets for water abstraction.

Table 1: Measured joint quantities.

Dip angle of joints	Comment	Amount of joints	Percentage
Shallow (0˚ - 45˚)	Usually thrust (compression) induced or decompressional	36	9.45%
Moderate (46˚ - 79˚)	Usually tensionally induced	188	49.34%
Steep (80˚ - 90˚)	Strike-slip, or Mode I tensional joints	157	41.21%
All joints (0˚ - 90˚)		*381*	***100%***

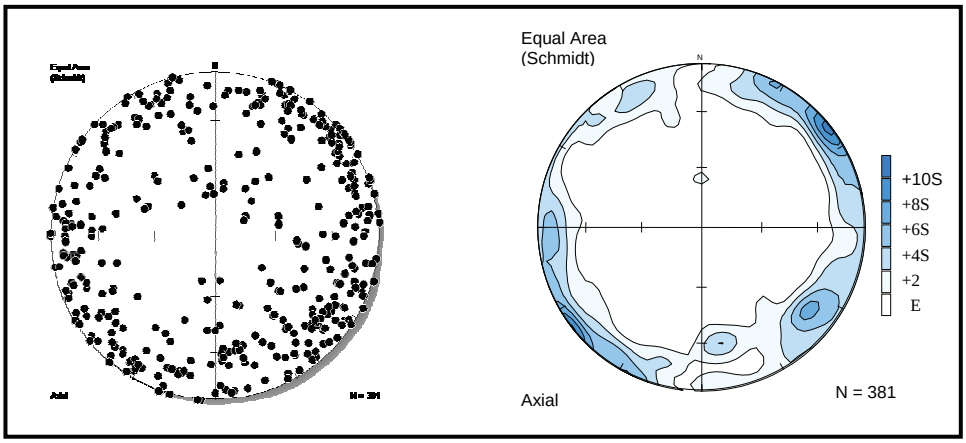

Figure 2: Poles to all joint planes and density distribution of all poles to joint planes.

Control factors on borehole productivity

General overview

The measurement of the productivity of boreholes in the study area is based on the transmissivities and recommended 'sustainable abstraction' rates that were obtained from over two thousand borehole entries in the GRIP database (**Figure 1**). It should be noted that different consultants and contractors were used to conduct the pumping tests over a number of years within the GRIP project framework. The data is therefore potentially influenced by long-term climatic fluctuations, seasonal rainfall and changes in groundwater extraction by farmers, communities and mines. Nevertheless, these factors were deemed to be of relatively low significance and do not fundamentally limit the veracity of the study. The distribution of *T*-values obtained from the GRIP datasets, based on the two groundwater regions, are shown in **Figure 3**.

The distribution is positively skewed and follows a lognormal distribution. Such distribution is frequently reported in regional studies of soils, fractured aquifers (e.g. Hoeksema & Kitanidis 1985, Nachabe & Morel-Seytoux, 1995) as well as for basement aquifers in Africa (Razack & Lasm, 2006). While transmissivities between 5 m^2/d and < 40 m^2/d can be generally expected, several boreholes with significantly higher T-values (outlier) push the arithmetic mean of transmissivities to 25 and 41 m^2/d respectively.

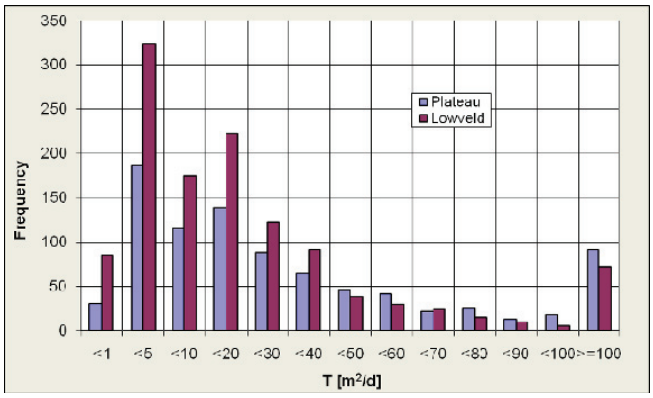

Figure 3: Distribution of transmissivities T [m^2/day] for the Pietersburg Plateau and Lowveld groundwater regions.

As a first step, the boreholes were grouped in accordance with the two groundwater regions found in the study area and therefore similar to the two surface WMA's 1 and 2. **Table 2** shows the corresponding mean values and levels of confidence that the specific mean is larger or smaller than the total population mean calculated on the basis of a one-sided Student *t*-test.

Geological influence on borehole productivity

To investigate potential geological influences, the boreholes were grouped in accordance with the geological or lithological setting (**Table 3**). Buffer zones that were used for the spatial extraction of boreholes included a 500 m inside and outside buffer surrounding granitic outcrops to represent the "granitoid (batholiths) contacts" and a 300 m zone adjacent to river courses to represent boreholes drilled "along rivers" (alluvial deposits).

Boreholes that target rivers (supposedly in alluvial deposits) and especially the Hout River Gneiss or the Bandelierskop intrusions are the most productive regional units as indicated by the above-average borehole yields and transmissivities (**Table 3**). On the other hand, boreholes in the granite intrusions have the lowest production capability and yield. Although most of the study area is located on crystalline rocks, the presence of Quaternary cover 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 suggests that high yields could be obtained in their sites of occurrence. While the geological analysis of the data set indicates the obvious, i.e. that the geology influences borehole productivity, the complexity of crystalline basement aquifers suggests that a larger number of factors influence their yield, as discussed in the subsequent section.

Table 2: Determined hydrogeological parameter based on the groundwater regions.

Determinant	Total N	BH depth [mbs]	SWL [mbs]	Sust Q [ℓ/s per 24h]	Transmissivity [m²/d]
Population mean	**2 093**	**60.50**	**15.31**	**1.21**	**31.85**
Pietersburg Plateau	1 213	62.83	15.99	1.62	41.13
Significance [%]		99.03	94.46	100.00	99.99
Lowveld	1 213	58.80	14.82	0.91	25.11
Significance [%]		98.55	94.89	100.00	100.00

The productivity of boreholes located in the Pietersburg Plateau is significantly higher than in the Lowveld region with average *T* values of 41.1 m²/d and 25.1 m²/d respectively.

Table 3: Determined hydrogeological parameter based on the geological setting of boreholes.

Determinant	Total N	BH depth [mbs]	SWL [mbs]	Sust Q [ℓ/s per 24h]	Transmissivity [m²/d]
Population mean	**2 151**	**60.89**	**15.25**	**1.20**	**31.63**
Bandelierskop Metapelites	36	67.77	22.25	1.46	45.58
Significance [%]		90.92	99.75	75.23	87.73
Goudplaats Gneiss	844	59.61	15.87	1.01	27.21
Significance [%]		92.83	94.91	100.00	99.60
Hout River Gneiss	392	63.15	17.21	1.73	47.74
Significance [%]		92.36	99.80	100.00	99.98
Granitoid contacts	131	58.57	14.45	1.18	29.96
Significance [%]		80.09	82.08	55.27	66.70
Quarternary cover	146	66.80	17.96	1.31	32.58
Significance [%]		98.60	98.60	82.35	59.29
Along Rivers	286	58.39	11.28	1.52	36.92
Significance [%]		91.70	100.00	99.93	95.85
Granite Intrusion	240	61.29	11.94	0.65	13.50
Significance [%]		58.78	100.00	100.00	100.00
Greenstones	76	60.88	16.45	0.92	29.34
Significance [%]		50.12	81.58	99.66	61.98

Lineament domains

Perhaps one of the most differentiating structural features of the study area is the spatial distribution and orientation of dyke swarms (**Figure 4**). 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). Stettler *et al*. (1989) subdivided parts of the Kaapvaal Craton and the Limpopo Belt in accordance with the prevailing aeromagnetic lineament pattern into five domains (**Figure 4**). The varying magnetic signatures of the domains most probably indicate differences in the tectonic history of the lithospheric rocks into which the dykes intruded. The magnetic lineaments therefore show an orientation that is dictated by an inherent fracture pattern in each particular domain of the crust. Recognition of these domains therefore provides a tectonic and morphostructural framework to describe hydraulic parameters on a regional scale.

The most common strike direction of lineaments in domain A is ENE. This direction is especially dominant along the southern boundary of domain A, where the strike direction of lineaments is probably controlled by the northward-dipping shear zones. Although the northern boundary of domain A lies north of the Soutpansberg trough, our area focuses on the crystalline rocks towards the south. Due to the considerable large east-west extent of domain A with varying lithologies, it was decided to differentiate domain A into the Hout River (HR) and Goudplaats (GP) gneiss portions. The magnetic lineaments in domains B and D occur infrequently, show less orientation preference and are, together with domain C and E, situated in areas of low-grade metamorphism. The high degree of random lineament orientation in domain B and D are attributed to oblique cuts across the granitoid intrusions and the Pietersburg and Giyani greenstone belts. Lineaments in domain C are mostly curved and show a preferred lineament orientation, which varies between NNE in the west and NE in the east.

The GRIP dataset was subdivided in accordance with the domains and the average hydrogeological parameters for each domain was determined and compared to the population mean (**Table 4**).

Domain A (Hout River Gneiss) can be regarded as the most productive groundwater domain with yields and T-values significantly above the population mean, while domain D with a less pronounced lineament orientation shows the lowest groundwater-yielding domain (statistical significance of > 99.99% based, on *t*-test, **Table 4**). Domain A (Goudplaats Gneiss) and domain C have similar average hydrogeological parameters, which suggests lithological or weathering controls on borehole productivity rather than lineament orientation. Domain B has above-average yields and transmissivities, but high-yielding boreholes within the domain could not be attributed to specific orientations of lineaments alone.

Table 4: Determined hydrogeological parameter based on the magnetic orientation domains.

Determinant	Total N	BH depth [mbs]	SWL [mbs]	Sust Q [ℓ/s per 24h]	Transmissivity [m²/d]
Population mean	**2 151**	**60.89**	**15.25**	**1.20**	**31.63**
Domain A Hout River Gneiss	243	69.52	19.93	1.92	54.64
Significance [%]		100.00	100.00	100.00	100.00
Domain A Goudplaats Gneiss	532	62.10	15.50	1.00	28.95
Significance [%]		90.34	75.18	99.98	92.76
Domain B	645	60.96	13.91	1.56	36.76
Significance [%]		59.06	99.94	100.00	96.75
Domain C	383	55.98	16.63	1.00	28.66
Significance [%]		99.96	99.17	99.89	89.35
Domain D	379	57.46	12.07	0.76	17.30
Significance [%]		98.47	100.00	100.00	100.00

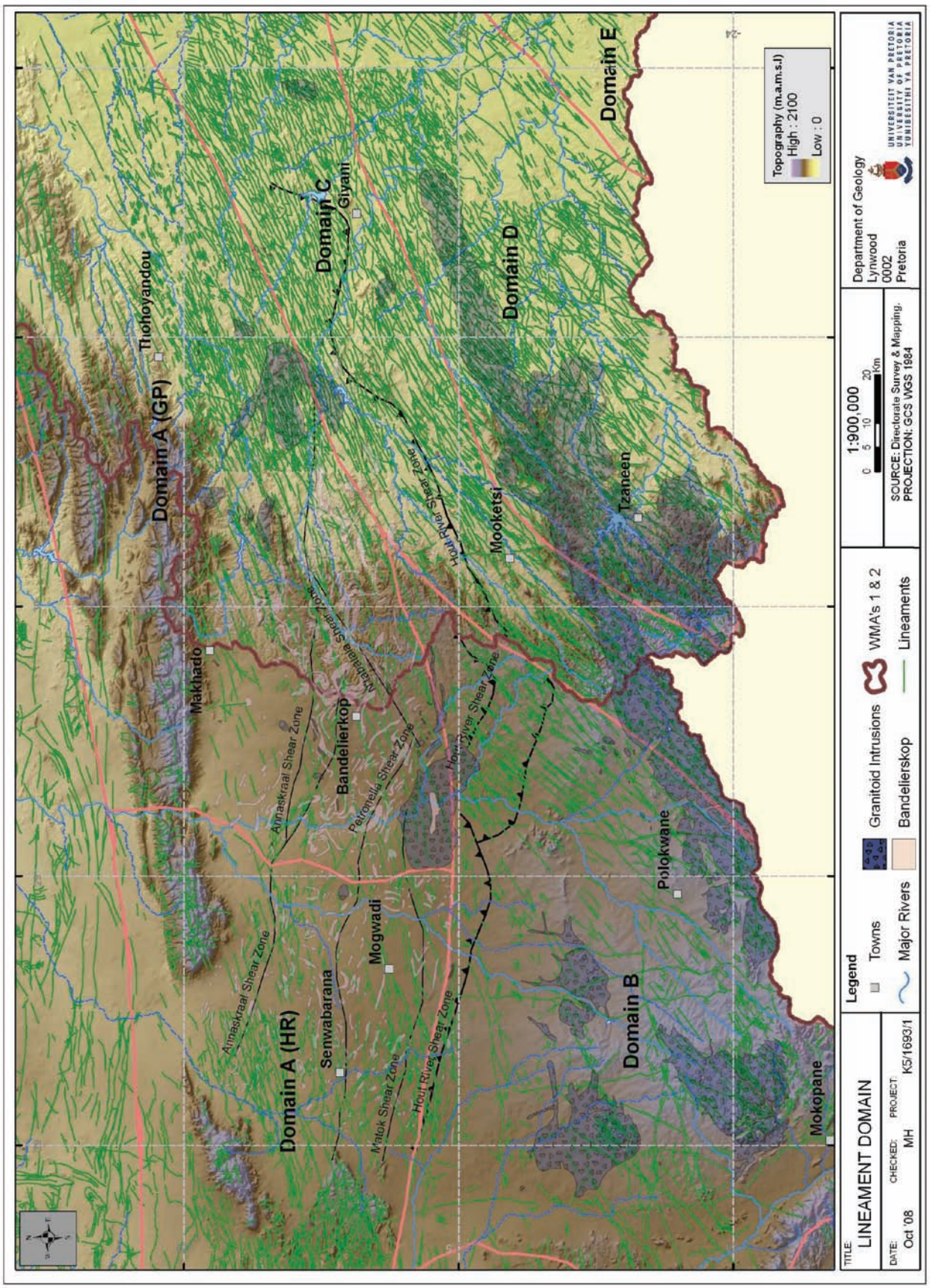

Figure 4: Aeromagnetic lineament map for the study area subdivided into five domains (Adapted from: Stettler *et al.*, 1989).

Table 5: Determined transmissivity based on control factors within each domain.

Control factor	Domain A Hout River Gneiss		Domain A Goud-plaats Gneiss		Domain B		Domain C		Domain D	
	N	T [m2/d]	N	T [m2/d]	N	T [m2/d]	N	T [m2/d]	N	T [m2/d]
Domain mean	**243**	**54.6**	**532**	**28.9**	**645**	**36.7**	**383**	**28.6**	**379**	**17.3**
Along Rivers	81	44.7	59	28.7	98	48.6	39	49.4	62	14.2
Significance [%]		92.3		51.9		97.5		97.1		96.1
Lineament 100 m	37	75.9	107	27.8	59	41.9	80	26.8	89	18.0
Significance [%]		89.4		58.7		77.9		59.8		59.5
Fault 100 m	4	56.7					5	63.0	3	6.5
Significance [%]		53.1						81.0		92.4
Goudplaats Gneiss			258	29.4	35	37.7	196	27.8	127	25.3
Significance [%]				55.1		53.8		59.8		97.3
Hout River Gneiss	47	79.1			287	37.8				
Significance [%]		88.6				59.2				
Quaternary Deposits	63	29.7	27	41.1	31	25.3				
Significance [%]		100.0		88.1		95.8				
Bandelierskop	11	94.0	26	18.2	4	30.7				
Significance [%]		91.7		99.6		66.3				
Granite			21	29.1	75	14.6	18	5.1	75	6.1
Significance [%]				50.5		100.0		100.0		100.0
Granitoid Contacts			24	32.3	48	*45.8*	11	7.1	18	7.2
Significance [%]				64.8		86.7		100.0		100.0
Greenstones			10	18.2	8	11.4	31	28.9	5	49.1
Significance [%]				90.1		100.0		51.4		91.6

Controlling factors within lineament domains

To identify factors that control above-average groundwater potential within each lineament domain, the pumping-test data for each domain were further classified on the basis of their distance to rivers (300 m), distance from faults (100 m), lineaments or geological contacts and lithology. All published lineaments (1:250 000 geological maps) and linear anomalies, captured (on high-resolution and low-resolution aeromagnetic maps) by the Council for Geosciences (CGS) as part of this project, were used to assess the productivity of borehole yields that are associated with lineaments (in most cases representing dykes). However, the subjective character of lineaments has been questioned by Tam *et al*. (2004). In this case, the characteristics of the structural feature that compound the lineaments, such as its topology, dipping angle and genesis, were disregarded. **Table 5** shows the corresponding mean transmissivities along with the levels of confidence that the value deviates from the domain (sub-population) mean.

Boreholes located near drainage channels are supposedly only above average in domain B and C. Alluvial material overlays or replaces the weathered overburden and creates a distinct intergranular aquifer type. However, below-average yields and T-values are found along the rivers in domain D, in comparison with the other domains. Domain D is predominantly covered by intruded granitoids and forms part of the topographically elevated Tzaneen escarpment (**Figure 1**), which is defined by Partridge and Maud (1987) as part of the escarpment erosion surface. The draining features in this area, therefore represent mostly headwaters that are incised into the basement rocks with a thin or absent alluvium, which explains the comparable low borehole productivity along rivers in this domain.

No attempt has been made to assess the productivity of the boreholes on the basis of the orientation of the rivers, which often follow structures, but it was assumed that the thickness of alluvial material overrides the strike of a potentially underlying structure. It is interesting to note the variable geological setting of high-yielding boreholes in the various domains. While within domain A (Hout River Gneiss), the highest yielding

and transmissive boreholes are found in the Bandelierskop intrusions, they represent poor targets in domain A (Goudplaats Gneiss).

Weathering thickness

The influence of rock weathering and the thickness of the regolith on the productivity of boreholes were not tested statistically or correlated with other influencing factors. However, a map of the thickness of weathering (**Figure 5**) that is based on the GRA II (Groundwater Resources Assessment phase II, Department of Water Affairs and Forestry) dataset show that the thickness of weathering does not appear to be a major controlling factor on a regional scale, especially if the area of high borehole productivity in domain A (Hout River Gneiss) is considered. In this domain, the depth of weathering ranges between 21 and 30 m, which is less than the weathering depth of up to 45 m in the south of Mogwadi, which has significantly lower borehole productivity. In the Lowveld groundwater region, the escarpment immediately east of the watershed has a weathering depth of 21 to 30 m, but increases to up to 45 m further east with borehole productivity decreasing with the distance from the escarpment. However, this phenomenon might also be attributed to the mountainous areas, which are often considered to be a constraint to borehole siting. It is envisaged that more accurate estimates of weathering depths could be obtained from borehole logs in the future.

Topographical setting of boreholes

The influence of topography on borehole productivity was assessed by using a smaller dataset that describes the physical setting of the drilling location as recorded in the GRIP database (**Table 6**). Boreholes in mountainous areas have deeper than average water levels and significantly lower transmissivities and sustainable yields, i.e. they are the most unfavourable topographical borehole locations. It is furthermore important to note that the average borehole depths are relatively constant throughout the dataset, with average borehole depths in mountainous areas exceeding the typical depth by approximately 7 m, while the static water levels is on average 8 m deeper. Since the topographical setting is directly related to the underlying geology, it is not an independent variable. Although the valley settings prove to produce fairly productive boreholes, flat surfaces also have higher than average transmissivities, suggesting that there are controlling factors other than topography on the productivity of the boreholes.

Table 6: Determined hydrogeological parameter versus topographical setting of boreholes and corresponding confidence levels.

Determinant	Total N	BH depth [mbs]	SWL [mbs]	Sust Q [ℓ/s per 24h]	Transmissivity [m^2/d]
Population mean	346	61.32	16.09	1.10	39.96
Flat Surface	167	61.81	15.27	1.23	46.99
Significance [%]		58.68	81.67	90.71	87.72
Mountainous	11	68.37	24.33	0.31	6.82
Significance [%]		77.60	90.95	100.00	100.00
Slope	125	60.28	17.89	0.99	35.23
Significance [%]		66.99	96.52	89.75	82.22
Valley	43	60.67	11.91	1.10	34.87
Significance [%]		57.61	99.94	50.40	74.12

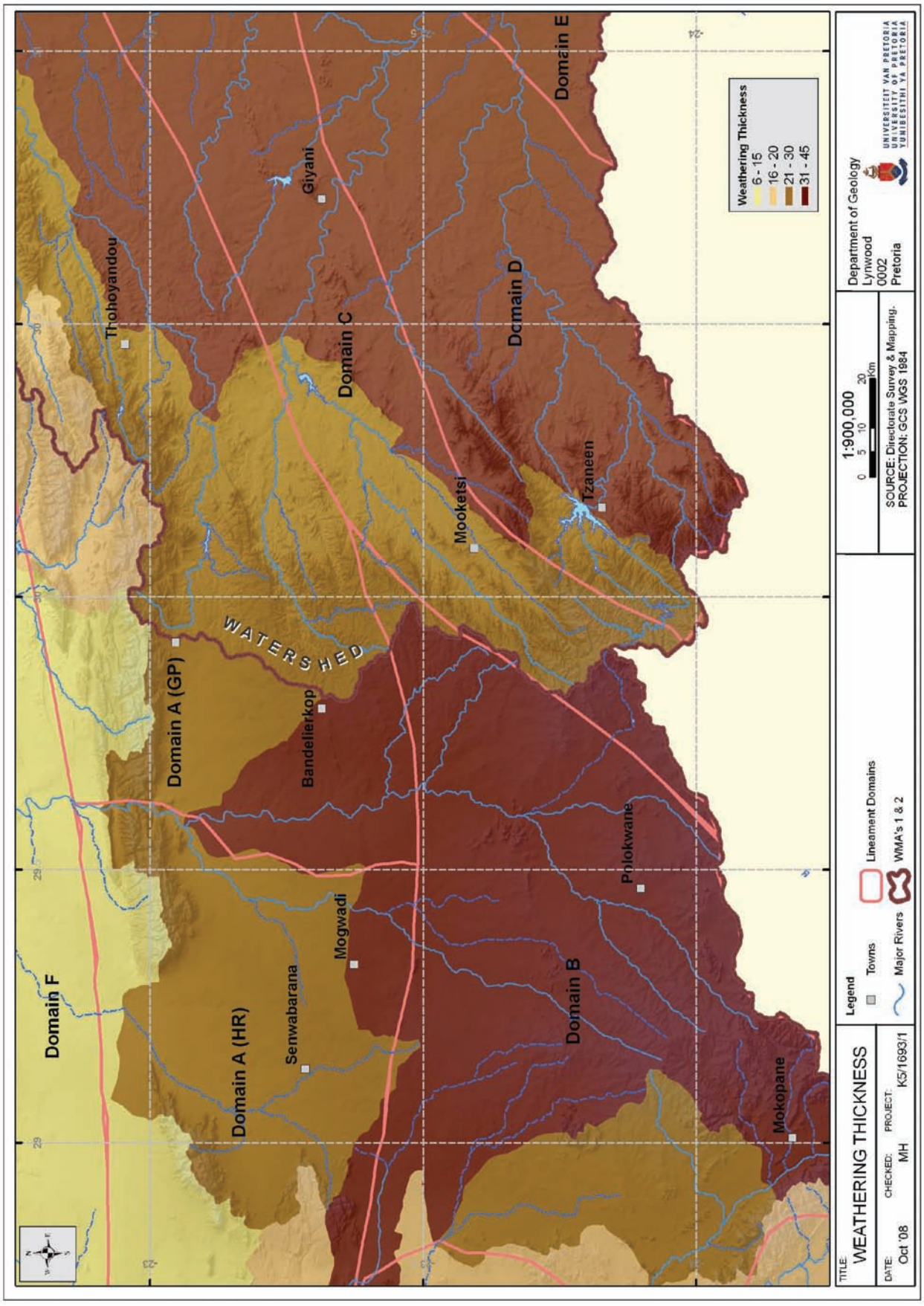

Figure 5: Weathering thickness on a quaternary catchment scale based on GRA II data

Discussion and conclusions

Granite intrusions of the Palmietfontein and Matok granites as well as the Schiel complex, in domain A, have higher yields than other domains. The southern boundary of domain A coincides closely with the Hout River Shear Zone. Therefore the higher grade metamorphism and series of shearing zones (e.g. Matok and Petronella) generally have resulted in more productive boreholes within the intrusions. The hydraulic parameters on the contacts zones of the granite intrusion in domain B are more prolific than in any other domain. As noted by Vegter (2003), the country rock is more intensely fractured in the aureoles and therefore its water-bearing properties were enhanced by the intrusions. Du Toit (1999) has investigated this matter in detail. Apart from the alluvial aquifers in domain B, these sites remain highly productive borehole yielding areas.

Boreholes that target lineaments appear only in domain A (Hout River Gneiss) and domain B transmissivities above the domain mean, which suggests a greater influence of structures on borehole productivity within these two domains. Domain A (Hout River Gneiss) is, in comparison to the other domains, generally high-yielding, with above-average yields and transmissivities for almost every tested factor (river, lineaments or lithology) compared to the other domains. The elevated productiviness of boreholes associated with lineaments in Domain B is attributed to their infrequent occurrence as larger shear or fracture zones, which form conduits for regional groundwater movement and therefore capture a larger recharge area. Only a few major faults were noted in the study area and where these faults were targeted (in domain C), they provided reasonable yields and above-average transmissivities. A detailed assessment of five pumping tests near faults revealed higher transmissivities for E-W striking faults.

Other observations made from the information obtained, is that the greenstones of domain C and, especially, domain D have higher yields and transmissivities compared to the greenstones of domain B, which suggests that the Giyani greenstones are better groundwater exploration targets than the Pietersburg greenstones.

This investigation reveals that several interrelated factors control regional borehole productivity in the basement rock aquifers of the Limpopo Province. Boreholes that exploit gneiss (sited with exploration methods), granitic contacts and alluvium present similar conditions regarding water supply, while younger less fractured and weathered granites indicate very low borehole productivity.

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Hydrogeochemistry of fluoride and salinization mechanism of groundwater in the Singida region, central Tanzania

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Abstract

This study focuses on the determination of factors that control high fluoride groundwater and salinization in basement aquifers of a semi-arid area in central Tanzania. Water samples were collected from productive dugouts, shallow wells and boreholes. The presence of ^{18}O, ^{2}H, and major cation and anion chemistry, including fluoride, was determined with the use of standard analytical techniques. A sodium-bicarbonate type of water dominates the study area. The ^{18}O - ^{2}H relationships suggest that the infiltration of water and groundwater has undergone evaporation while in some cases preferential flow mechanisms are suggested. Shallow wells and dugouts were found to have higher concentrations of both fluoride and chloride and this fact is partly attributed to the effect of evapotranspiration. The main mechanism for fluoride input into groundwater as well as salinization is attributed to the leaching of surface and near-surface soil salts, especially trona. No clear relationship was observed between the depth of wells/boreholes and fluoride concentration. Similarly, there is hardly any clear relationship between the fluoride concentration and the geomorphology of the study area. A more detailed investigation is needed to determine the relationship between sampling depth, fluoride concentration and salinization.

Introduction

High fluoride concentration in groundwater is one of the most important health-related geo-environmental problems that result in fluorosis. Fluorosis is rampant in both central and northern Tanzania, despite the fact that the two areas are covered by different geological formations. The central Tanzania area is occupied by fractured basement rocks in a semi-arid environment and has been studied less than northern Tanzania, which is dominated by volcanic rocks and a humid climate. Fluoride in groundwater occurs in the form of the anion F^-. Although traces of fluoride are present in many water sources, higher concentrations are often associated with volcanic rocks. In some African countries, concentrations exceed national and international standards for fluoride in drinking water supplies, which are typically within the range of 1-2 mg/ℓ. In countries in which the soil is rich in fluoride-bearing minerals, the national standards of fluoride in drinking water may be set relatively high. For example, in the United Republic of Tanzania, the fluoride concentration can be up to 8 mg/ℓ (Mambali, 1981).This value exceeds the WHO guideline for drinking water of 1.5 mg/ℓ (WHO, 1993). High fluoride concentrations have been reported in association with rift zones, volcanic rocks and granitic (Ca-poor) basement rocks (Bugaisa, 1971; Kilham and Hecky, 1973; Nanyaro *et al*., 1984).

This study was conducted in the northern Iramba district, which is located in semi-arid central Tanzania at elevations that range from 1 062 to 1 744 m above mean sea level(**Figure 1**). The study area falls within the Tanzanian craton at the margins of the East African Rift System which is volcanically active and has rocks that contain high fluoride-bearing minerals. The hydrothermal activities of the rift faults favour the dissolution of these minerals. Minerals such as villiaumite and fluorite are often present in these rocks.

Groundwater in the study area occurs in the saprolite and in fractured basement aquifers that have static water-level that is generally measured at 10 m below ground surface. Groundwater for domestic water supply is exploited from shallow wells and boreholes. The concentration of fluoride in groundwater is attributed to factors that include evaporation, leaching of soil salts and dissolution of fluoride-bearing minerals. The saprolite is approximately 15 m thick and overlays the less weathered bedrock (saprock). Boreholes as deep as

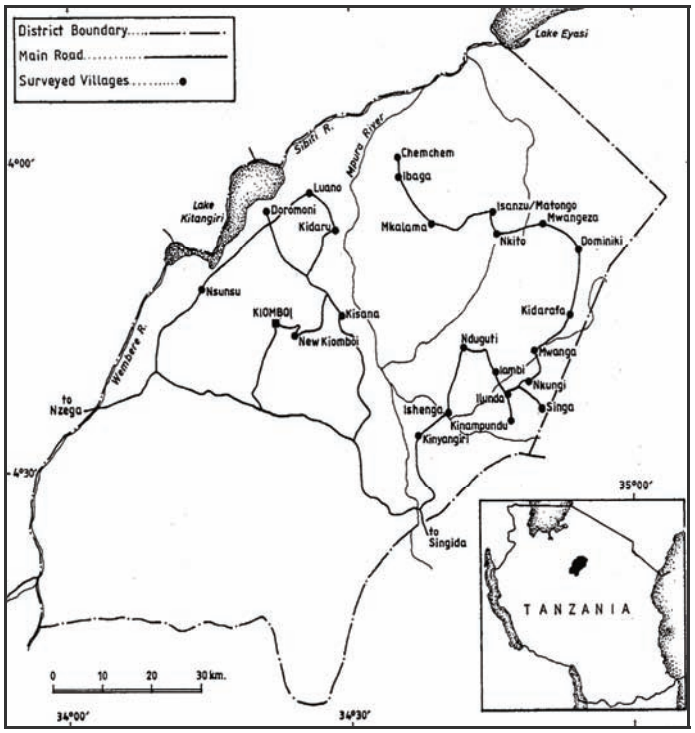


Figure 1: Location map of Iramba District showing study area (Kabuhu, 1996).

90 m, shallow wells of up to 10 m and dugouts of less than 1 m are constructed as groundwater supply points among various communities in the area.

Several studies have been conducted in volcanic rocks in Tanzania to investigate the occurrence of fluoride in groundwater, but hardly any studies have been undertaken on basement rocks. This study was conducted to find answers to the following basic questions:

1. What are the processes that control fluoride occurrence in groundwater in fractured basement aquifers?
2. How is the fluoride concentration related to the depth of wells and boreholes?
3. What is the relationship between the fluoride concentration and the geomorphology of the study area?
4. What are the nature and controls of the overall chemical character of groundwater in this area?
5. What are the mechanisms that are responsible for groundwater salinization in semi-arid areas and fractured basement aquifers?

Intensive groundwater sampling was carried out covering on both shallow and deep groundwater flow systems in the area. Dugouts that had been constructed in streambeds, shallow wells and boreholes located at various altitudes and within different rock types were sampled. Major and minor chemistry and stable isotopes were determined in various laboratories.

Materials and methods

Geological mapping

Preliminary geological mapping was conducted at the scale of 1: 50 000 (**Figure 2**). The mapping was conducted in various geomorphologic units at various altitudes. Basement rocks, including high-grade metamorphic rocks, along with granitic rocks and quaternary alluvial sediments, were observed. The area is characterized by mountains and valleys that are at altitudes that range from 1 480 m to 1 750 m above mean sea level.

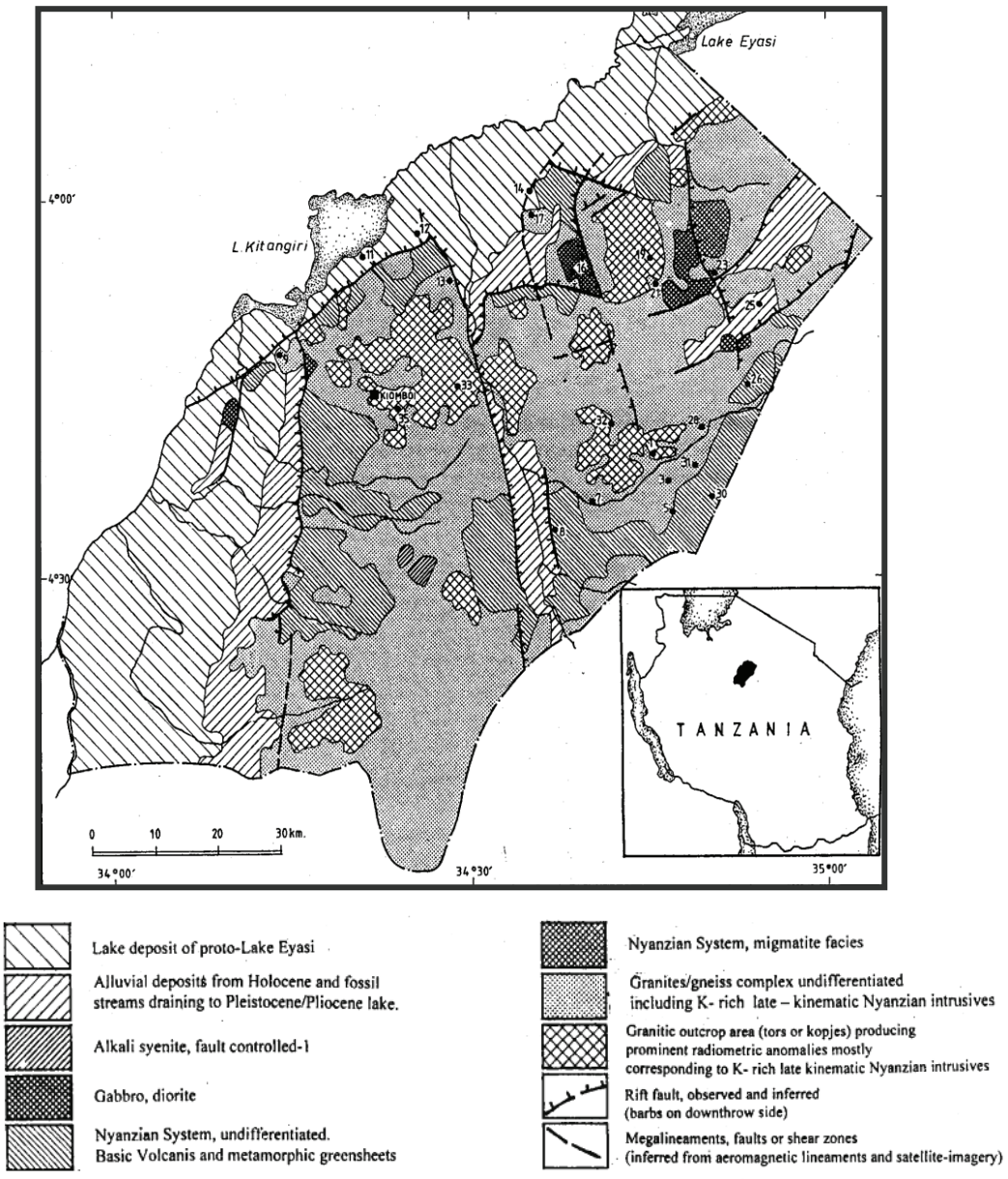


Figure 2: Geological map of the study area

Water sampling

Random water sampling was adopted for this study and standard methods were used for the determination of the chemical and physical characteristics of the water as described by the APHA (1985). Samples were collected from various sites at variable altitudes and water sources including boreholes, shallow wells and dugouts. Six sub- samples were collected at each sampling site, all of which were filtered with the use of 45 µm filter papers. Two of the sub-samples were collected in 30 mℓ polyethylene bottles and then acidified with 0.6 mℓ of 6 N HCl and with 0.3 mℓ of 6 N HNO_3. One sub-sample was collected in a 60 mℓ polyethylene bottle for stable isotope analyses. Glass bottles of 40 mℓ capacity were used for collecting the rest of the water samples for fluoride determination. Thereafter all samples were stored in a cool box during fieldwork and then in the refrigerator at the Department of Geology of the University of Dar Es Salaam before sending them to the British Geological Survey in the UK for laboratory analysis. **Table 1** shows village and location names of the sampling sites as well as their altitude, latitude and longitude.

Table 1: Location of the water samples

Sample Number	Water Source	Village	Location	Altitude (m amsl)	Latitude S (Degrees)	Longitude E
IR1	B	Iambi	Kikundya	1 503	4.351	34.752
IR2	W	Iambi	Kihau	1 481	4.351	34.769
IR3	B	Ilunda	Mtundua	1 526	4.349	34.800
IR4	W	Ilunda	Ilunda	1 527	4.368	34.797
IR5	B	Kinampundu	Mwembe	1 561	4.404	34.789
IR6	B	Kinampundu	Kisutu	1 550	4.415	34.794
IR7	W	Ishenga	Madukani	1 459	4.389	34.687
IR8	D	Kitangiri	Stream	1 485	4.457	34.616
IR9	B	Nsunsu	Soweto	1 100	4.223	34.233
IR10	W	Nsunsu	Ng'unga	1 105	4.199	34.222
IR11	D	Doromoni	River	1 062	4.090	34.330
IR12	D	Luono	River	1 066	4.064	34.397
IR13	W	Kidaru	Kidaru	1 065	4.051	34.579
IR14	W	Chemchem	Shuleni	1 116	4.108	34.491
IR15	D	Chemchem	Mission	1 121	4.050	34.582
IR16	W	Mkalama	Mkailu	1 253	4.106	34.644
IR17	B	Ibaga	Manamba	1 171	4.078	34.590
IR18	D	Ibaga	River	1 182	4.085	34.601
IR19	B	Matongo	Hindamili	1 569	4.083	34.744
IR20	W	Matongo	Mponoelo	1 554	4.089	34.747
IR21	B	Nkito	Miula	1 574	4.146	34.748
IR22	B	Nkito	Kinyantungu	1 594	4.148	34.768
IR23	W	Mwangeza	Dar es salaam	1 413	4.091	34.815
IR24	B	Mwangeza	Kisene	1 460	4.103	34.814
IR25	B	Dominiki	Mzanga	1 468	4.132	34.919
IR26	B	Kidarafa	Kidarafa A	1 672	4.211	34.935
IR27	B	Kidarafa	Hailosi A	1 709	4.211	34.910
IR28	B	Mwanga	Mpaligogo	1 580	4.269	34.889
IR29	W	Mwanga	Singida Street	1 542	4.288	34.866
IR30	B	Singa	Kagera	1 610	4.400	34.859
IR31	B	Nkungi	Nkungi	1 554	4.339	34.835
IR32	W	Nduguti	Uswahilini	1 569	4.302	34.700
IR33	W	Kisana	Kintamba	1 736	4.248	34.482
IR34	W	Kisana	Kisana	1 744	4.238	34.480
IR35	B	New Kiomboi	Magula	1 562	4.256	34.389
IR36	W	Lulumba	Water Department	1 596	4.267	34.393

B = Borehole; D = Dugout in the riverbed; W = Shallow well

Laboratory methods

Chemical analyses of water samples were conducted at the British Geological Survey in the UK. Major elements were determined by ICP-AES following the analytical techniques described by Banks *et al*. (1998b, c). Measurements for Cl were conducted with the use of automated colorimetry. Analyses for fluoride were conducted at the Department of Geology, University of Dar es Salaam, with the use of an Orion ion specific electrode, following the methodology described by Frant and Ross (1966). The fluoride electrode was calibrated

at 23°C. Standard fluoride concentrations of 0.1 mg/ℓ, 0.2 mg/ℓ, 0.5 mg/ℓ, 1 mg/ℓ, 5 mg/ℓ, 10 mg/ℓ, and 20 mg/ℓ were prepared for establishing the calibration curve. About 3 ml of each standard was mixed with 3 ml of Total Ionic Strength Adjustment Buffer (TISAB), and measured in millivolts (mV) of fluoride with the use of the Orion fluoride electrode to obtain the calibration curve. The (TISAB) was added to each sample to provide a constant ionic strength background, thereby minimizing variations between samples and standards (Hitchon, 1995). The voltage values of fluoride were taken at constant potential readings. For electrical conductivity (EC) measurements the EC meter was calibrated at room temperature with the use of 1413 µS/cm and 718 µS/cm solutions. The stable isotopes of ^{18}O and ^{2}H were determined with the use of a mass spectrometer at the British Geological Survey in the UK.

Results

Hydrogeology of the study area

The study area is characterized by Quaternary alluvium and lake deposits as well as Precambrian granites and greenstones (**Figure 2**). Granite rocks dominate the area and are known to contain elevated concentrations of fluoride-bearing minerals. However, the extent to which these minerals influence the levels of fluoride in groundwater in this area is not yet known. Groundwater is always encountered in weathered and fractured zones at depths of about 10 meters below ground surface. A saprolite of about 15 meters covers the basement although exposed basement formations in some areas are not uncommon. In riverbeds, which are mainly covered with sands, groundwater occurs at about half a meter below ground surface. Groundwater occurrence and flow seem to be fracture controlled. The static water level, at about 5 to 10 m below ground surface, is highly variable among adjacent boreholes, which indicates the existence of discrete fracture systems. Pumping-test data show that the facture systems have hydraulic conductivity values of about 10^{-4} m/sec and storativity values of about 10^{-3}. Deep groundwater occurs under confined conditions while shallow groundwater occurs mainly under water table conditions.

Most of the water samples were collected from Precambrian granite terrain with fluoride concentrations above 3 mg/ℓ. Fluoride concentrations below 1.5 mg/ℓ have also been found in the same terrain. The exceptions are some samples that were located in the Quaternary lake deposits, alluvium and in the greenstone rocks (**Figure 2**). Precambrian granites contain a high proportion of high-fluorine bearing minerals such as mica, amphiboles and occasionally fluorite. These minerals probably contribute to the observed elevated fluoride concentrations in groundwater.

Although elevated fluoride concentration is found to be predominant in the granite terrain, the relationship between fluoride concentration in groundwater and the geology seems rather obscure. It is therefore unclear whether the high fluoride concentrations are related to bedrock geology or to other factors that could lead to secondary enrichment.

Hydrochemistry

Fluoride concentrations

The results obtained are given in **Tables 2**, **3**, and **4** with the sources from which the samples were collected. It was found that 72 % of the water samples had fluoride concentrations that exceed the WHO guideline of 1.5 mg/ℓ for drinking water (WHO, 1993). The majority of the samples (52.7%) were collected from shallow groundwater sources of which 73.7% had a fluoride concentration that is above the WHO guideline, while 70.6% of the boreholes had a fluoride concentration that is above the guideline.

The highest concentration of fluoride appeared in a water sample that was collected from the riverbed of the Luono River (sample IR 12). It may be attributed to the leaching of surface or near-surface soil salts that had concentrated in the soil matrix as a result of evaporation. The lowest concentration appeared in a shallow well at the New Kiomboi Water Department. This area is also characterized by low salinity as indicated by the low electrical conductivity values. This finding may indicate the bypass flow of water through macropores, which result in a minimum of water-rock contact time during infiltration and percolation to the water table.

The presence of fluoride in groundwater is generally a natural phenomenon that is influenced by local and regional hydrogeological conditions (Agrawal *et al.*, 1997). Differences in fluoride concentrations in the shallow wells and dugouts are large, even at very short distances. This observation is similar to that made by Latha *et al*. (1999). Changes in fluoride concentration among adjacent boreholes and wells may indicate hydraulic and lithologic heterogeneity in aquifer formations.

Table 2: Fluoride and major ion concentrations in dugouts.

Sample Number	HCO_3 Mg/l	SEC µS/cm	Cl mg/ℓ	TON mg/ℓ	F mg/ℓ	SO_4 mg/ℓ	Ca mg/ℓ	K Mg/ℓ	Mg Mg/ℓ	Na Mg/ℓ	Ion Balance%	δ^2H (‰)	δ 18O (‰)
IR8	663	1 223	73.25	4.98	1.59	33.6	77.1	3.1	48.1	157	2.52	-9.9	-1.99
IR11	296	550	14.32	1.65	1.46	10.6	39.1	3.5	5.97	86.7	2.26	-15.5	-3.32
IR12	845	1 660	128.6	6.07	14.33	66.5	7.7	5.7	2.07	449	2.37	-20.1	-4.08
IR15	443	753	31.08	-0.22	2.01	21.5	42.6	2.6	15.2	123	1.33	-13.1	-2.44
IR18	172	369	35.06	-0.22	1.36	9.2	37.3	2.1	9.43	35.5	3.07	-16.3	-3.56

Table 3: Fluoride and major ion concentrations in shallow wells

Sample Number	HCO_3 mg/ℓ	SEC µs/cm	Cl mg/ℓ	TON mg/ℓ	F mg/ℓ	SO_4 mg/ℓ	Ca mg/ℓ	K Mg/ℓ	Mg mg/ℓ	Na mg/ℓ	Ion Balance%	δ^2H (‰)	$\delta^{18}O$ (‰)
IR2	566	964	39.21	2.55	5.14	11.5	49.5	1.1	20.6	173	4.08	-15.2	-3.11
IR4	750	1470	69.34	6.58	5.26	48.1	18.1	4.4	18.6	318	2.07	-16.38	-3.57
IR7	312	663	35.79	11.43	3.1	8.3	67	3.5	14.1	70	3.58	-15.6	-3.38
IR13	307	766	63.58	2.09	2.97	44.4	33.8	1.4	10.9	139	4.61	-16.6	-3.04
IR14	269	491	24.62	-0.22	2.27	9.1	40.7	1.3	9.98	62.4	2.89	-23.6	-5.15
IR10	340	806	51.92	6.09	2.19	36.9	59.8	0.9	14.4	105	3.05	-6.9	-2.17
IR16	518	1 172	139.4	2.74	4.41	29.4	59.1	4.9	27.7	205	3.78	-10.2	-2.47
IR20	536	1 012	41.02	3.29	2.61	56.2	59.3	< 0.5	27.1	167	4.62	-18.3	-3.77
IR23	600	1 436	160	0.33	8.73	67.7	47.4	5.4	17.3	284	1.57	-21.4	-3.81
IR29	707	1 127	47.23	7.61	4.16	14.2	51.6	2.9	47.1	193	4.05	-16	-3.24
IR32	247.5	769	39.07	25.1	1.62	34.3	55.1	17.1	23.2	71.8	3.55	-17.5	-4.29
IR33	37	146	4.08	5.36	0.49	8	5.5	10.9	2.89	11.7	1.51	-13.1	-3.31
IR34	44	191	2.55	0.77	0.67	4	3.3	1.4	1.19	15.8	2.95	-10.5	-3
IR36	16	58.4	4	-0.22	0.21	2.4	4.3	1	0.23	5.7	5.31		

Table 4: Fluoride and major ion concentrations in boreholes

Sample Number	HCO_3 mg/ℓ	SEC µS/cm	Cl mg/ℓ	TON mg/ℓ	F mg/ℓ	SO_4 mg/ℓ	Ca mg/ℓ	K Mg/ℓ	Mg mg/ℓ	Na mg/ℓ	Ion Balance%	δ^2H (‰)	$\delta^{18}O$ (‰)
IR3	490	853	8.26	4.11	4.64	21.9	52.1	10.1	32.2	98.4	4.11	-19.8	-4.06
IR1	489.7	1007	46.78	0.77	2.85	6.6	73.3	5	24.3	127	8.49	-18.3	-3.69
IR5	569	1027	48.84	16.97	2.33	9.6	77.7	14	53.2	94	2.36	-14.5	-2.73
IR6	449	808	56.66	1.65	1.57	13.9	83.6	3.4	26.2	77.7	2.27	-18.17	-3.78
IR9	291	389	2.23	-0.22	1.42	2.2	73.8	1.7	9	12.9	1.60	-13.8	-3.19
IR17	201	382	18.64	0.33	1.87	7.3	27.6	1	8.61	49.9	3.43	-13.6	-3.51
IR19	569	1013	82.48	0.49	2.86	34.1	70.1	4.9	25.8	175	3.71	-16.1	-4.02
IR21	576	947	69.11	7.15	2.04	44.4	99.6	1.1	38	121	2.14	-22.8	-4.93
IR22	602	662	36.05	5.93	1.46	5	76.3	9.1	19.2	47.6	-1.57	-23.2	-3.98
IR24	444	765	41.25	0.82	1.85	7.3	53.4	1.5	24.2	97.1	1.54	-15.5	-3.54
IR25	632	871	31.71	2.41	2.01	19.9	84	6.7	41.9	103	1.90	-22.7	-3.65
IR26	488	822	42.99	8.23	4.5	8.6	71.1	1.8	27.8	117	4.78	-18.1	-3.75
IR27	430.7	923	26.7	30.1	0.82	11.4	100	17.6	46.7	60.5	7.81	-15.4	-4.03
IR28	557	971	48.71	13.79	0.99	60.7	111	5.3	42.3	96.2	2.26		
IR30	589	1187	83.01	9.85	1.46	36.9	76.2	33	74.3	81	2.96	-19	-4.28
IR31	583	1055	43.44	23	1.79	39.7	104	14.7	56.9	78.2	1.53	-19	-4.44
IR35	445	766	23.98	0.99	2.44	37.3	68.6	0.9	29.2	82.3	3.35		

TON =Total Oxidized Nitrogen

Table 5: δ^2H (‰) and $\delta^{18}O$ (‰) content of local rainfall

$\delta^{18}O$(‰)	-6.09	-9.35	-5	-0.4	0.25	-2.27	-6.76	-3.06	-2.99	-5.18
δ^2H(‰)	-33.7	-58.4	-18.2	19.8	21	-2.1	-40.7	-15.9	-8.9	-33.6
$\delta^{18}O$(‰)	-4.42	-3.65	-4.27	-6.22	-7.71	-7.1	-7.98	-5.69	-7.71	-0.27
δ^2H(‰)	-22.5	-9.7	-17.8	-32.6	-46.4	-42.8	-50.2	-30.9	-44.9	13
$\delta^{18}O$(‰)	0.48	-1.48	-1.78	-1.83	-1.57	-1.71	-4.73	-5.83	-5.83	-9.07
δ^2H(‰)	17.1	-3.9	2.1	-1.4	-3.4	-2.5	-20.8	-37.9	-57.2	-74.4
$\delta^{18}O$(‰)	-10.4	-8.28	-8.97	-5.34	-4.26	-8.79	-0.85	-1	-1.05	-2.41
δ^2H(‰)	-57.2	-55.2	-61.1	-26.4	-19.3	-55.2	4.7	6.3	1.2	-7.3
$\delta^{18}O$(‰)	-7.65	-4.52	-5.44	-6.1	-5.43					
δ^2H(‰)	-45.4	-20.3	-27.7	-33.4	-34.5					

Major cation and anion chemistry

Na^+ concentrations are found to be higher than any of the other cations (Ca^{2+}, K^+, and Mg^{2+}) as shown in **Tables 2, 3 and 4** and are positively correlated with fluoride concentrations. Elevated Na^+ concentrations may be due to cation exchange where Ca^{2+} from groundwater is adsorbed on clayey materials in exchange of Na^+. Another possible reason for the higher Na^+ concentration could be dissolution of trona ($Na_2CO_3.NaHCO_3.2H_2O$), a white salt commonly found in the semi-arid East African Rift Valley with lots of fluoride. While conducting fieldwork, trona was found in almost all the dry riverbeds that have flow towards the study area during the wet season.

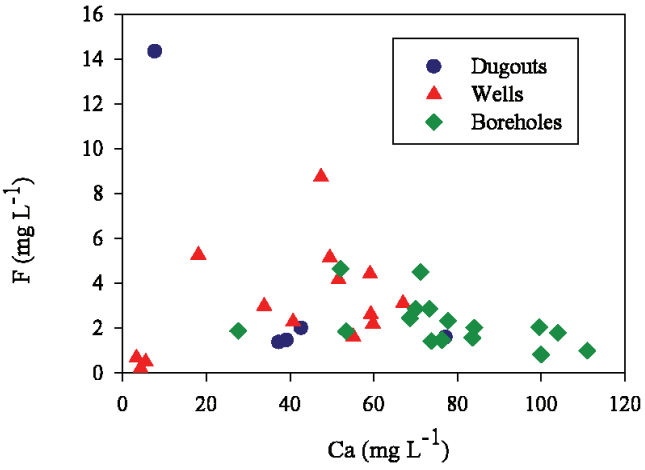
Large variations in chloride concentrations were observed in the groundwater, which may be attributed to evaporation of rainfall, leaching from the surface and/or soils salts and minor contributions from acidic rocks. High concentrations of chloride were observed in the wells that are within sediments that are predominantly composed of materials that derive from the volcanic area (faults of the Rift Valley). Fuge (1988) reports that chloride occurs in minerals such as sodalite ($Na_4\ Al_3\ Si_3\ O_{12}\ Cl$). According to Fuge (1977), fluorine and chlorine occupy the hydroxyl sites of hydroxy silicates, such as micas and amphiboles, and also apatite. Fluorine is richest in granite rocks, while chlorine is richest in the hydroxy minerals of basic rocks.

The occurrence of SO_4 can be associated with volcanic activities (Haile, 1999). Other sources of SO_4 include rainfall, gypsum dissolution, oxidation of pyrite and agricultural fertilizers.

Total oxidized nitrogen (TON) values in the study area are high (see **Table 4**) although agricultural fertilizers are not used in this area. The elevated values (of TON) suggest domestic pollution by the leaching of sewage from pit latrines into the groundwater flow system. Livestock farming could be another source of pollution as large numbers of grazing cattle were observed in the study area.

The majority of boreholes have a high calcium and low fluoride concentration, which suggests that Ca concentration in the bedrock of the aquifers plays an important role in limiting the amount of fluoride. Shallow wells contain low calcium with high fluoride concentrations, except for those shallow wells in Kintamba and Kisana that are located at the highest altitude of the area (**Figure 3**).

Figure 3: Relationship between Ca and F in the various water sources of the Northern Iramba District



The highest fluoride concentration observed in a dugout in the bed of the Luono River had the lowest concentration of Ca^{2+} and highest concentrations of both Na^{+} (**Figure 4**) and HCO_3^{-} (**Figure 5**). This finding may be attributed to the dissolution of trona ($Na_2CO_3.NaHCO_3.2H_2O$), an evaporite mineral that is commonly found in the East African Rift System and is always contaminated with fluoride. The latter may also indicate that evaporation processes took place and therefore concentrated salts on the surface and within the near-surface soils with subsequent leaching that leads to elevated concentrations in the groundwater system.

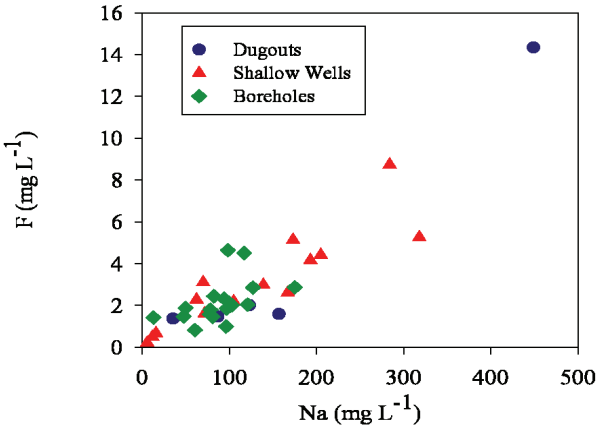


Figure 4: Relationship between Na+ and F- in different water sources in Northern Iramba District

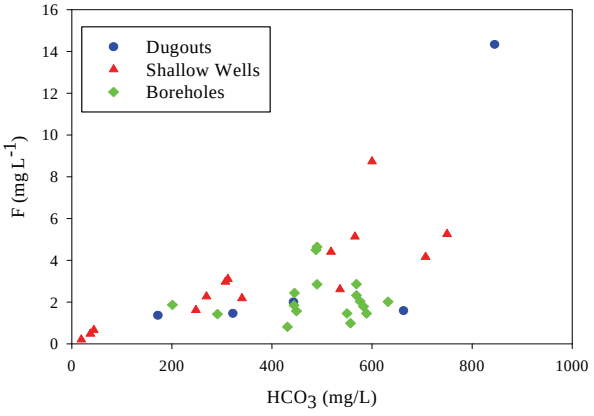


Figure 5: Relationship between F and HCO_3 in different water sources in Northern Iramba District

A relationship between salinity (EC values) and fluoride concentration (**Figure 6**) has a positive correlation, which indicates that fluoride mobilisation through the leaching process results in an increase in the salinity values of the groundwater due to the dissolution of easily leachable salts such as trona.

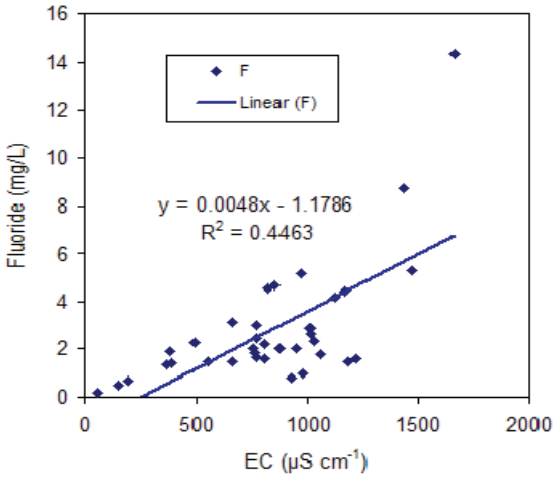


Figure 6: Relationship between salinity and F values in the various water sources in the Northern Iramba District

Alkalinity was also found to be positively correlated with fluoride concentration, albeit to a low extent. The Piper diagram (**Figure 7**), which was prepared in accordance with the modification by Back (1966), shows that water generally contains lower concentrations of calcium and magnesium in comparison with sodium and potassium. Bicarbonate is the dominant anion. Most of the boreholes contain water that has no dominant cation - HCO_3-type and most of the dugouts and shallow wells contain a Na-HCO_3 type of water. The predominantly Na-HCO_3 water type could be attributed to the dissolution of near-surface salts.

Stable isotopic ratios

Evaporation had an impact on the groundwater of the study area, which is characterized by a semi-arid climate. The ^{2}H and ^{18}O values range from -6.90‰ to -23.60‰ and -1.99‰ to -5.15‰ respectively. This range could be attributed to heterogeneity on the soil surface, which affects the infiltration rates of the surface water and brings about the modification of the isotopes through evaporation effects. The mean values for dugouts are -14.98 and -3.08 (n = 5); for shallow wells, -15.48 and -3.39 (n =13); and for boreholes, -18.00 and -3.84 (n =14) for ^{2}H and ^{18}O respectively (**Table 6**).

Table 6: Mean δ ^{18}O (‰) of the various water sources

Water Source	Mean δ ^{18}O (‰)
Rainfall	- 4.46
Dugouts	-3.08
Shallow wells	-3.39
Boreholes	-3.84

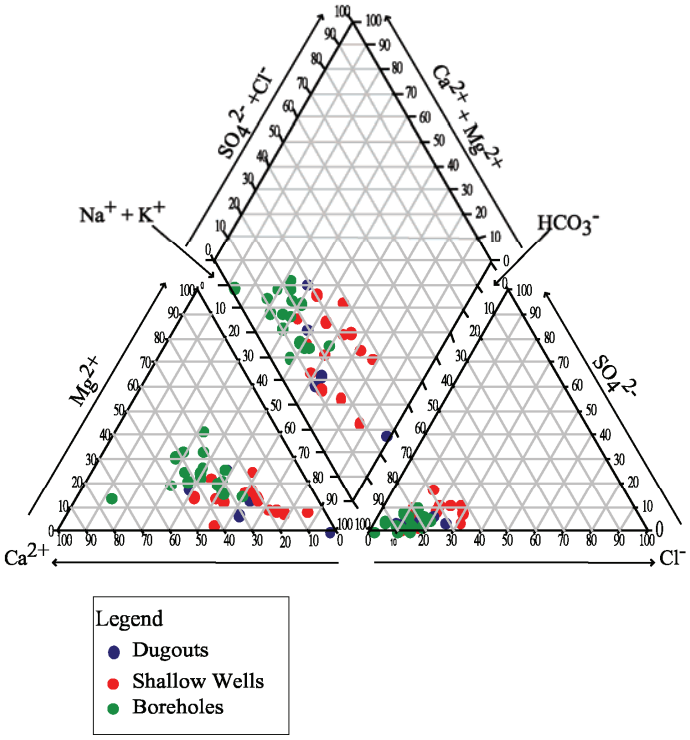


Figure 7: Piper trilinear diagram for the groundwater of the Northern Iramba District

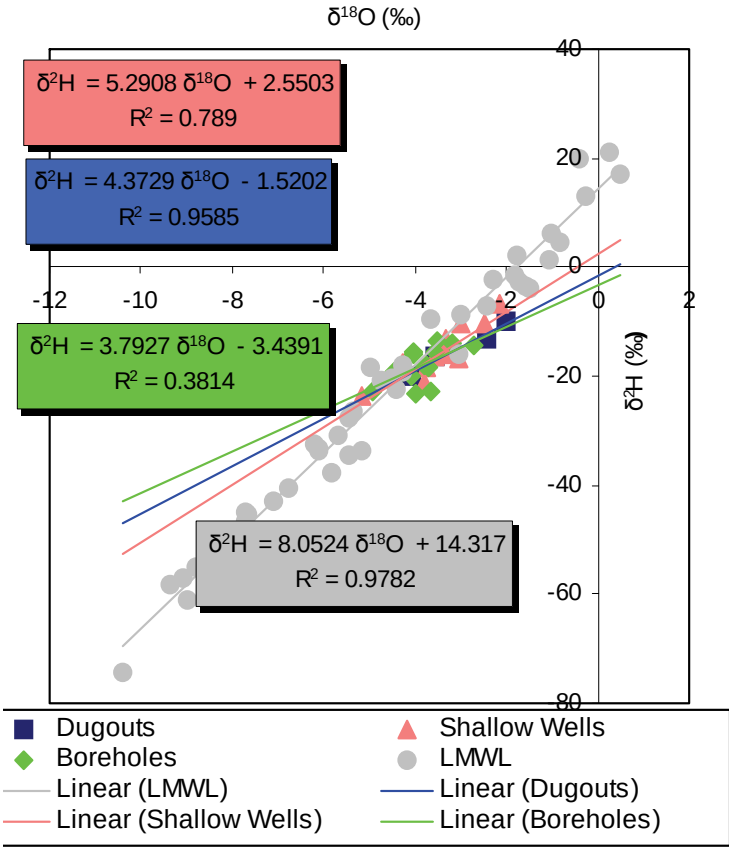


Figure 8: Relationship between δ^2H and $\delta^{18}O$ in the various water sources of the Northern Iramba District. LMWL indicates the rainfall data from the Local Meteoric Water Line

The slope of 5.3 for the shallow wells (**Figure 8**) suggests that surface water/runoff in this area has undergone evaporation before and during infiltration, which resulted in the enrichment of both ^{2}H and ^{18}O of the shallow groundwater. A comparison to the mean $\delta^{18}O$ value of the rainfall (**Table 6**) supports the observation shown in figure 8. In addition, the mean data for the dugouts and the resultant slope of 4.4 for the dugouts support the surface to subsurface evaporation processes of infiltrating water.

The mean stable isotope data for boreholes, that are less enriched than both the dugouts and shallow wells, indicate that the isotopic character of deeper groundwater may result from a mixture of evaporated surface runoff before infiltration and direct infiltrating/recharge of rainfall through bypass flow mechanisms in macropores. The bypass flow mechanism of groundwater recharge is typical in the basement fractured aquifers of central Tanzania as observed by Nkotagu (1996) at the Makutupora groundwater basin in the Dodoman craton. A relationship between $\delta^{18}O$ and fluoride concentration (**Figure 9**) show the same fluoride values to vary with different $\delta^{18}O$ values with no clear pattern. However, most data are concentrated between $\delta^{18}O$ –3‰ and -4‰ with fluoride values at about 3 mg/ℓ. This indicates that similar processes are responsible for fluoride enrichment in the various groundwater sources. As indicated, bypass flow mechanisms may play a major role in the groundwater recharge processes within the study area.

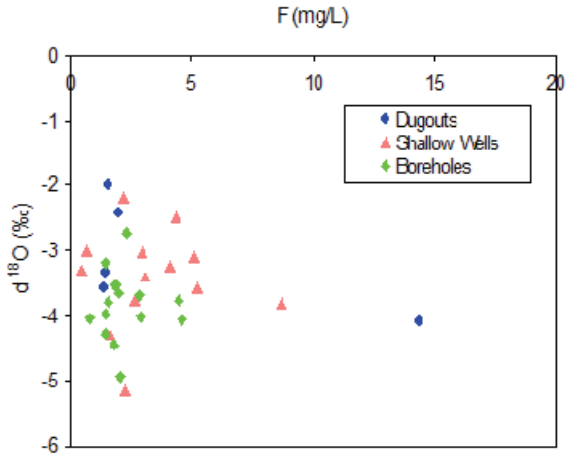


Figure 9: Relationship between $\delta^{18}O$ and fluoride concentration in the various water sources of the Northern Iramba District.

A relationship between fluoride concentrations and depths of boreholes/wells (**Figure 10**) generally shows that the groundwater from dugouts (mean depth = 0.5 m, mean [F-] = 4.15 mg/ℓ, n = 5) and shallow wells (mean depth = 6 m, mean [F-] = 3.31 mg/ℓ, n = 11) have higher concentrations of fluoride than the groundwater that was abstracted from boreholes (mean depth = 49 m, mean [F^-]= 2.17 mg/ℓ, n= 8) for the water sources with known depths. Groundwater sources that are deeper than 40 m have lower fluoride concentrations than groundwater that was abstracted at depths less than 30 m below ground level. This difference may be attributed to the leaching of near-surface salts that are formed due to the repetitive evaporation processes. The range of fluoride concentrations in shallow wells, from 0.5 to 6 mg/ℓ, at the same depths, and dugouts to a lesser extent, supports the view that fluoride leaching and subsequent infiltration of groundwater may be taking place under different heterogeneous soil conditions (**Figure 10**). The narrow range of fluoride concentrations, of about 2-3 mg/ℓ, for the groundwater that was abstracted through deeper boreholes may imply a similar or uniform process of fluoride enrichment with depth (**Figure 10**).

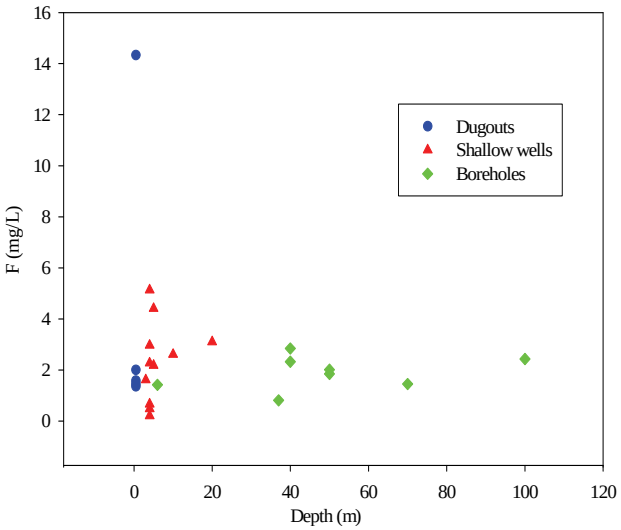


Figure 10: Variation of fluoride with depth for various water sources in the Northern Iramba District

Subsurface evapotranspiration tends to concentrate fluoride and other salts in solution. In groundwater sources that are deeper than 40 m, this effect is not as significant in comparison with the shallower groundwater sources. The dissolution of minerals through water-rock interaction contributes significantly to the release of fluoride and other elements into groundwater.

Conclusions

Fluoride concentration in 72% of the groundwater samples was found to have fluoride concentration that is above the WHO guideline value of 1.5 mg/ℓ. Four factors that bring about the chemical character of high fluoride groundwater in the study area were determined and it was found that the leaching of surface and near-surface soil salts lead to the high concentration of fluoride and other major ions in the groundwater. Mineral dissolution of CaF_2 and NaF plays an insignificant role in elevating fluoride concentrations in the groundwater of the study area. The subsurface evaporation process contributes to the elevated fluoride concentration in groundwater as indicated by the stable isotopes data. Fluoride concentration in groundwater is highly variable, suggesting the heterogeneity of basement aquifers, both in terms of hydraulic (fractured/non-fractured) and lithologic characteristics. It has been noted that geomorphology plays an insignificant role in the fluoride concentration of various groundwater sources. However, a challenge remains in respect of understanding optimum depths of the construction of wells with acceptable levels of fluoride concentration for the improvement of the quality of public water supplies.

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Hydrogeochemical processes that influence the groundwater chemistry of basement aquifer systems, Namaqualand

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Abstract

The groundwater resources for the Namaqualand region are developed predominantly in the basement rocks. The infiltration and flow of water is controlled by the prevailing complex fracture network and can vary in space and time. Such conditions relate to structurally controlled flow systems and varying water chemistry amongst closely spaced fracture systems.This article summarises the processes that influenced the groundwater chemistry and resulted in the dominant NaCl character of the groundwater. In addition, emphasis is placed on a mineral-dissolution approach that is based on the reaction between primary minerals and CO_2-charged water to produce the measured dissolved constituents. As a result, the effects of both carbonate and silicate weathering processes are discussed to explain concurrent changes in the groundwater composition. It is possible to spatially distinguish between dilute, shallow circulating and relatively young groundwater systems compared to more brackish, slower circulating and relatively older systems. The relatively dilute end-member is associated with dynamic, actively recharged groundwater systems with rapid through-flow rates occurring in the higher lying mountainous regions or with infiltration through highly transmissive fracture zones within the lower lying valley systems. The more brackish end-member, associated with the valley systems, or the lower lying regions, is characterized by a localized, predominantly vertical flow component and possibly a lateral flow component that may approximate an intermediate flow system.

Introduction

The study area

The study area, situated between latitude 17° 00' - 18°30' and longitude 29°00'- 30°30', includes the Buffels River catchment (F30) as well as parts of catchments F40 and F50. The area is classified by three physiographic regions in accordance with topography, altitude and landforms (**Figure 1**). These regions are the higher lying Bushmanland Plateau to the east, the Namaqualand highlands (which is the escarpment zone) and the lower lying coastal area to the west (Visser 1989).

Namaqualand consists of seven communal areas, namely the northern Richtersveld, southern Richtersveld, Steinkopf, Concordia, Komaggas, Pella and Leliefontein. Namakwa Water supplies surface water from the Orange River to the larger towns only, such as Springbok, Nababeep, Okiep and Kleinzee. All of the rural villages as well as state-owned and privately owned farms depend on groundwater for domestic and stock water supply.

The study area falls in the arid, hot (BWh), tropical desert climatic region of South Africa, according to the Koeppen classification. The climate of the study area is determined by altitude, topography and distance from the sea (Midgley *et al.*, 1994). The region can be classified as arid to semi-arid with mountainous regions having higher rainfall than the arid lowland due to orographic effects. Rainfall occurs mostly during the winter months while snow in the highest mountainous regions was observed during the summer months. Potential evapotranspiration can be as much as 12 to 15 times the precipitation. This high evaporation to precipitation ratio means that salts will easily form on the surface as well as in the subsurface (Campbell *et al.*, 1992 and Van der Sommen and Geirnaert, 1988).

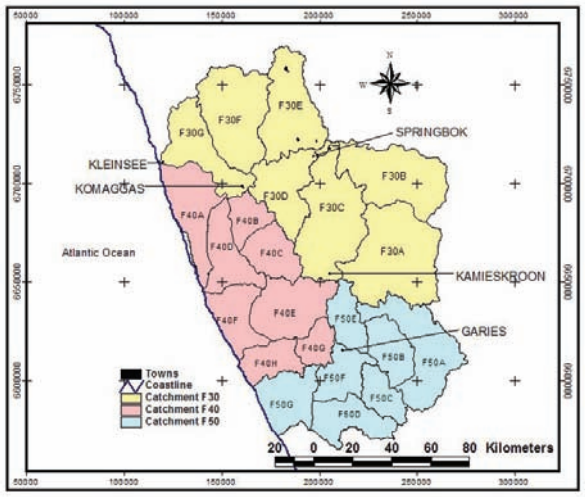

Figure 1: The study area compromising of secondary drainage catchments F30, F40 and F50.

Methodology

Ninety-six groundwater samples were selected to represent the groundwater composition (in terms of mineral saturation indices calculations) for the Buffels River catchment. Sensitivity analyses, in terms of varying the relevant input parameters (i.e. field pH vs. laboratory pH, etc.), were performed to test the robustness of the thermodynamically calculated mineral saturation indices for a specific groundwater composition. The groundwater chemistry data, upon which the conceptual models are based, was collected over the period 1997 to 1999. The boreholes were not optimally positioned, while the depth and construction of boreholes were generally unknown. Furthermore, the groundwater samples collected, represent a mixed sample volume due to different inflows emanating from possibly numerous water strikes in a particular borehole.

In addition, information on the mineralogical 'make-up' of the aquifer system as well as a reasonable understanding of the hydrogeochemical controls (including weathering processes) on the activities of the ions in solution is essential to constrain the interpretation based on mineral saturation indices. For example, pyrite minerals were frequently observed in rock samples and the groundwater had a characteristic 'rotten egg' smell in the vicinity of the town of Garies. The following minerals seem to have a major influence on the groundwater composition for this catchment (**Table 1**). The numerous lithological units and associated mineral phases within the study area prevented any further reduction or prioritization of the mineral phases that may influence the groundwater composition.

Table 1: The minerals that have a major influence on the groundwater composition of this catchment, as derived from mineral saturation indices that were calculated with the use of the WATEQF chemical speciation model of Plummer *et al*. (1992).

Supergroup	Group	Minerals
Framework Silicates	1. Feldspar group 1.1 Plagioclase subgroup 1.2. Alkali subgroup 2. Silica group	Albite to Anorthite K-feldspar (i.e. Microcline) Quartz & Chalcedony
Sheet Silicates	Mica group Clay mineral group Chlorite Talc	Kmica (eg. Biotite, Muscovite, Phlogopite, etc.) Kaolinite, Illite & Ca-montmorillonite
Non-Silicates	Carbonate minerals	Calcite, Aragonite, Rhodochrosite, Dolomite Strontianite & Witherite
	Sulphate minerals	Gypsum, Anhydrite, Barite & Celestine
	Halides	Fluorite
	Hydroxides	Gibbsite

Groundwater chemistry

Dominant groundwater types

The groundwater of Namaqualand is generally very similar in character with a dominant NaCl signature throughout the recorded EC ranges and can be described as end-point waters and/or slowly circulating, relatively old groundwater(**Figures 2**). The few groundwater samples with either a Ca-HCO_3 or Na-HCO_3 character may be attributed to elevated partial pressure of CO_2 due to root respiration and microbiological activity as well as carbonate dissolution in the soil zone, driven by selective and localised recharge processes(**Figures 3**). The few Na-SO_4 and Mg-SO_4 type waters are associated with mining and/or agricultural activities in the area.

The dominant NaCl character of the infiltrating waters is a result of either the direct infiltration of NaCl (or Na-K/Cl) dominated precipitation (**Table 2**) or the preferential dissolution and leaching of the more soluble evaporitic salts during the infiltration process. The water table fluctuations are assumed to be minimal for the Namaqualand region. Salt dissolution occurs as the water infiltrates through the weathered overburden. Alternatively, the direct evaporation of precipitation results in the dry deposition of salts. The dominant ions in precipitation are Na (or K) and Cl (**Table 2**).

Table 2: Most of the precipitation in the area has a NaCl or Na-K/Cl character (Adams *et al.*, 2004).

Site ID	pH	EC(mS/m)	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	NH_4^{+}	HCO_3^{-}	Cl^{-}	SO_4^{2-}	NO_3-N
Spk 1 9h15 8-7-01	5.3	8.1	3.36	0.54	2.14	2.84	0.49	0.37	1.99	0.02	3.05
Spk1 11h30 24-8-01	5.8	1.2	0.16	0.08	0.35	1.05	0.14	0.44	0.42	0.01	0.32
Spk1 11h45 21-8-01	6	1	0.05	0.07	0.94	1.09	0.18	0.3	3.10	0.02	0.29
Spk2 8h30 5-7-01	6	2.3	0.29	0.25	1.20	0.01	0.26	0.45	1.82	0.01	0.64
Spk2 9h30 10-8-01	5.8	2.1	0.16	0.27	1.79	0.70	0.10	0.31	2.21	0.02	0.43
Spk2 16H30 4-7-01	5.6	4.8	0.05	0.11	0.65	0.68	0.24	0.23	0.85	0.02	0.41
Spk2 16H45 18-7-01	5.6	2.2	0.13	0.30	2.32	0.10	0.11	0.31	3.28	0.02	0.51
Spk3 8H30 19-7-01	6	3.2	0.14	0.31	2.16	0.01	0.3	0.16	3.15	0.02	0.77

The Na/Cl character of the lower salinity groundwater in the mountainous regions is probably determined by the Na/Cl (or Na-K/Cl) character of the precipitation in areas where direct rainfall recharge is dominant and the preferential dissolution and leaching (to a minor extent) of highly soluble Na/Cl salts to the subsurface. Isotopic signatures confirm that direct rainfall recharge dominates in the higher lying, higher rainfall areas such as the highest reaches of the Kamiesberg and Wildeperdehoek mountain ranges. The driving forces of the above-mentioned process are the dilute infiltrating waters and a reduced evaporation to rainfall ratio for the higher lying regions of Namaqualand.

The evaporation of surface water and soil moisture in the unsaturated zone results in the deposition of evaporitic salts. Above average, periodic precipitation results in the dissolution and predominantly vertical leaching of the evaporated salts to the saturated zone. Various authors attribute the NaCl character of groundwater to the preferential dissolution and leaching of the highly soluble evaporitic NaCl salts. The less soluble salts (i.e. calcite and gypsum) may only partially dissolve while any subsequent evaporation process may result in the re-precipitation of these salts. Such a process of re-precipitation will preferentially increase the concentrations of Na and Cl compared to the other major cations and anions.

The Na/Cl character of the higher salinity groundwater in the lower lying regions of Namaqualand is predominantly related to the dissolution and periodic leaching of highly soluble salts, particularly Na/Cl salts, to the subsurface. The isotopic signatures of these groundwaters indicate that the effects of evaporation, related either to the infiltration of evaporated surface waters or the leaching of previously evaporated salts, are dominant for the lower lying, lower rainfall areas. The driving forces for the above-mentioned process are the periodic recharge events, coupled with a high-evaporation to low-rainfall ratio.

The significant contribution attributed to the dissolution and leaching of evaporative salts to the salinity (i.e. EC) of the groundwater masks the effects of other processes, such as the carbonate and silicate weathering processes, the effects of cation exchange and oxidation-reduction reactions. The dissolution and leaching of evaporative salts may also reduce the weathering capacity of the water (i.e. groundwater) with regard to other mineral phases, such as carbonates and silicates, due to the common ion effect.

Vertical variations in the chemical composition of groundwater are evident through comparisons of perennial natural springs of both relatively fresh and highly mineralized waters. The depth of circulation of the highly mineralized springs seems to be limited due to the average surface temperatures of these waters. The distinctive characteristics of the spring systems seem to be residence time that influences the water-rock interaction reactions and thus result in varying groundwater chemistry. The highly mineralized springs may represent intermediate to 'regional' groundwater flow systems.

The proposed aquifer system (**Figure 4**) has a linear geometry that is associated with the structurally controlled valleys. The aquifer system may be laterally extensive, depending on the nature of the fault systems. A micro-fissured model with predominantly fissure flow was adopted for the fractured, crystalline rocks of Namaqualand. Infiltration of water occurs along vertical to sub-vertical fractures with lateral flow along horizontal to sub-horizontal pseudo bedding planes. The water chemistry can vary considerably among closely spaced fracture systems. The model displays a dominant vertical flow system (i.e. an infiltration phase) driven by local relief and an intermediate flow system driven by gradients along these laterally extensive valley systems.

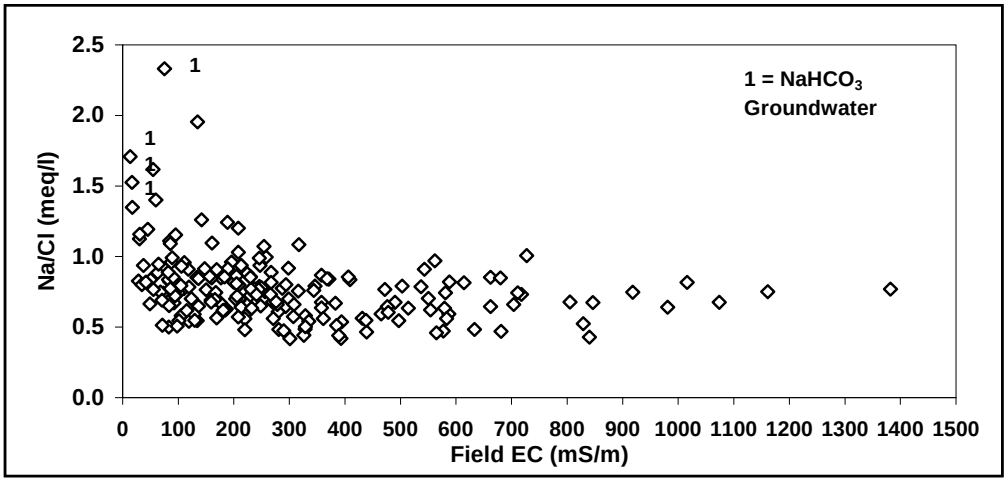

Figure 2: The Na/Cl – field EC relation for groundwater in Namaqualand. Some $NaHCO_3$ waters are indicated (1).

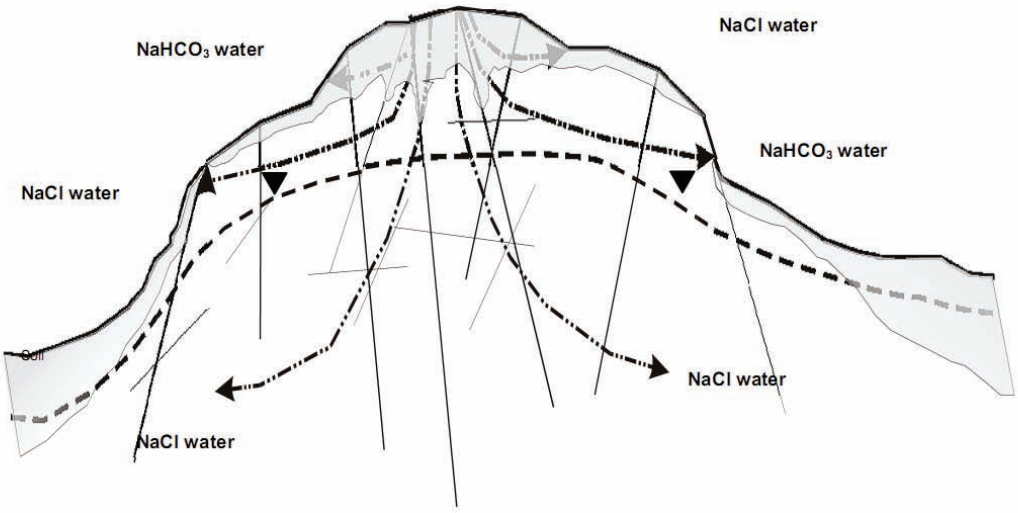

Figure 3: Conceptual model for Na-HCO_3 type water in the soil zone (Kamiesberg mountain range), representing a dynamic, fracture-dominated flow system.

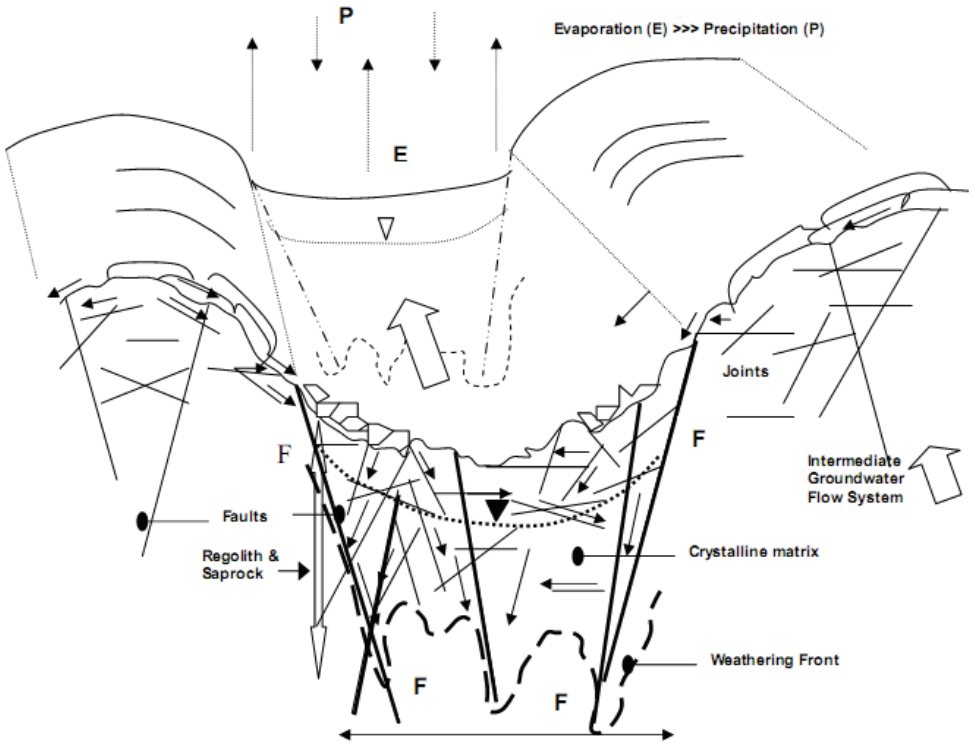

Figure 4: Proposed aquifer geometry and local to intermediate flow regimes for a typical structurally controlled valley within secondary drainage catchment F30.

Silicate weathering

The concentrations of $Si(OH)_4$ as well as the [Na]/[H], [Ca]/[H] and [K]/[H] ratios increase with continued weathering (i.e. incongruent dissolution) of aluminosilicate minerals. Feldspar dissolution ceases only when the water compositions attain equilibrium with respect to a specific feldspar mineral (Freeze and Cherry, 1979). Long residence times associated with sluggish to almost stagnant flow conditions are required to attain equilibrium with respect to feldspar minerals.

The groundwater compositions, expressed in terms of log $[Ca^{2+}]/[H^+]$ and SiO_2 as well as log $[K^+]/[H^+]$ and SiO_2, generally plot in the kaolinite stability field above the solubility limit of quartz but below the solubility limit of amorphous silica. This indicates that the most likely stable alteration product formed, due to the incongruent dissolution of aluminosilicate minerals, is kaolinite. On log $[Na^+]/[H^+]$ vs. SiO_2 diagrams (**Figure 5**) the groundwater compositions, including the higher salinity groundwater, plot in the Na-montmorillonite stability field indicating the probability of equilibrium or near -equilibrium conditions with Na-montmorillonite as a weathering product. The alteration of feldspars and micas to kaolinite and montmorillonite are thus important processes for groundwater in silicate terrains such as Namaqualand. Clay minerals may, however, exist as unstable amorphous precipitates or meta-stable clay mineral intermediates for extensive periods (Freeze and Cherry, 1979), therefore cast doubt on whether true equilibrium with the clay minerals is attained.

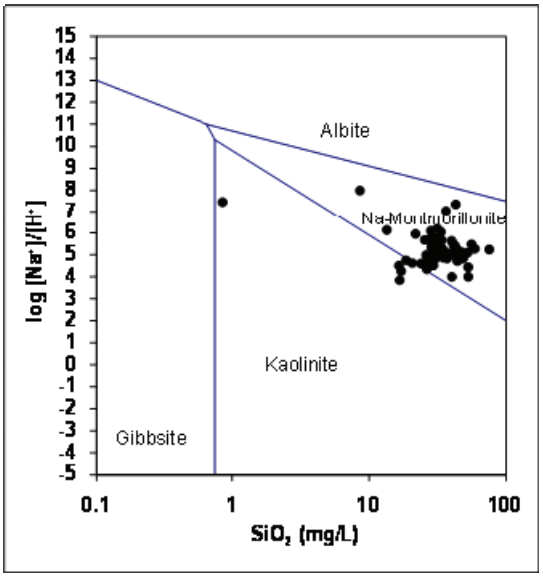

Figure 5: Log $[Na^+]/[H^+]$ vs. SiO_2 phase diagram for groundwater composition of the Buffels River catchment (F30).

The distribution of the groundwater compositional data within the kaolinite and Na-montmorillonite stability fields indicate that the groundwater compositions are likely to be in equilibrium or near-equilibrium conditions with both weathering products. This may indicate that the reactions between the groundwater (or soil water) and the primary minerals are masked by reactions with the more reactive secondary clay minerals.

The composition of water that plots near the kaolinite-gibbsite boundary is influenced by dilution with fresh rainfall (and possibly runoff) and is described as water (or precipitation) dominated, dilute systems (Langmuir, 1997). Rock dominated waters are found in closed systems that are not affected by fresh, diluting and recharging waters. Such waters approach equilibrium with regard to silicates and aluminosilicates and are characterised by relatively higher pH, K^+ and silica values. Most of the groundwater samples seem to fall within the latter category. However, the effects of evaporation mask the contribution of weathering to the salinity and composition of the groundwater.

Mineral saturation indices

The saturation states of groundwater compositions, as a function of salinity (i.e. EC) for various mineral phases, are better illustrated with a log IAP/KT range of –10 to +10 (Appelo and Postma, 1993). Variation in mineral composition for the isomorphic plagioclase range (i.e. albite to anorthite) may result in variable reaction kinetics (i.e. dissolution and precipitation) for the feldspar minerals (Appelo and Postma, 1993). The saturation state of a groundwater composition with regard to plagioclase feldspar minerals can therefore vary with the saturation state of the groundwater compositions with regard to albite and anorthite (**Table 1**). Solid solution, at higher temperatures, between plagioclase feldspars and alkali feldspar, further adds to the uncertainty. The variation in the saturation state of the groundwater compositions with regard to the carbonate minerals may be controlled by the minerals calcite, aragonite, rhodochrosite, dolomite, strontianite and witherite. Whether the above-mentioned minerals are present within the lithological 'make-up' of the aquifer system must be confirmed by detailed mineralogical studies.

The degree of saturation, for a particular groundwater composition, influences the concentrations of the dissolved constituents. Subsaturation of a groundwater composition with regard to mineral phases results in further dissolution, while supersaturation results in the re-precipitation of minerals. Conditions of disequilibria (i.e. both subsaturation and/or supersaturation) can be maintained due to a number of factors. Considerable residence time is necessary for carbonate dissolution to attain equilibrium under field conditions (Freeze and Cherry, 1979).

Degassing or a reduction in the P_{CO2} can also result in the groundwater compositions becoming supersaturated with respect to carbonate minerals. The incongruency relations with regard to the varied carbonates, but especially with regard to the aluminosilicate minerals, also influence the chemical evolution of the groundwater. In addition, conditions of disequilibria can also be maintained due to cation exchange and the common-ion effect.

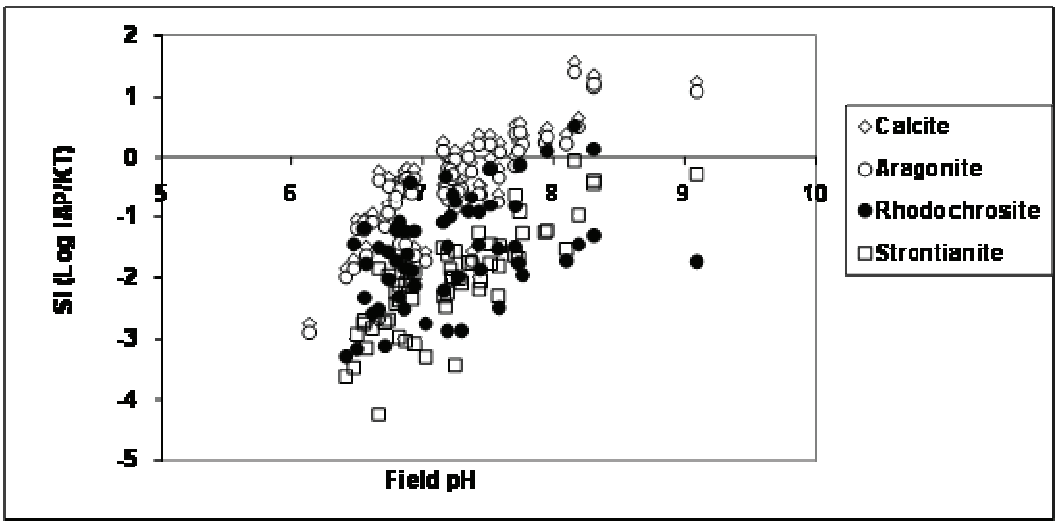

Figure 6: The saturation states of groundwater compositions, as a function of field pH, for various carbonate minerals.

Reaction with carbonate minerals

The groundwater compositions (**Figure 6**) are predominantly saturated to supersaturated with regard to the carbonates calcite, aragonite and dolomite, while being undersaturated to saturated with rhodochrosite and strontianite. The groundwater compositions become increasing saturated to supersaturated with carbonate minerals as the pH increases. The higher salinity groundwater compositions (**Figure 7**) of the pre-Bushmanland Gamoep region are saturated to supersaturated with regard to the carbonate minerals (i.e. calcite, aragonite, rhodochrosite, etc.).

Feldspar and silica group minerals

The groundwater compositions, above a pH value of 6.5, are generally saturated to supersaturated with regard to the feldspars albite and k-feldspar, and range from being undersaturated to super-saturated with regard to anorthite (**Figure 8**). The groundwater becomes even more supersaturated with increasing pH with regard to these feldspar minerals. Trend lines for the feldspars albite and anorthite indicate that the saturation state of a groundwater composition with regard to plagioclase feldspar minerals can vary between the two end members of an isomorphic range (**Figure 9**). Such groundwater compositions are saturated to super-saturated with silica throughout the recorded EC ranges (**Figure 9**).

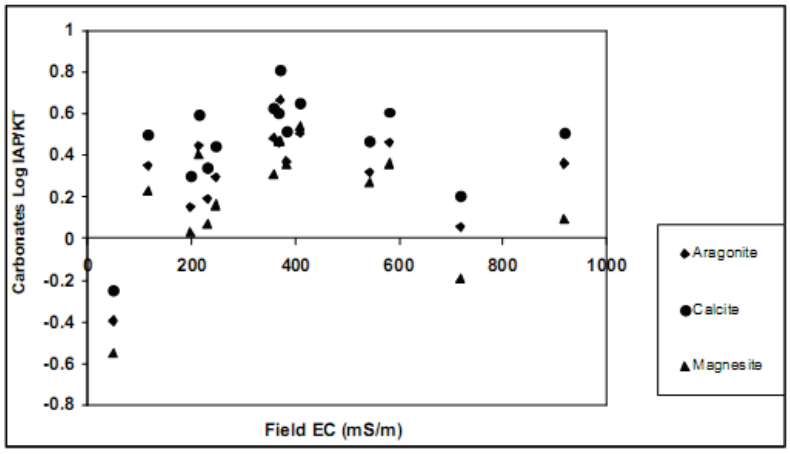

Figure 7: The saturation states of groundwater compositions, as a function of salinity (i.e. lab EC), for various carbonate minerals in the Gamoep region.

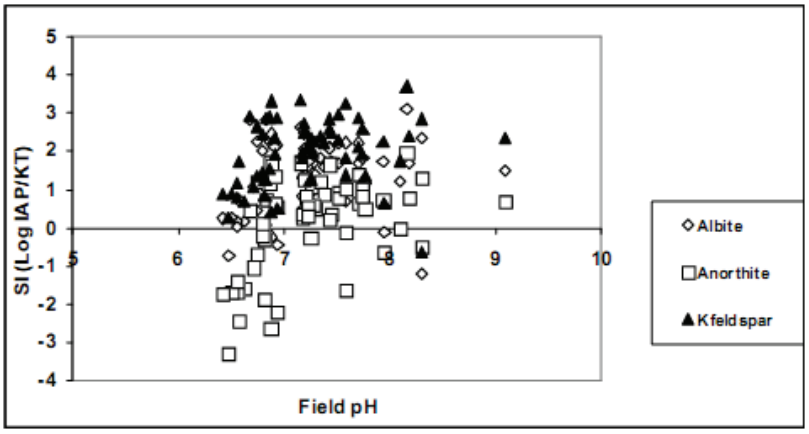

Figure 8: The saturation states of groundwater compositions, as a function of field pH, for plagioclase and alkali feldspar minerals.

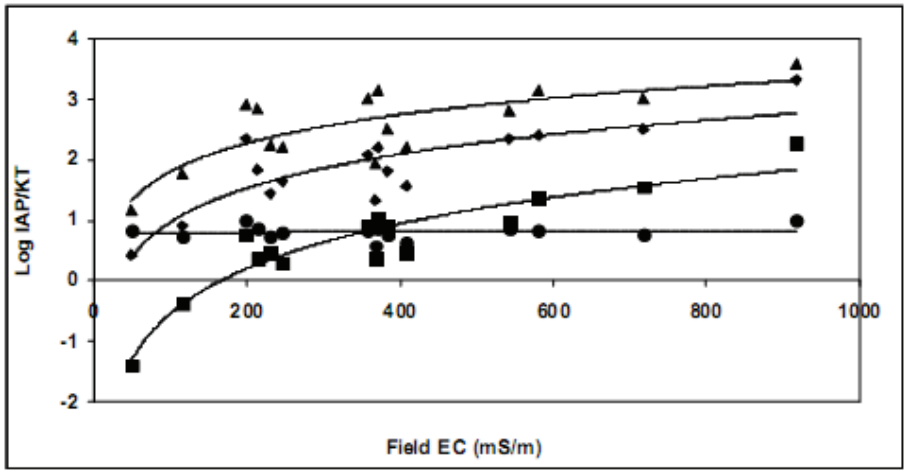

Figure 9: The saturation states of groundwater compositions, as a function of salinity (i.e. Field EC), for plagioclase and alkali feldspar minerals in the Gamoep region. The arrows indicate that the saturation state of a groundwater composition with regard to plagioclase feldspar minerals can vary between the saturation states for the isomorphic range from albite to anorthite.

Micas, clay minerals, chlorite and talc

The groundwater compositions are likely to be supersaturated with the most common potassium (K) micas such as biotite, muscovite, phlogopite and lepidolite. A decrease in the SI values above a pH value of 7.2 is observed for gibbsite and potassium (K) micas.

The groundwater compositions tend to be supersaturated with kaolinite, Ca-montmorillonite and illite (i.e. the clay mineral group). A decrease in the SI values above a pH value of 7.2 is observed for each of these clay mineral phases (**Figure 10**). The groundwater compositions approach equilibrium with respect to chlorite and talc below pH values of 7, while becoming increasingly supersaturated with chlorite and talc above pH values of 7.2.

Sulphates and fluorite (a halide)

The groundwater compositions are undersaturated with gypsum, anhydrite and celestine while being saturated with barite. Furthermore, the groundwater compositions are subsaturated with fluorite below pH values of 7, while being in equilibrium with fluorite above pH values of 7.

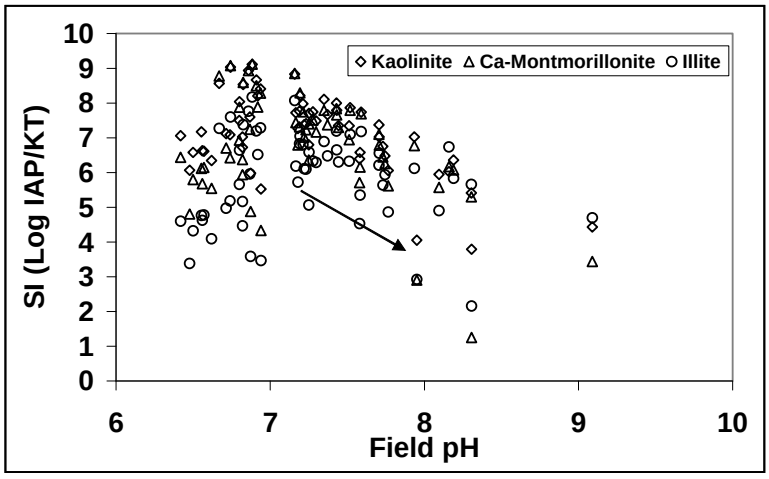

Figure 10: The saturation states of groundwater compositions, as a function of pH, for the clay mineral phases (i.e. kaolinite, Ca-montmorillonite and illite).

Hydroxides

The groundwater compositions tend to be undersaturated to saturated with an amorphous aluminium hydroxide phase ($Al(OH)_3$) below a pH value of 7. The SI values of the amorphous aluminium hydroxide phase ($Al(OH)_3$) decreases below the equilibrium level (i.e. SI = 0) above a pH value of 7.2 (**Figure 11**). The groundwater compositions are also likely to be supersaturated with gibbsite. A similar decrease in the SI values above a pH value of 7.2 is also observed for gibbsite.

Although the groundwater compositions tend to be in equilibrium with an amorphous aluminium hydroxide phase ($Al(OH)_3$), it is supersaturated with the crystallized aluminium oxide or hydroxide phases such as gibbsite, potassium (K) micas and the clay mineral group. This can be ascribed to the much higher solubility of the amorphous aluminium hydroxide phase ($Al(OH)_3$) compared to the crystallized aluminium oxide or hydroxide phases.

The slow reaction kinetics of silicate minerals (including clay minerals) can result in uncertainties about the stability of the intermediate weathering products. The groundwater, however, tend to react with both the primary mineral phases and the weathering products (eg. the clay minerals) or at least with an intermediate, meta-stable phase.

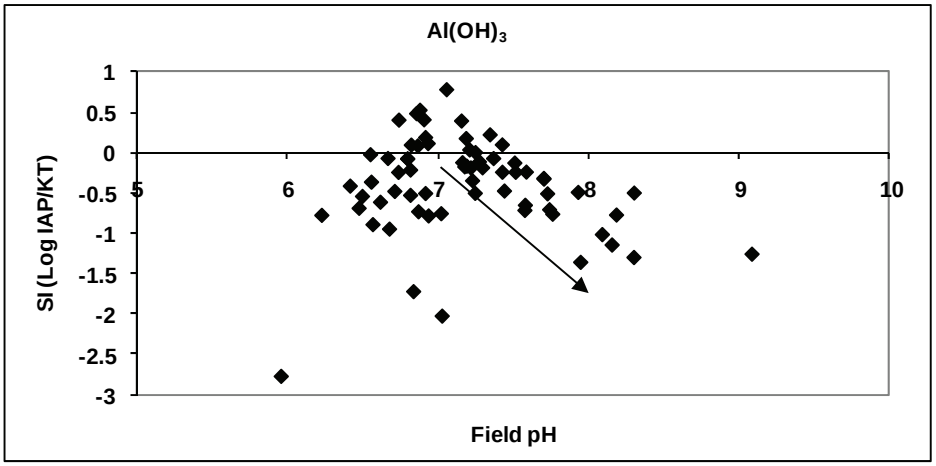

Figure 11: The saturation states of groundwater compositions, as a function of pH, for an amorphous aluminium hydroxide phase ($Al(OH)_3$).

Sources for dissolved constituents

Various ion activity ratios were used to determine the origin of ions in solution. The dissolution of carbonate minerals results in an increase in the pH and bicarbonate (HCO_3^-) concentrations while certain cations are leached to the groundwater (Langmuir, 1997; Appelo and Postma, 1993; Kay, 1985 and Freeze and Cherry, 1979). The weathering of aluminosilicate minerals also results in the leaching of cations as well as silica with a simultaneous rise in the bicarbonate (HCO_3^-) concentrations and pH values. An increase in the cation concentrations is generally associated with an increase in the dissolved bicarbonate concentrations, even to an extent where carbonate precipitation may result from the weathering of aluminosilicate minerals (Appelo and Postma, 1993). Redox reactions, in particular sulfate reduction, also produces HCO_3^-.

The relations between the cations (Ca^{2+}, Na^+ and Mg^{2+}) and HCO_3^-, based on the molar ratios of these ions produced during the incongruent weathering reactions for various aluminosilicate minerals, are tabulated (**Table 3**) and illustrated in **Figures 12 and 13**. In addition, molar ratios between cations for similar weathering reactions are tabulated. The molar ratios (**Figures 12 and 13**) indicate that the incongruent weathering processes of various aluminosilicate minerals cannot alone account for the groundwater compositions.

Table 3: Expected molar ratios for the weathering reactions of some aluminosilicate minerals (after Appelo and Postma, 1993).

Silicate Minerals	Ions	Molar Ratios
Albite to Kaolinite	$Na^+ : HCO_3^-$	1 : 1
Anorthite to Kaolinite	$Ca^{2+} : HCO_3^-$	1 : 2
Augite to Kaolinite	$Ca^{2+} : HCO_3^-$	1 : 3.7
Augite to Kaolinite	$Mg^{2+} : HCO_3^-$	1 : 4.3
Pyroxene to Kaolinite	$Ca^{2+} : Mg^{2+}$	1 : 0.7
Biotite to Kaolinite	$K^+ : Mg^{2+}$	1 : 2
Olivine (Forsterite) dissociation	$Mg^{2+} : HCO_3^-$	1 : 2

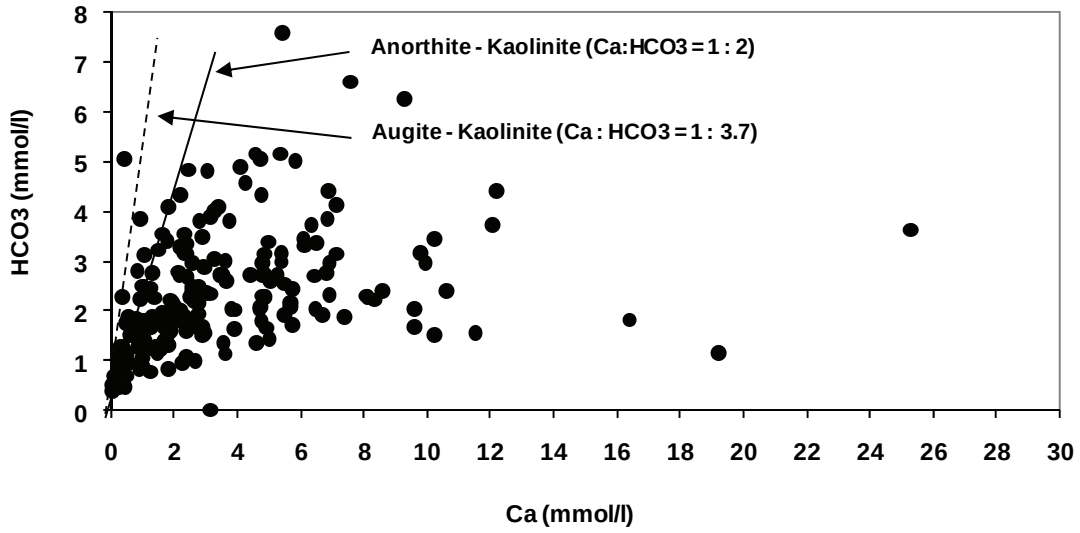

Figure 12: The relationships between Ca^{2+} and HCO_3^- compared to the anorthite to kaolinite as well as the augite to kaolinite weathering reaction lines (after Locsey and Cox, 2000).

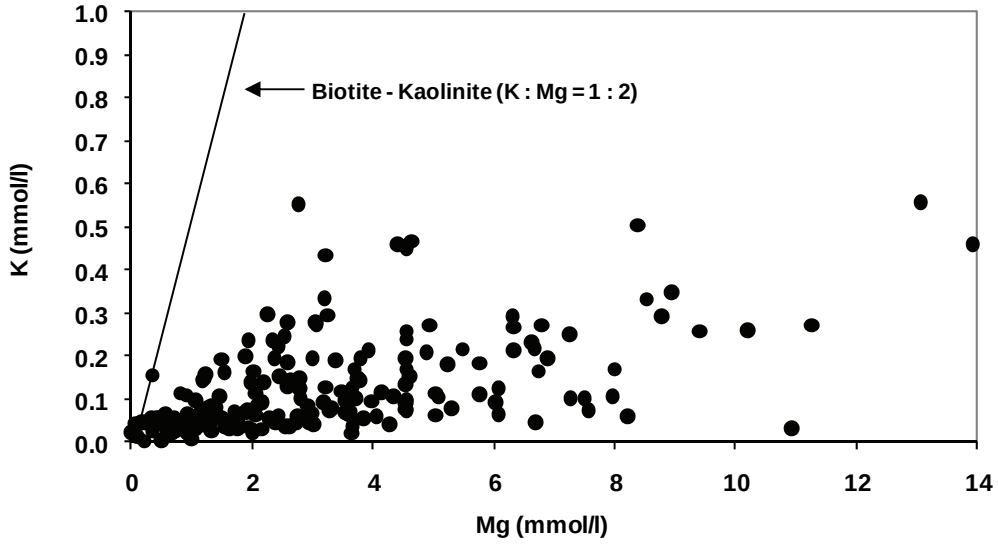

Figure 13: The relationships between K^+ and Mg^{2+} compared to the biotite to kaolinite weathering reaction line.

Sami (1992) also used the Na/Cl ratio to distinguish between a marine/oceanic input (Na/Cl = 0.86), halite dissolution (Na/Cl = 1), aluminosilicate (i.e. albite) weathering and cation exchange processes. A $(Ca+Mg)/HCO_3$ ratio of 0.5 accounts for carbonate and inosilicate minerals (i.e. pyroxenes and amphiboles) as probable sources of dissolved Ca and Mg. Ratios of $(Ca+Mg)/HCO_3$ in excess of 0.5 may indicate other sources of dissolved Ca and Mg, re-dissolution and leaching of gypsum and cation exchange processes rather than HCO_3 depletion through the formation of carbonic acid (H_2CO_3) which is dependent on the pH conditions (Sami, 1992).

The Na/Cl ratio of the groundwater (**Figure 14**) decreases gradually with increasing salinity to a value lower than the equilibrium Na/Cl ratios for both oceanic water input (i.e. Na/Cl = 0.86) and halite dissolution (i.e. Na/Cl = 1). The depleting Na concentrations, relative to the Cl concentrations, may be due to the dissolution of salts other than halite (i.e. NaCl), or the result of cation exchange processes through the exchange of dissolved Na for bound Ca and Mg.

The $(Ca + Mg)/HCO_3$ ratio, in all groundwater samples, exceeds the value of 0.5 and increases with increasing salinity. An increasing trend for the $(Ca + Mg)/HCO_3$ ratio with increasing salinity indicates that Ca and Mg are added to the groundwater at a greater rate than HCO_3. The increasing $(Ca + Mg)/HCO_3$ ratio also indicates that the sources of Ca and Mg are varied, in addition to carbonate dissolution and the weathering processes of inosilicate minerals. The increasing Ca and Mg concentrations in solution, relative to the HCO_3 concentrations, may be due to the dissolution of evaporitic salts in addition to the weathering of the carbonate and aluminosilicate minerals. The increasing Ca and Mg concentrations may also be due to the remobilization of evaporitic gypsum. Cation exchange processes, through the release of bound Ca and Mg in exchange for dissolved Na, will also increase the Ca and Mg concentrations in solution. According to Kay (1985) and Freeze and Cherry, (1979), the weathering products that form on mineral surfaces as a result of incongruent dissolution processes have significant cation exchange capacities capable of changing the ion ratios in groundwater.

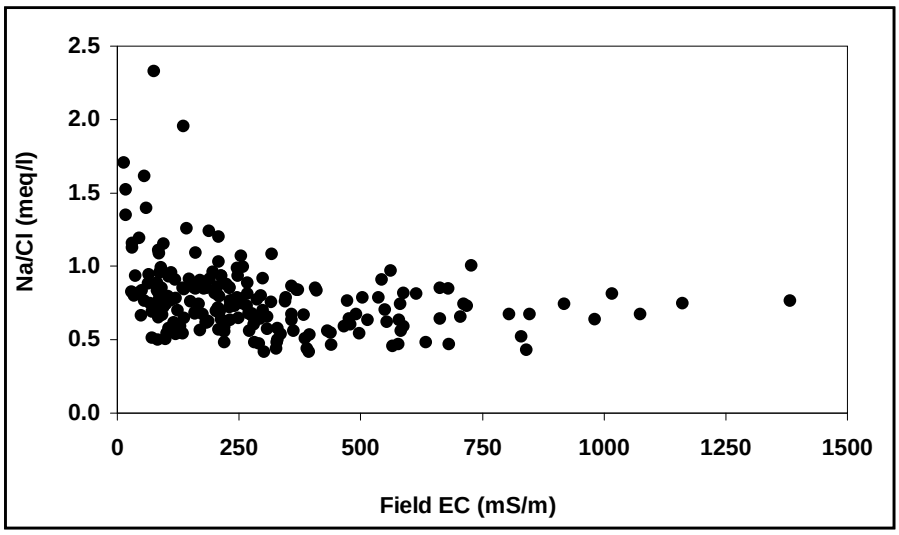

Figure 14: The Na/Cl – Cl ratio for groundwater in Namaqualand.

Trends for dissolved constituents

The activity ratios of [Na]/[H], [Ca]/[H] and [K]/[H] increase with increasing salinity, indicating active weathering of the aluminosilicate minerals. The rate of change for the latter ratios is also more pronounced for the lower salinity groundwater with EC values less than 150 mS/m. The [Na]/[H], [Ca]/[H] and [K]/[H] relations remain fairly constant for the higher salinity groundwater. Kay (1985) suggested that the weathering of the secondary clay minerals become more important as weathering proceeds.

A strong relation (**Figure 15**), in respect of the groundwater of the Buffels River catchment (F30), exists between %Si (as a percentage of cations), $\%HCO_3$ (as a percentage of anions), ^{18}O (oxygen-18) and ^{2}H (deuterium) with increasing electrical conductivity (EC). The %Si - $\%HCO_3$ - ^{18}O - ^{2}H relation with increasing electrical conductivity can be used to spatially

distinguish between dilute, shallow circulating and relatively young groundwater systems compared to more brackish, slower circulating and relatively older systems. The decreasing %Si and $\%HCO_3$ values suggest a reduction in the weathering capacity, with regard to the aluminosilicate and probably the carbonate minerals, of the higher salinity groundwater within the lower lying valley systems. The more enriched ^{18}O - ^{2}H values with increasing EC are related to the increasing effects of evaporation.

The %Si - $\%HCO_3$ - ^{18}O - ^{2}H relation also suggests a continuous hydrochemical evolution between the dilute, shallow circulating and relatively young groundwater systems and the more brackish, slower circulating and relatively older systems. However, the two end-member groundwater systems represent separate systems in a spatial context. The relatively dilute end-member is associated with dynamic, actively recharged groundwater systems with rapid through-flow rates that occur in the higher lying mountainous regions, or with infiltration through highly transmissive fracture zones within the lower lying valley systems. The more brackish end-member, associated with the valley systems or the lower lying regions, is characterized by a localized flow component (i.e. an infiltration phase) and possibly an intermediate flow component (i.e. a lateral flow phase). The infiltration phase is characterized by repetitive processes of dissolution and leaching of evaporative salts, while an inferred, sluggish, lateral flow phase is driven by reduced gradients within the valleys.

Stratification, representing a variation in EC with depth, in the water column was recorded in one borehole near the town of Tweerivier. The spatial illustration of the %Si - $\%HCO_3$ - ^{18}O - ^{2}H relation therefore indicates that stacked, multiple flow systems dominate, which differ in terms of flow rates and the factors influencing the groundwater flow and chemistry, including the recharge rate, hydraulic gradient and hydraulic conductivity. Regional recharge areas, within the Buffels River catchment, can also be identified through this relationship.

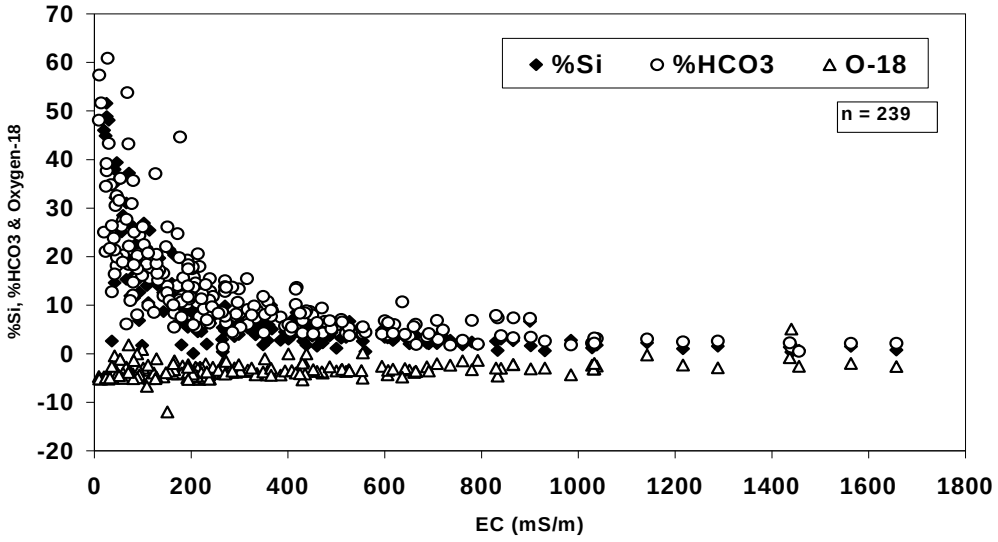

Figure 15: The relationship between %Si (as a percentage of cations), $\%HCO_3$ (as a percentage of anions), ^{18}O (oxygen-18) and ^{2}H (deuterium).

Conclusions

The dominant NaCl character of the groundwater is a result of either the direct infiltration of NaCl dominated precipitation and the preferential dissolution and leaching of the more soluble evaporitic salts during the infiltration process. The groundwater remains a NaCl type water throughout the recorded EC ranges.

Active weathering processes, with regard to various mineral phases, are evident throughout the EC range for the lower salinity groundwater. The dilute and relatively aggressive groundwater, associated with higher lying regions, controls the weathering (eg. acid-base reactions) of the mineral phases, while the significant head differences (related to differences in elevation for these mountainous areas) result in dynamic flow systems in which equilibrium is difficult to attain while the weathering products are continuously removed. Active weathering processes thus dominate in the higher lying

regions where direct rainfall recharge is dominant and contribute significantly to the dissolved load of the groundwater. Active weathering processes can also occur in lower lying areas as a result of infiltration through preferred pathways such as the weathered material at the base of gneissic domes or through highly transmissive fracture zones. Such groundwater systems are regarded as shallow circulating and relatively young.

A reduction in the weathering capacity, with regard to especially the aluminosilicate and probably the carbonate minerals, is suggested for the relatively higher salinity groundwater in the lower lying regions of Namaqualand. The reduction in the weathering capacity of the higher salinity groundwater can be related to the infiltration of evaporated waters or the leaching of evaporated salts, the increasing concentrations of dissolved constituents with residence time (i.e. the degree of saturation of the groundwater with various mineral phases), the incongruent relations of various minerals (including carbonates and aluminosilicate minerals), a reduction in the $CO_{2(aq)}$ (in closed systems), the effects of cation exchange, the common-ion effect or even to the coating of primary minerals by residual clay minerals. The lower lying regions of Namaqualand are characterized by intermittent, periodic recharge events, lower hydraulic gradients within the valley systems and varying hydraulic conductivity values within the saprock to saprolite aquifer zone. Such groundwater systems are regarded as brackish, slower circulating (under reduced hydraulic gradients) and relatively older systems.

The groundwater chemistry is therefore dependent on the point of sampling in either a dynamic or an evaporation-dominated, sluggish groundwater system. Stacked, multiple flow systems dominate. They differ in terms of the factors that influence both the groundwater flow and chemistry, including the recharge rate, hydraulic gradient and hydraulic conductivity. The rate of groundwater flow influences the reaction rates with primary and secondary mineral phases which in turn influence the resultant groundwater chemistry. Superimposing and probably masking the latter processes is the direct infiltration of NaCl dominated precipitation and the preferential dissolution and leaching of the more soluble evaporitic salts during the infiltration process.

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Towards sustainable utilization of basement aquifers in southern Africa

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Abstract

Basement aquifers, although minor in hydrogeological terms, are of vital importance for small-scale water supply in Southern Africa. Already between 60-90% of communities in rural southern Africa are served from groundwater sources and in particular from basement aquifers. This role of groundwater in the region has become a strategic one, because of the shift in political priorities in Africa to poverty alleviation and socio-economic development that are expressed in the Africa Water Vision and national and international targets, like the Millennium Development Goals. With the main focus having been on water supply infrastructure development, many problems continue to occur with this water service, including poor operation and maintenance of small groundwater schemes, rapid pollution of rural water supplies and sudden failure of schemes during drought. Based on the experience of such ultimately unsustainable use of small-scale groundwater supplies in both Africa and India, a shift from the present relatively restrictive concept of groundwater management to one of groundwater governance is proposed. In addition to the traditional resource perspective this concept should include a strong focus on empowering stakeholders and an institutional platform of policy, planning, financing, regulation and capacity building in order to sustain the initiatives.

Introduction

Much of southern Africa is underlain by crystalline basement rocks. In these areas, the basement forms a minor aquifer known as basement aquifer. Although minor in hydrogeological terms, such aquifers are of vital importance for small-scale water supply, providing water for villages and small towns in areas where there is often no alternative source of perennial water (Wright and Burgess, 1992).

Basement aquifer characteristics

Basement aquifers are composite, comprising a variable thickness of weathered overburden, overlying bedrock, the upper part of which is frequently fractured. The weathered overburden is usually the main groundwater storage compartment, although boreholes may be developed in the underlying fractured bedrock. Where the regolith is thick and the water table shallow, yields may sustain a hand pump, but where the weathering is much thinner and the water table deeper, the regolith is unlikely to be usable.

Many factors determine the degree of rock weathering. Weathered material composition and aquifer properties can vary significantly, even at a local scale. Viable aquifers wholly within the fractured bedrock are a rare occurrence because of the typically low storativity of fracture systems. To be effective, development of the bedrock component requires interaction with storage available in overlying or adjacent saturated regolith or other suitable formations such as alluvium. Despite the regional occurrence of weathered basement rock, the actual aquifer response is usually very localized due to discontinuities within the fracture system being tapped or due to the constraints within the low permeability regolith. These features are commonly reflected in a significant borehole failure rate and a wide range of yields. Because of the small storage of basement aquifers the recharge component is important for sustainable utilization of the water resource.

The natural chemical quality of groundwater from basement aquifers in tropical regions of Africa is considered to be of acceptable quality. Within temperate climatic zones, TDS varies between 100 mg/ℓ to 300 mg/ℓ, whereas in semi-arid regions TDS values commonly exceed 2 000 mg/ℓ (Chilton and Forster, 1995).

Development constraints

Current development constraints for these basement aquifers have been summarized well by Wright and Burgess (1992) and include the following:

- The frequent high failure rate of boreholes, commonly in the range of 10-40%, with the higher rates in drier regions or where the weathered overburden is thin;
- Shallow occurrence and fissure permeability of the bedrock aquifer component which makes for susceptibility to surface pollutants;
- The low storability of basement aquifers, which may therefore deplete significantly during sustained drought periods. Recharge is also sensitive to certain land-use changes, notably those associated with desertification.

These constraints still hold today and are exacerbated by a tendency to focus on water infrastructure delivery at the expense of operation and maintenance in order to meet national and international delivery targets.

The natural hydrogeological environment exerts the dominant control over the availability of groundwater resources for any type of development and the corresponding water supply development costs and difficulties. This relationship has been summarized in **Figure 1** and **Figure 2** below for the various types of rural groundwater use and for the five broad groups of aquifers commonly occurring in tropical latitudes of the developing world (Foster *et al*., 2000).

The most favourable locations are often associated with geological features (such as fault zones and fractures), which encourage deeper weathering and may also be local foci of recharge. (Foster *et al*., 2000).

The general conclusion from these two figures is that basement aquifers (WCB in **Figure 2**) are only adequate for domestic and livestock water supply. Under exceptional circumstances of deep and extensive weathering, basement rocks are being used for commercial irrigation (IWMI, 2002), but this has no relevance for a general conclusion on the role of basement aquifers. More importantly, research and practice in South Africa has shown that good planning and systematic resource exploration can extend the scope of basement aquifers into the bracket of small-scale irrigation and piped village water supply, even under unfavorable geological conditions (Sami *et al*., 2002).

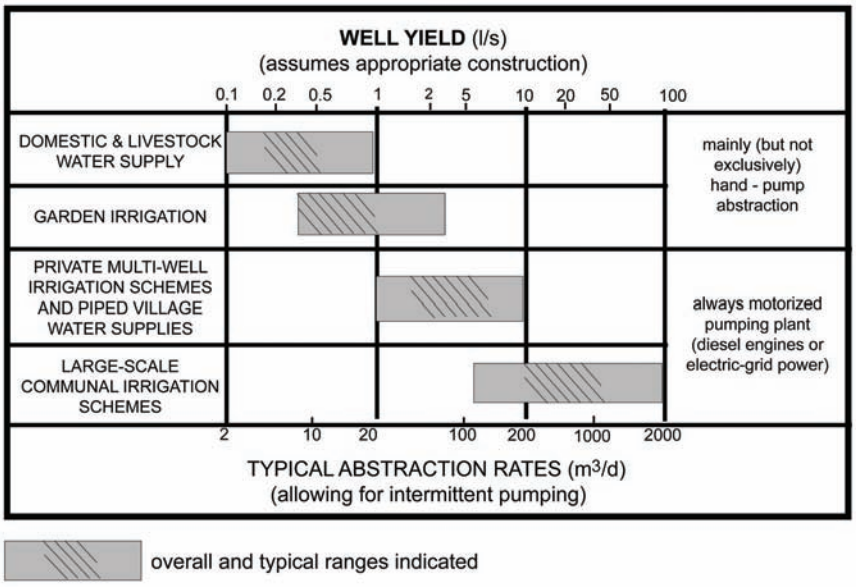

Figure 1: Variation of well yields and abstraction requirements for various types of rural groundwater use

Note: Those that do not require a motorised pumping plant do not threaten groundwater resource sustainability and thus need only minimal regulation, appropriate hydrogeological investigation and engineering design protocols. Foster *et al*., 2000.

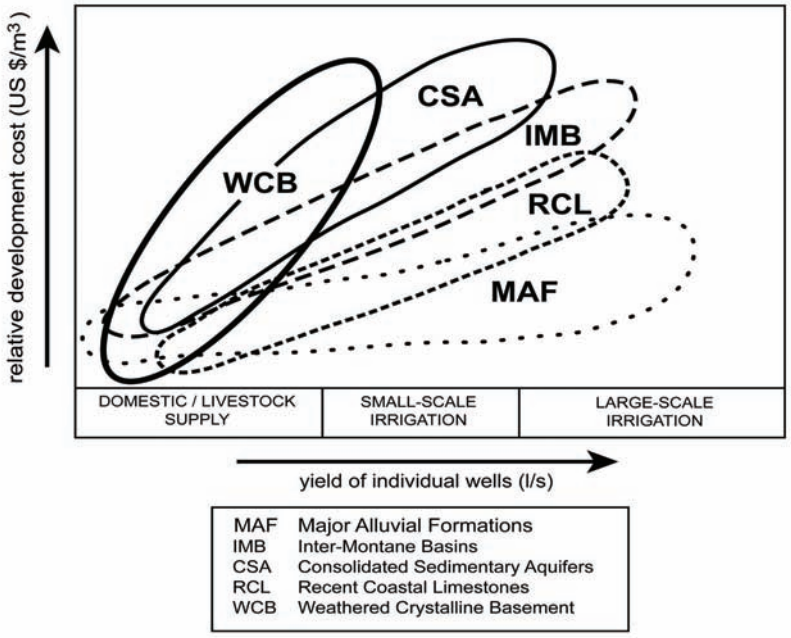

Figure 2: Variation of groundwater supply development options/costs with aquifer type

Note: Generalized development cost for desired yields and overall yield limitations (Foster *et al*., 2000).

The changing role of groundwater

The changing role of groundwater can best be illustrated by the example of South Africa. Until the advent of the current National Water Act of 1998, groundwater was defined in law as "private water" and was considered to be of local importance only. The predominately hard rock systems, of which basement aquifers make up a major part, only contributed about 12% to total bulk water supply. With the democratisation of the country in 1994, there was a strong policy shift towards the provision of basic services, including water and sanitation services, to the entire population as soon as possible. The indication at that time was that 12 million people or 30% of the population did not have the most basic water supply. By now the backlog has been reduced to 4 million and groundwater has played a major role in this regard. This is illustrated in **Table 1,** which shows the various sources (surface water, groundwater or a combined source) for community water supply in six of the nine provinces of South Africa.

It is clear that, overall, groundwater supplies more than 60% of the country's population with water and it increases to 90% in some provinces.

This is in line with international trends in which groundwater worldwide is considered to be a reliable source of drinking water. Its special characteristics also make it ideally suitable for various forms of conjunctive use, together with other water resources, thereby achieving a more optimum utilization of the total resource.

Already the rural domestic use from groundwater in South Africa has increased from 120 million m^3 per annum in 1986 to 310 million m^3 per annum in 2000. This use only represents 15% of total groundwater use, which is still largely used for commercial irrigation in a few areas (65% of total groundwater use). However, in the predominantly low-yielding basement rock areas, of which the Limpopo province is a typical example, most of the groundwater use is for domestic water supply.

A similar picture of groundwater's growing importance is emerging from other countries in southern Africa that have a high proportion of basement aquifers. In Zimbabwe 70% of the rural population relies on groundwater (Sunguro *et al.,* 2000) and in Swaziland this figure is as high as 90% (Integrated Regional Information Networks, 2002).

Table 1: Groundwater for domestic use in South Africa

Water Resources	PROVINCES											
	Eastern Cape		Kwazulu-Natal		Limpopo		North West		Northern Cape		Free State	
Communities	Number	%	Number	%	Number	%	Number	%	Number	%	Number	%
Surface Water	898	16	940	8	5	0	292	16	88	36	163	57
Groundwater	4 234	75	10 073	89	1 415	58	152	83	150	62	92	32
Combined Sources	510	9	268	2	1 041	42	20	1	5	2	32	11
Totals	**5 642**		**11 281**		**2 461**		**1 874**		**243**		**287**	

It is clear from the above statistics that groundwater, and in particular basement rock groundwater, plays a dominant role in meeting Millennium Development Goals with regard to the provision of basic water services.

This raised profile of groundwater is reflected in a recent survey of major groundwater management issues in South Africa. The following are the issues that are relevant for basement aquifers:

- Groundwater as a strategic resource for community water supply, even in surface water-rich catchments;
- Groundwater as a conjunctive use source throughout the country and particularly in water-stressed areas;
- Groundwater as a driver of sensitive aquatic ecosystems, e.g. spring systems, riverbase flow, habitat and wetlands;
- Need for pro-active protection of groundwater resources, because of the widespread impacts of pollution, particularly in urban and mining environments, but also in the rural agriculture and settlement situation.

In line with this recognition of groundwater's national importance in South Africa, its legal status has changed form "private water" in the former act (Water Act, 1956) to a "significant resource" that is subject to the same management measures as surface water in the act (National Water Act, 1998). This includes authorization of all uses that exceed basic human needs. Registration of drillers and the provision of all water borehole information to a national database are seen to be a further step to control groundwater development. Such strict controls already exist in Zimbabwe, where, in terms of the Water Act of 1998 and the ZINWA Act of 1998, seven catchments have been defined that will be manned by catchment councils that are responsible for granting permits.

To improve planning, development and management in Zimbabwe, new groundwater regulations and guidelines have been developed for borehole drilling and construction, groundwater use, monitoring and reporting. Sub-catchment councils are the lowest official tier and will regulate and supervise the exercising of rights to water within their areas (Sunguro *et al.*, 2000).

Problems relating to sustainable utilization of basement aquifers

Like most other renewable natural resources, groundwater has come under increasing human development pressures during this century. Because of its unique role in the landscape and its largely unseen nature, groundwater and the aquifers that host it are particularly vulnerable to these impacts. Lack of understanding of groundwater in a hydrological systems context has maintained traditional perceptions of groundwater access and use that are intensely 'private', irrespective of its legal status. Its large-scale exploitation, in particular for irrigation, is really a phenomenon of the late 20th century and is related to advances in pumping and drilling technology rather than a development that is based on broad national needs.

Such increasing groundwater usage has had unexpected consequences in many parts of the world, inducing widespread draw-down externalities, including the depletion of the all-important shallow aquifers.

Table 2: Key issues relating to sustainable use of basement aquifers in southern Africa

Issue	Manifestations (examples)
Access to basic water supply	In 2000, 36% of the African population was still unserved and this had only improved by 5% since 1990. The rural coverage is much worse and stood at 74% with no access to a basic water supply. (Interim African Water Development Report 2003).
Reliability of supply	Poor operation and maintenance; Inadequate local management; Poor efficiency and useful life of investment (Foster *et al.*, 2000)
Failure of supply during droughts	Sudden failure – no early warning; Water quality deterioration during drought; Ineffectiveness of emergency response; Problems with emergency infrastructure (Calow *et al.*, 1997; Houston, 1992; Wright, 1992; Lovell,2000; and Foster *et al.*, 2000).
Water supply for productive use	Lack of integrated rural development; Top-down approaches do not allow for community choices; Little focus on productive use of groundwater resources while working to meet the basic water supply targets (Braune, 2001).
Regulation for protection and use of resource	Future dangers in the utilization of groundwater are derived more from the quality than the quantity (Villarroya, 1994); Newly established rural water supplies are rapidly polluted (Foster *et al.*, 2000); Over-exploitation of groundwater is largely related to commercial use.
Information, awareness, understanding	Ad hoc groundwater exploration; No systematic data base and resource assessment; Inadequate investment in groundwater information (Foster *et al.*, 2000); Inadequate planning – not the same as for surface water resources. (Braune, 2005).
Institutional capacity	Sustainable development, including groundwater development, requires local action; National and donor-driven programmes to meet basic water supply targets – little development of local capacity; Inadequate capacity of new local institutions; Inability of local/regional institutions to introduce effective controls (Foster *et al.*, 2000).

Besides the serious socio-economic consequences of the loss of a life-giving resource, particularly for vulnerable rural communities, there are clear signs of irreversible impacts on the environment through the drying up of entire landscapes, e.g. destruction of wetland and terrestrial ecosystems as well as migration of poor quality water. Furthermore, the disposal of human waste is increasingly affecting the utility of groundwater resources. Groundwater is particularly vulnerable to this kind of over-use, because the impacts can remain hidden for many years and by the time they are discovered, they are very difficult and costly to remediate. Again, the problem has only become acute with heavy use as in the case of industrialization, modern agriculture and dense settlements.

These problems are also very prevalent in southern Africa, as illustrated in **Table 2** with reference to various issues relating to the sustainable use of basement aquifers.

Developing countries are often more dependent than industrial countries on their natural resources – soil, water, fisheries, forests, minerals – and the poor within developing countries are the most dependent. With investment capital generally scarce, the low productivity of human capital and the destruction of natural resources loom large as constraints to economic progress in many developing countries.

The particular setting of the regions with widespread basement aquifer occurrence can be described as arid to semi-arid, largely low-income rural areas. They are characterized by water shortages in spite of low levels of water use, even relative to low availability, due to a lack of financial resources, technical expertise and institutional support. It is exactly these areas that are so clearly captured in the Africa Water Vision (Organization for African Unity *et al.,* 2000). The shared vision is for:

> *"An Africa where there is equitable and sustainable use and management of water resources for poverty alleviation, socio-economic development, regional cooperation, and the environment."*

This vision is in line with the most recent thinking on Integrated Water Resources Management (IWRM), which aims to strike a balance between the use of resources for livelihoods and conservation of the resource to sustain its functions for future generations. It promotes social equity, environmental sustainability and economic efficiency (Department of Water Affairs and Forestry, 2005).

Because of national and regional priorities, the key focus in Africa is still on the provision of basic services. This is because Africa, at this stage, has the lowest water supply and sanitation coverage in the world, with 300 million, or more than 1 in 3 Africans, not yet having access to safe water (World Water Forum, 2006). The provision of basic water and sanitation is an essential part of water's contribution to poverty eradication. Basement aquifers play a major role in this regard. However, basic water services do not make adequate provision for productive livelihoods. The rural poor often rely for their livelihoods on cultivating food, gathering natural products and other water-dependent productive activities. Also, the productive uses of water can provide an income source that is both dependent on and explicitly linked to the water supply, thereby providing both an incentive (willingness) and means (ability) to pay for system maintenance, which is an important factor in supply sustainability (Braune, 2001). In addition, in future much greater attention will have to be paid to the environmental sustainability dimension of IWRM.

Interventions for sustainable utilization of basement aquifers

Introduction

Holistic thinking on water resource management has also found its way into the groundwater community. Foster (2000), with considerable experience of groundwater on the African continent, considers the achievement of sustainable and optimized aquifer management to be amongst the most important, least recognized and highly complex natural resource challenges that face society. He considers it to be a long-term, multi-disciplinary and multi-faceted activity, which should recognize and respect hydrogeologic and socio-economic diversity and that requires considerable investment in terms of institutional development and systematic data collection.

Mukherji and Shah (2005), based largely on their experience of basement aquifers in India, see the challenge as a paradigm shift from the relatively restrictive concept of groundwater management to groundwater governance. According to these authors, sustainable groundwater management anywhere in the world will require the blending of three distinct perspectives (Mukherji and Shah), namely:

1. The characteristics and behavior of the groundwater resource (resource perspective);
2. The characteristics and behavior of the resource-user community (user perspective); and
3. The institutional framework under which the resource is appropriated and used (institutional perspective).

This appears to be a useful grouping for the discussion of a number of interventions, which together can lead to a more sustainable utilization of basement rock groundwater, as illustrated in the concluding section.

Considering the key issues relating to sustainable utilization of basement aquifers (**Table 2**) together with the African Water Vision and its proposed roll-out, these interventions are identified and discussed briefly below.

Resource perspective

The following appear to be traditional hydrogeologist tasks, but they will all have to be executed more systematically and be more focused on the higher-level objective of sustainable development.

- Improving understanding of hard rock aquifer systems from a sustainable utilization perspective, including:
  - the recharge behavior;
  - the usable storage and its reliability during droughts;
  - water quality protection;
  - the interdependence of groundwater and surface water resources and the conjunctive use implications;
  - improved water balance models that are based on data available in developing countries;
  - classification of water resources in terms of their characteristics, human use and role in the landscape;

  - appropriate policy instruments (Foster, 2000; Pietersen, 2005; Mukherji and Shah, 2005; Issar, 1998; Farr *et al.*, 2005).
  - Analyzing the implications of the greater use of basement rock aquifers for supporting food security (Mukhirji and Shah, 2005);
  - Building institutional, technological and human capacity for effective water management (Organization of African Unity *et al.*, 2000);
  - Raising awareness of water management issues with decision-makers, water users and civil society (Organization of African Unity *et al.*, 2000);
  - Conducting research and development on water resources issues (Organization of African Unity *et al.*, 2000).
- Establishing a sustainable system for data collection, management and dissemination, including standardization and harmonization of data (Organization of Africa Unity *et al.*, 2000);
- Focusing available information more strongly on various clients, in particular pre-feasibility studies with information and indicators that will facilitate decision-making, e.g. groundwater vulnerability, development cost for a range of yields, and development risks. The cost effectiveness and sustainability of groundwater resources should be demonstrated on an ongoing basis (Rovira, 2003, Beekman *et al.*, 2005).
- Establishing drought monitoring systems that extend beyond rainfall, surface water and food security indicators to groundwater and groundwater supply status, including the appropriate prediction of future hydrogeological conditions (Farr *et al.*, 2005);
- Inclusion of social and economic data in the water resource data collection (Mukherji and Shah, 2005);
- Facilitating access to knowledge and information through various approaches and technologies, including the Internet (Organization of African Unity *et al.*, 2000; Mukherji and Shah, 2005);
- Supporting drought-proofing programmes during rainfall deficit periods and ensuring the sustainable use of groundwater from low-storage heterogeneous aquifers through demand-based groundwater resource management (Kulkarni *et al.*, 2004);
- Utilizing integrated groundwater exploration approaches (hydrocensus, tectonics and geodynamics analysis, strain analysis for field structural mapping, remote sensing, ground-based geophysics) as part of systematic and planned groundwater development (Sami *et al.*, 2002);

Water-user perspective

The user perspective, illustrated below, continues to be widely neglected, whereas there is growing evidence that it is vital for the achievement of sustainable development.

- Empowering water users and stakeholder organizations in order to help ensure equitable access, joint decision-making and self-management or shared management, wherever possible (Garduno *et al.*, 2003);
- Meeting of basic human needs of water users in terms of a safe water supply and sanitation as well as an adequate supply for sustainable food security (Organization of African Unity *et al.*, 2000);
- Involving women in decision-making and the implementation of groundwater supply schemes and food security development programmes to harness their unique role in the rural society (Organization of African Unity *et al.*, 2000; Hay *et al.*, 2005);
- Working towards demand-responsive approaches that allow the demands of the user to guide the key investment decisions. This establishes clear links between what users want and what they are willing to pay for in cash, kind, labour and time (Braune, 2001);
- Utilizing water-user associations and other appropriate forums to strengthen the user advocacy role and achieve new partnerships and joint management of the common resource (Braune and Karar, 2003; Garduno *et al.*, 2003);
- Involving users in technology selection to help ensure ownership, cost recovery and community management (Pietersen, 2005; Murray and Tredoux, 2002; Lovell, 2000, DWAF, 2005);
- Involving communities in water husbandry and water conservation to ensure effective use of the scarce supply and the integration of different water sources into the supply chain depending upon availability and demand at certain times (Hay *et al.*, 2005);
- Utilizing networking, e.g. in the Rural Water Supply Network or the Global Water Sanitation Hygiene (WASH) forum, to share experiences of how to accelerate action plans and to strengthen the advocacy role (Aleobua, 2004).

Institutional perspective

Water users, service providers and good supporting science and technology can not achieve sustainable resource development on their own. The South African example has clearly shown that an institutional platform of policy, planning, financing, regulation and capacity building is necessary to draw different stakeholders towards the achievement of common objectives. Such institutional needs include the following:

- Establishing a solid legal/institutional framework that creates equity and clarity for all the stakeholders involved (Garduno *et al.*, 2003);
- Developing and implementing institutional reform and capacity-building, in particular at the local level. Mainstreaming management at the lowest appropriate level and creating institutional arrangements for full stakeholder participation (Organization of African Unity *et al.*, 2000);
- Directing and co-ordinating groundwater development for the meeting of basic human needs, food production and socio-economic development (Organization of African Unity *et al.*, 2000);
- Integrating water and sanitation investments with primary health care strategies as well as waste disposal and storm water drainage (Braune, 2000a);
- Introducing more effective planning and cost-effective implementation approaches for the establishment of hundreds of small localized schemes in respect of groundwater and other low-cost appropriate technologies for community supplies (Braune, 2000a);
- Developing coping strategies that address the community's livelihood challenges as they relate to water and learning to handle hydrogeological uncertainty and communicating the associated risk (Foster, 2000; Pietersen, 2005);
- Increasing attention to groundwater resource protection (Foster, 2000);
- Broadening the skills base of those involved in groundwater resource management and governance to achieve a much more multi-disciplinary approach (Mukherji and Shah, 2005).
- Securing sustainable financing from national and international sources, not only for tackling urgent water needs and for water resources management, but also for information generation and management. Due to its concealed nature, its vulnerability and slow response to impacts and its past neglect, groundwater needs systematic attention to resource monitoring (Organization of African Unity *et al.*, 2000; Braune, 2000b; Tuinhof *et al.*, 2003).

Basement aquifers will in future clearly require the much broadened management approach outlined above in order to achieve sustainable resource utilization. This is due to, on the one hand, their strategic importance of providing water for domestic use and increasingly for sustainable food security and other local productive uses and, on the other, their vulnerability to various human impacts.

Conclusions

Although minor in hydrogeological terms, basement aquifers are of vital importance for small-scale water supply, because they provide water for villages and small towns in areas where there is often no alternative source of perennial water.

These basement rock groundwater resources have attained strategic importance in recent years as a result of the shift in political priorities in Africa to poverty alleviation and socio-economic development. In response to national and international targets, like the Millennium Development Goals, there has been widespread water supply infrastructure development from groundwater. Already between 60-90% of communities in rural southern Africa are served from groundwater sources.

With the main focus having been on water supply infrastructure development, many issues relating to a more sustainable utilization of these groundwater resources have remained unaddressed. Widely occurring problems include poor operation and maintenance of small groundwater schemes, rapid pollution of rural water supplies, sudden failure of schemes during drought and a general lack of capacity for groundwater resource management and protection at the local level.

Based on experience of utilizing hard rock aquifers for community water supply and small-scale irrigation, authors in Africa and India see the challenge to be a paradigm shift from the relatively restrictive concept of groundwater management to groundwater governance. According to these authors, sustainable groundwater management anywhere in the world will require the blending of the following three distinct perspectives:

1. The characteristics and behavior of the groundwater resource (resource perspective);

2. The characteristics and behavior of the resource-user community (user perspective); and
3. The institutional framework under which the resource is appropriated and used (institutional perspective).

In terms of the resource perspective, a much more systematic focus will have to be introduced on the various users, with information that should facilitate decision-making that is related to the sustainable utilization of the resource, e.g. socio-economic information, groundwater development costs and risks. Sustainable systems for data collection, management and dissemination must be a priority.

Under the user perspective, the crucial focus should be on empowering water users, in particular women, and stakeholder organizations in order to help ensure equitable access, joint decision making and self-management or shared management of water services and of the underlying aquifers.

However, water users, service providers and good supporting science and technology can not achieve sustainable resource development on their own. A strong institutional platform of policy, planning, financing, regulation and capacity building is necessary to draw different stakeholders towards common objectives and to sustain the initiatives.

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Current practices and future needs for managing basement aquifers in Zimbabwe

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Abstract

Groundwater plays a pivotal role in the socio-economic development of Zimbabwe as up to 70% of the rural population relies on groundwater for a secure and safe drinking water supply and in certain instances, for watering their animals. Most of the rural communities rely on basement aquifers as their main source of groundwater. Expanding urban and rural populations and the growing industrial, mining and agricultural sectors have placed an increasing stress on the available water resources and consequently there is a need for proper assessment, planning, development and management of groundwater resources in Zimbabwe to avoid over-exploitation and degradation of its quality.It is broadly within this context that new legislation, regulations and guidelines were developed to ensure that the drilling and construction of boreholes is done professionally and for the effective and efficient utilisation and management of groundwater resources. The current Water Act, the regulations and guidelines form part of an ongoing 'Water Sector Reform' programme that was initiated by the government in 1993.The groundwater regulations and guidelines aim at ensuring that all groundwater development procedures are undertaken consistently within a framework of integrated water resources management and provide a basis for standardised data collection and reporting procedures. The critical issue of groundwater resources management concerns: (i) the maintenance of good quality water and (ii) not unnecessarily compromising the abstraction quantity.

Introduction

Overview of the state of groundwater resources

About 70% of the Zimbabwe's close to 14 million people live in the rural areas and have groundwater, mainly from basement aquifers, as their main source of water for primary purposes (drinking, laundry, watering of gardens and animals and, to some extent, irrigation). The total annual abstraction of groundwater in these areas is estimated to be 35 x 10^9 m^3, which comes from ~50 000 boreholes. The total groundwater abstraction for the agricultural sector is estimated to be 350 x 10^6 m^3. Groundwater is also abstracted for established towns such as the City of Bulawayo and Chipinge in the south-western part and eastern part of the country respectively. Emerging towns, commonly known as growth points, which are located in the heart of rural areas (e.g. Gokwe) and rural institutions (e.g. schools and health and business centres) also benefit from groundwater resources for their water requirements. Overall, groundwater presently contributes less than 10% to the total water use in Zimbabwe. More groundwater exploration and exploitation is needed to secure the future development of the rural areas and urban centres although the extent of the development will be constrained by the availability and quality of groundwater. **Figure 1** below shows the distribution of various aquifers in Zimbabwe. It is apparent that close to two-thirds of the country is underlain by crystalline basement aquifers, which makes the development and management of groundwater resources in them a daunting task.

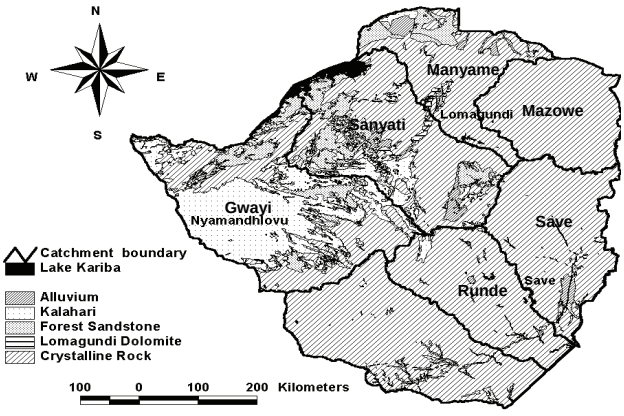

Figure 1: Distribution of aquifers in the various catchment areas in Zimbabwe.

Water sector reforms in Zimbabwe

The assessment, planning, development and management of all water resources in Zimbabwe are all part of a government mandate that is executed by the Department of Water Development (DWD) in the Ministry of Rural Resources and Infrastructure Development. The government, after realising the need for improved water resources planning and management to meet the increasing demand for water, initiated a comprehensive water sector reform programme in 1993 with the support of the donor community. As a way of ensuring the effective and efficient management of water resources, the government deliberately formed a parastatal known as the Zimbabwe National Water Authority (ZINWA), which has taken over most of the responsibilities of the DWD and manages water resources on a river basin or catchment basis. Policy formulation and regulatory functions are still the responsibility of the DWD. The first phase of the programme culminated in the enactment of legislation, namely the Water Act and the ZINWA Act, in 1998. These Acts were enacted after thorough stakeholder involvement and consultations. Seven catchments were created (see **Figure 1)** and are manned by ZINWA through its catchment offices. Catchment councils (CCs), (*see section on Institutional setup, functions and responsibilities*) are responsible for granting groundwater abstraction permits for the commercial use of water. Sub-catchment councils (SCCs), the lowest official tier, regulate and supervise the exercising of rights to water within their areas of jurisdiction.

The ZINWA and Water Acts are supported by various regulations, statutory instruments and guidelines (*see section on Legislation and guidelines*). These instruments provide a more detailed and enforceable legal framework for groundwater resources development, utilisation and management. Regulations will ensure that each component of the IWRM concept is put into perspective, thereby yielding sustainable development, utilisation and management of groundwater resources without compromising its quality and quantity.

Legislative and institutional framework for groundwater management

Various legal instruments were put in place to ensure the effective and efficient assessment planning, development and management of (ground)water resources.

Legislation and guidelines

Water Act (1998)

Zimbabwe's Water Act of 1976 was repealed in 1998. The aim of the Water Act of 1998 is to address the weaknesses of the Water Act of 1976 in order to improve equity and the access to water by all stakeholders as well as the effective and sustainable management of water resources by stakeholders. The following are the major changes in the new Act:

- Water rights are abolished and water permits of a fixed duration introduced. Permits are subject to review and renewal.
- Groundwater is elevated to the same status as surface water and the two are now jointly referred to as water resources, thereby effectively removing the concept of private water (ownership of water is now vested in the state). The concept of the hydrologic cycle is fully recognised.
- The priority date system in the issuing of water during times of scarcity has been discarded.
- The environment is appreciated as a rightful user of water.
- The pollution of water resources now attracts heavy fines and the principle of "polluter pays" has been adopted.
- The administration of the Act is now less cumbersome.
- Water resources management is devolved to stakeholders through the formation of catchment councils and sub-catchment councils, which are technically and professionally backed by ZINWA through catchment offices.

Groundwater resources development

With regards to groundwater resources development, the Act highlights the following matters:

- The need for the development of catchment outline plans (COPs), which outline the concept of integrated water resources management (IWRM). COPs provide information on current water usage (demand), available groundwater resources, future demand and ways of developing additional groundwater resources without mining the resource.

- The development of groundwater resources is restricted in water-shortage areas (areas where groundwater resources are being heavily depleted) or in water development restriction areas (areas where water utilisation in a catchment is approaching the catchment's water potential).
- The need for permits to control groundwater development, i.e. groundwater abstraction volumes and groundwater quality.
- The minister responsible for water resources may reserve the use of water resources in an area for an indefinite period for future use.
- The setting up of appropriate institutions, namely: the Zimbabwe National Water Authority (ZINWA), catchment councils (CCs) and sub-catchment councils (SCCs) to assist in the development of water resources.

Groundwater resources management

In relation to groundwater resources management, the Act outlines the following matters:

- Groundwater monitoring to ensure that no undesirable effect result from groundwater abstraction, i.e. the compromising of groundwater quantity and quality.
- Maintenance of groundwater records to provide the necessary hydrogeological data for use in groundwater management.
- The need for permits to monitor the groundwater abstraction quantities and consequently the regulation of the amounts abstracted.
- Control of abstractions in water-shortage areas and in water-development restriction areas to ensure the sustainability of groundwater resources.
- The need for regulations to reinforce the Act.
- The setting up of appropriate institutions, namely: the Zimbabwe National Water Authority (ZINWA), catchment councils (CCs) and sub-catchment councils (SCCs) to assist in the management of water resources.
- Penalties for offences.

Water (permit) regulations (2001)

The water (permit) regulations provide a legal framework for both surface water and groundwater development, use and management. The surface water and groundwater regulations were combined to avoid duplication (limiting bureaucracy; single permit numbers for both groundwater and surface water) to minimize abuse and hopefully to break down barriers between the two professions.

Regarding groundwater, the regulations aim at enforcing the guidelines for groundwater development; use and management of groundwater resources; and monitoring. They serve as supporting legislation to the Act. Regulations do not go through the laborious process of promulgation as does the Act and therefore certain aspects can be changed to suit the changing requirements or conditions on the ground. Authorisations for drilling boreholes or sinking commercial wells and abstraction permits are a prerequisite.

Groundwater resources development

In relation to groundwater resources development, the regulations highlight the following matters:

- The need to apply for authority for borehole drilling as a means to control groundwater development.
- The minimum requirements for borehole siting, drilling and construction.
- Submission of relevant hydrogeological information obtained prior to and during the drilling of borehole(s) as this will improve the hydrogeological knowledge of the area concerned and eventually of the catchment and the country as a whole.
- The need for professionals to site boreholes that will be used for commercial purposes.
- A hydrogeological appraisal is required for specific permits (*see permitting section below*). The information will help in further refining the guidelines on abstraction volumes for general abstraction permits and hence provide a mechanism for continuous review and updating of the regulations.
- The issuing of abstraction permits is aimed at ensuring controlled groundwater development.

Groundwater resources management

With reference to groundwater resources management, the regulations highlight the following:

- Issuance of different types of abstraction permits with different groundwater abstraction quantities. This ensures that only the permitted volumes of groundwater are abstracted with the ultimate aim of

ensuring sustainable utilisation of groundwater resources.

- Permit conditions that are attached to each permit also aim at ensuring sustainable utilisation of groundwater resources and therefore the facilitation of effective management.
- Bestowing groundwater monitoring functions on the permit holder ensures that all the necessary records are collected on time. This arrangement also cuts the costs of ZINWA, the CC or SCC to carry out continuous or periodic monitoring.
- Punishable offences that enforces adherence to the permit conditions..

Permitting

The various types of groundwater abstraction permits are classified as general, specific, temporary and provisional.

General groundwater permit

This permit is issued where the abstraction occurs within one's own property with no influence on the neighbouring or adjacent properties. Volumes of groundwater to be abstracted relate to the property/land size and the natural rainfall region.

Specific groundwater permit

The permit is granted where the abstraction is beyond that of a general permit as groundwater abstraction will definitely affect the adjacent properties. Boreholes intended for this permit have to be sited by an approved professional such as a hydrogeologist or geophysicist.

Provisional groundwater permit

This permit is issued prior to the finalisation of a final permit (general or specific).

Temporary groundwater abstraction permit

This permit is granted for a limited/short period only.

The forms needed for the application and processing of the authorities for borehole drilling and abstraction permits are included in the regulations. These forms can be changed to suit requirements without gazetting. Applications for borehole drilling authorisation and permits for abstraction are submitted to the catchment council through the appropriate sub-catchment council.

Catchment council regulations (2000)

The regulations resulted in the establishment of catchment councils. They also outline the functions and powers of the councils in respect of groundwater development and management.

Sub-catchment council regulations (2000)

The regulations resulted in the establishment of sub-catchment councils. They also outline the functions and powers of the councils in respect of groundwater development and management.

Water (waste and effluent disposal) regulations (2000)

These regulations provide the guidelines and concepts for water quality monitoring. Four effluent classes are identified, viz, blue, green, yellow and red and each has its own standards. The blue category means that the effluent poses no significant environmental risk whereas red represents very poor quality effluent that would result in water pollution and environmental damage. Partial treatment of such effluent could be required. Each class has its own effluent disposal charge and it is quite high for the red class. The intention is to discourage the disposal of poor quality effluent. The following principles guide water quality monitoring:

- Permits are required for the disposal of effluent.
- The polluter pays for the policing of the regulations through permit application fees.
- The onus for monitoring is on the permit holder who is obliged to provide the appropriate records to ZINWA.
- The polluter is responsible for remedial actions.

Notices

A number of notices have also been gazetted to support the Act and the regulations. They include the Water (Establishment of Catchment and Sub-catchment (Councils) Notice (2000).

Guidelines

A first draft document was completed in 1999 and it forms the basis of the discussion in this section. The guidelines have the following aims:

- Providing a framework that is based on the concept of Integrated Water Resources Management (IWRM) for optimum development and use of groundwater on a sustainable and equitable basis.
- Providing a basis for standardised data collection and reporting procedures.
- Assisting groundwater developers and end users by establishing a standardised basis for groundwater development, use and monitoring.
- Assisting catchment councils to implement water resources management strategies (they complement the Waste Water Regulations and Guidelines (2000) and guidelines for water allocation (2001).

The IWRM concept described in the guidelines document refers to all the stages of groundwater resources (GWR) assessment, planning, development and management with the following specifications:

- Assessment: quantitative and qualitative aspects of GWRs and water demand (borehole (BH) siting, etc.).
- Planning: matching water supply and water demand (production of catchment outline plans).
- Development: design and implementation of groundwater projects (BH drilling and construction; pumping tests; equipping, etc.).
- Management: operation and maintenance of water supply systems (monitoring, data collection, and control of BH drilling and groundwater use - authorities for BH drilling and abstraction permits for groundwater usage).

Institutional setup, functions and responsibilities

The effective and efficient administration and management of water resources under the Water Act (1998) requires the establishment of bodies external to the government. This requirement resulted in the formation of the Zimbabwe National Water Authority (ZINWA) in 2000 and catchment councils and sub-catchment councils with specific roles and responsibilities. (**Figure 2**).

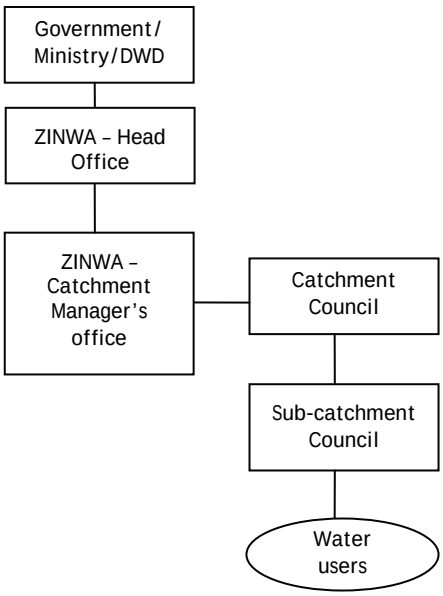

Figure 2: Institutions involved in groundwater resources assessment, planning, development and management and the relations between them.

Government/Ministry/Department of Water Development (DWD)

The government, represented by the Department of Water Development in the Ministry of State for Rural Resources and Infrastructural Development, has the following responsibilities:

- Policy and regulation formulation.
- Solution of problems in groundwater resource management in the context of national economic development.
- Provision of funds for setting up and running groundwater management schemes.
- Seeking external support for groundwater development and management.

Zimbabwe National Water Authority (ZINWA)

ZINWA was established by an act of parliament, the ZINWA Act (1998). It is a corporate and legal entity, and, subject to the Act, may perform all acts that corporate bodies may by law perform. ZINWA, as a parastatal, is mandated with the assessment, planning, development and management of all water resources. It has the following functions:

- Administeration and management of the Water Act in close liaison with the DWD.

- Maintenance of and updating of the national groundwater database.
- Advising CCs, SCCs and end users on the best ways of developing and managing groundwater.
- Backstopping catchment manager's offices (catchment hydrogeologists) by providing technical and professional support on groundwater resources development and management.
- Plan, source funds and implement national projects on groundwater resources development and management.
- Institute and co-ordinate reviews of groundwater regulations to improve management of groundwater resources.
- Conduct groundwater resources research.

ZINWA Catchment Manager's Office (CMO)

ZINWA is represented at the catchment level by the catchment manager's office and is manned by staff in the fields of human resources, surface water, groundwater and water quality. This office interacts directly with the catchment council, sub-catchment council and end users. Its functions are:

- Advising CCs, SCCs and end users on the best ways to develop and manage groundwater.
- Producing the groundwater component of the catchment outline plan (COP).
- Assessing applications for borehole drilling and make recommendations to the CC.
- Assessing permit applications and make recommendations to the CC.
- Proposing permit conditions and monitors compliance.
- Conducting hydrogeological investigations.

Catchment council (CC)

Seven catchments were established that were based on the major river systems and each catchment has a catchment council. Catchment councils comprise members who are water users under the jurisdiction of the catchment concerned. The membership cuts across the spectrum of water users, from communal and resettlement farmers to small-scale and large-scale commercial water users such as industry, mining, urban centres and agriculture.

Sub-catchment council (SCC)

Each catchment is divided into a number of sub-catchments that are based on the main tributaries of the major river in the catchment and are represented by sub-catchment councils. Sub-catchment councils comprise members who are water users under the jurisdiction of the sub-catchment concerned. The functions of an SSC are:

- Receiving borehole drilling and permit applications.
- Regulating and supervises groundwater utilisation in the sub-catchment.
- Liaison with the CC on issues related to groundwater.

End users (EUs)

End users represent the lowest echelon of groundwater development and management and are responsible for:

- Observing permit conditions.
- Collecting, maintaining and submitting monitoring data (water levels, abstractions, water quality, etc.) to the catchment manager's office and to the CC.
- Providing peer pressure or influence in the sustainable utilisation and management of groundwater resources.

Integrated groundwater management

It has since been realised that the treatment of groundwater resources and surface water resources as separate entities does not yield tangible results. The treatment of groundwater resources as "private water' actually created problems, because anyone could drill a borehole and abstract the water without considering his neighbours. The effect of this scenario in some areas was that boreholes inevitably interfered with the water sources of others and thereby provided a of potential source of conflict.

Key elements of management

The key elements of groundwater management are enshrined in law (the Water Act and the supporting regulations). These elements are:

No private ownership of water

The ownership of all water is vested in the state and therefore no one shall store, abstract, apportion, use or

deal with water beyond the provisions of the Act. This ensures the sustainable development and management of groundwater resources.

Catchment outline plans (COPs)

Every river system is required to have a COP, which will among other things contain available water resources and the sources; utilisation of the water amongst the various sectors; maximum permissible levels of pollution; development strategies; water reserved for future use; priorities in the utilisation, etc. COPs ensure the optimum development, utilisation and management of water resources, because the concept of the hydrologic cycle will be considered holistically with the effect of avoiding the development and utilision of only one component of the cycle. Effective and sustainable development and management of water resources will be instituted to ensure equity and the equal access to water resources by all stakeholders. COPs will be developed along the lines of the IWRM concept and the conjunctive use of both surface water and groundwater resources will be instituted where feasible. COPs provide a water 'balance sheet' of a catchment.

Authorisation for borehole drilling

All boreholes to be drilled for commercial purposes require an authority from the respective catchment council. The drilling authorities are an avenue of ensuring that information on boreholes that are used for commercial purposes is lodged with the appropriate institutions involved in water resources management. The information is used in deriving the most appropriate management strategies.

Abstraction permits

In order to abstract groundwater for commercial purposes, an abstraction permit is required (*refer to section on Water (Permit) Regulations (2001*). Volumes granted for abstraction can be apportioned between surface water and groundwater and due regard is given to other stakeholders within the sub-catchment, including the environment. The permits provide an effective way of managing groundwater resources.

Measurements

The monitoring of groundwater resources (ground-water level fluctuations and water quality and abstraction volumes) has been bestowed on the water user or permit holder. The data is submitted regularly to the appropriate office where it is analysed and used in determining the best management strategies and practices.

Monitoring

The sub-catchment council will regulate and supervise the exercising of rights to water within the area of its jurisdiction. The council will also ensure that permit holders adhere to the permit conditions. However, ZINWA will undertake periodic field monitoring to ensure that the correct data is being provided to it and that permit conditions are being complied with. Violators will be prosecuted.

The law might be explicit on issues relating to groundwater management, but dealing with groundwater resources management in crystalline basement aquifers is nevertheless, an insurmountable challenge.

Progress and lessons learnt

Instituting changes, particularly regarding to water, which is generally perceived to be 'God given', is no mean task. There is a need for a change of attitude.

Progress to date

The progress that has been achieved to date relates to the implementation of precursor activities to groundwater management. These include the establishment of the necessary institutions and structures; promulgation of the appropriate laws; stakeholder awareness; human resources training; and the setting up of a countrywide rainfall chloride deposition monitoring network. Management strategies such as the issuance of drilling authorities and abstraction permits; fines for non-compliance with permit conditions; monitoring and data/information collection have also been introduced.

Lessons learnt

It is very difficult to change the human mindset with regards to the need to utilise and manage groundwater resources effectively, because the notion has always been that the water is 'God given'. There is therefore a need to:

- Conduct extensive stakeholder meetings and awareness campaigns with regards to the effective and efficient utilisation and management of groundwater resources. These actions could be complemented by using the printed and electronic media.
- Have fully capacitated and decentralised institutions that will ensure the timely provision of services to stakeholders.

- Have a sound logistical setup to undertake the necessary follow-ups and monitoring.
- Produce educational flyers in the vernacular to ensure that all stakeholders understand the requirements in respect of effective and efficient groundwater utilisation and management. The printed and electronic media could be useful in this regard.

There is still a lot to be done in regards to the actual implementation of groundwater management in crystalline aquifers. The need involves the expansion of the chloride deposition monitoring network, setting up of groundwater level fluctuation networks and monitoring of groundwater quality. There is currently a strong bias towards sedimentary aquifers.

Future needs for managing basement aquifers

The effective management of basement aquifers requires the drawing of information, knowledge and experiences from the sub-region. In this regard there is need to establish the current experiences in the sub-region and to share them amongst the countries.

Comparison with South Africa and Zambia

There has been a general review in the way that water resources are managed within the sub-region. The status in South Africa, Zambia and Zimbabwe is discussed in **Table 1**.

It is apparent that the three countries are at various stages in regard to groundwater development and management.

Groundwater management

Groundwater management plays a pivotal role in socio-economic development of the rural communities that rely on groundwater resources for their livelihood. Good management strategies and practices can only be instituted if sufficient knowledge exists regarding the

Research needs and priorities

The institution of sound groundwater management strategies and practices in basement aquifers is a tall order, given the complexity of these aquifers and that they are highly heterogeneous. There is a need to have a sound control of data pertaining to the aquifer characteristics in order to determine, with a certain degree of accuracy, the sustainable yields of the aquifers. The challenge is therefore to come up with practical groundwater investigations as well as development and management strategies and practices that benefit the stakeholders.

Groundwater investigations

Research should focus on the most appropriate technologies that will be able to detect groundwater occurrence and the nature of the aquifers (aquifer characteristics/parameters).

Groundwater development

There is a need to establish the best methodologies for developing the groundwater resources without mining the resource and affecting its quality.
aquifer characteristics, recharge, quantification of the resource and its quality. There is therefore a need to undertake sub-regional case studies on the establishment of groundwater management strategies and practices, which other countries could draw upon or to which they could add their experiences.

Table 1: Comparison of Zimbabwe with South Africa and Zambia

Issue/Country	Zimbabwe	South Africa	Zambia
Water Act	New Water Act (1998): • no more water rights • all water vested in the state • abstraction permits required for commercial use of water	New Water Act (1998): concerns: • equity • cost-recovery and efficiency • abstraction licences	Under review. National water policy (1994) broadly defines requirements of groundwater development and management
Regulations	a) Water (Permit) Regulations (2001): provide a legal framework for both surface water and groundwater development, use and management b) Water (waste and effluent disposal) regulations (2000): provide the guidelines and concepts for water quality monitoring and effluent disposal	not yet developed	not yet developed
Guidelines	Provide: a) a framework based on the Integrated Water Resources Management concept (IWRM) for optimum development and use of groundwater on a sustainable and equitable basis b) a basis for standardised data collection and reporting procedures c) assistance to groundwater developers and end users by establishing a standardised basis for groundwater development, use and monitoring d) assistance to catchment councils in implementing water resources management strategies	For: a) Integrated Groundwater Management b) Rural Water Supply Management	not yet developed
Institutions	a) National Government b) Zimbabwe National Water Authority (ZINWA) c) Catchment councils (CCs) d) Sub-catchment councils (SCCs)	a) National Government Catchment b) Management Agencies c) Water User Associations d) Water Services Authorities	a) National Government b) Other institutions being established
Basement aquifers studies	**Limited**. Studies are mostly focussed on geophysical investigations	**Average**. Focus has been on geophysical investigations	**Limited**. Mostly siting of boreholes for rural water supplies

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Challenges of basement aquifers in southern Africa

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Abstract

Access to a continuous water supply from basement rocks remains a priority issue for many people living in southern Africa. This paper considers the current knowledge of this important groundwater resource and the challenges that are being faced.Five major challenges are identified that relate principally to the spatial and temporal variability of basement aquifers; a misunderstanding of why wells and boreholes fail; improved siting and appropriate technology choice; robust economic appraisal; and various social and institutional arrangements that are present within user communities and are being used during development. It is critically important to identify what people actually want from their water point. Such identification requires a balance between prescriptive and adaptive programmes to cater for community choice; ownership and maintenance while dealing with the highly variable ground conditions; and growing demands on the resource. The shortcomings of drought-relief drilling programmes are also highlighted.These diverse challenges prevail despite the considerable investment that has been made in groundwater development. Some new ways of doing business are required if the challenges are to be overcome. Action research within applied water supply programmes is suggested. It focuses at two levels. The one level concerns strategic studies to help integrate the knowledge gained from past programmes and to create the necessary partnerships between those in different disciplines and who represent different stakeholders. The other level concerns specific interdisciplinary studies to fill gaps in knowledge and to address key constraints such as how to best use reliable existing water points and how to better site and select new water points. Comparative cost-benefit analyses is critical in this approach. So too, is the development of policy that promotes more accountability, such as payment for water reliably delivered rather than per water point sited or per metre drilled.

Introduction

Much of southern Africa is underlain by crystalline basement rocks, the most common being granites and gneisses, quartzites, schists and dolerites. The water in these 'hard rocks' is vital because it is widespread and because, for millions of people, there is no readily available alternative supply.

At present these aquifers are exploited either by the use of shallow hand-dug wells (typically 1 metre in diameter and up to 20 metres deep) or mechanically-drilled boreholes (typically 0.15 metre in diameter and up to 100 metres deep), but the yields of water are often low and many fail during drought (**Table 1**). For example, forty per cent of all wells and boreholes in Zimbabwe failed in the 1991/92 drought. The reasons for this are a complex mix, namely, water points are constructed in haste, in response to drought, in difficult hydrogeological terrain, without appropriate geophysical expertise, without sufficient planning to cater for highly variable ground conditions, community choice, ownership or maintenance.

New supply programmes also tend to focus on only two social aspects, namely, improved access to a limited domestic supply and improved sanitation. This focus is due in part to the difficulties of abstracting sufficient groundwater. It is also due in part to a misunderstanding of why wells and boreholes fail, which has led to a belief that abstraction should be limited to conserve the resource. It means, in practice, that little attention is being paid to the investigation of exactly what type of water point a community would prefer and how they might like to use the water economically to develop and protect their own livelihoods. The diverse range of small-scale, money-making strategies that can be associated with water points (e.g. irrigation) have not formally been promoted and, in fact, have been discouraged where they are considered to jeopardise domestic supply. These problems are compounded in cases in which a single water point has to serve many families. When a problem arises it is not attended to because the users have been given neither the capacity nor the authority to own and repair what has become, in effect, a state-owned common property resource.

Ironically, groundwater in most dryland areas is considered to be an underutilized resource. Future dangers then derive from the declining quality rather than from the declining quantity of water. Certainly, current groundwater use by rural people in southern Africa is extremely low in comparison with the potential of the resource. It is typically less than 4 per cent of long-term mean annual recharge where recharge is of the order of 2 to 9 per cent of mean annual rainfall (Wright and Burgess, 1992; Chilton and Foster, 1995; Vegter, 1995; Lovell, 2000).

The challenges to improve water supply from basement aquifers in southern Africa are thus diverse and multi-faceted. They range from technical and social to institutional, economic and political. The first, and perhaps most obvious, relate to the spatial and temporal variability of the groundwater itself and to the current misunderstanding of why wells and boreholes fail.

Table 1: Borehole yields in a drought-relief drilling programme, Masvingo Province, Zimbabwe (source: DDF, 1994)

District	No. of boreholes	Percentage of borehole yields			
		Dry	<0.3 ℓ/s	0.3 - 0.6 ℓ/s	>0.6 ℓ/s
Chivi	12	26	33	33	8
Zaka	11	8	46	46	0
Chiredzi	12	33	25	33	9
Bikita	12	25	50	8	17
Gutu	40	14	33	13	40
Masvingo	50	0	34	28	38
Mwenezi	12	17	25	33	25
Total	**149**	**13**	**34**	**25**	**28**

Understanding why wells and boreholes fail

Basement aquifers are complex in occurrence and spatially highly variable. They vary hugely in groundwater potential over very short distances (**Figure 1**). They have very little primary porosity, unlike sandstones and other sedimentary rocks. Instead, they have a secondary porosity due to weathering and fracturing which permits limited storage and limited flow of water. It is the weathered and often clayey overburden, known as the regolith, that provides the main groundwater storage and fractures that provide the main conduits for flow.

Dug wells are completed in the regolith with resulting low yields, unless the well is sited in the maximum depth of saturated weathering and the permeability of this weathering is reasonable. Boreholes, on the other hand, are completed in the underlying fractured bedrock with resulting low yields, unless interconnected fractures, which draw on sufficient water stored in the regolith, are intercepted. Siting is clearly critical. With inadequate siting comes poor connectivity between regolith and bedrock and shallow depths of saturated weathered overburden (**Figure 2**). These factors cause failure as water tables fall annually through natural recession (due to gravity and deep-rooted vegetation) and continuously through drought. The problems are compounded in low permeability conditions or where abstraction is too high. Localized water table drawdown upon pumping restricts water from entering from the surrounding aquifer and manifest as a general decline where water points are close together.

Added to this spatial complexity is the temporal uncertainty of rainfall and recharge in semi-arid areas. **Figure 3** shows the annual and cumulative departure from long-term mean annual rainfall that was recorded in parts of Zimbabwe and Zambia. Although there is no evidence of an overall decline in rainfall, the trends indicate cycles of above-average and below-average rainfall. When rainfall is generally low for an extended period (for example 13 years in Zimbabwe over the period 1980-93 and 16 years in Zambia over the period 1979-95) recharge fails to match natural recession and groundwater levels fall. This natural fall causes sources to dry up if they were sited hastily or for convenience (say near to homesteads) rather than in optimum groundwater locations. Under these conditions people are forced to walk further to other operational water points and water sources.

Modelling catchment hydrology clearly shows that low groundwater levels in Zimbabwe in the early 1990s were

due to the extended period of low rainfall and were not due to human impact, either through abstraction or land use change (Butterworth *et al.*, 1999). Water points failed, because they were inadequately sited to cope with the natural recession during this period, which is typically 100-200 times greater than current human abstraction each year (Lovell *et al.*, 1998). In this environment it is pointless to reduce already low levels of abstraction to 'conserve' the resource. Furtheremore, there is no action to prevent extended periods of low rainfall. However, there is much that can be done to make better use of the groundwater resource while it is there (before natural recession takes it away) and to cope better during the next drought. That some water points remain reliable, even under the harshest of conditions, is testimony to the potential of the resource and to the importance of careful siting and water point design. It also highlights the need to plan with communities how best to utilize these existing reliable water points.

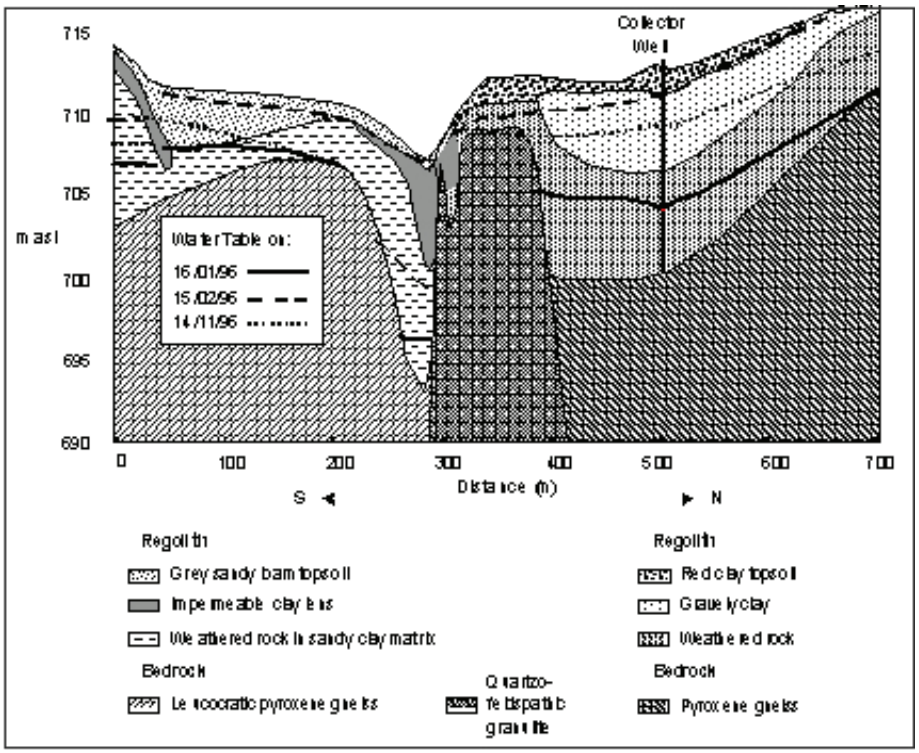

Figure 1: Spatial variability in groundwater potential recorded across Romwe Catchment in Zimbabwe (redrawn from Moriarty and Lovell, 1998a)

Improved siting

From a technical perspective, improved siting holds the key to more reliable water supply from basement aquifers.

A review of siting techniques was undertaken by the British Geological Survey between 1984-94 in the basement aquifers of Zimbabwe, Malawi and Sri Lanka. The most important conclusion drawn in each case was that it is very difficult to pick out suitable sites on a local scale, because basement aquifers vary hugely in groundwater potential over very short distances (see also **Figure 1**). Remote sensing; electrical resistivity traversing and depth sounding; moving coil electro-magnetic profiling; and seismic refraction that are used in combination with local knowledge, geological maps and reports, can, under favourable conditions, help to identify the weathered, saturated fracture zone and to map its extent. However, these measures do not possess the necessary spatial resolution to resolve the smaller-scale features that tend to be of critical importance to the success of a water point at any particular site (Greenbaum, 1987; BGS, 1989; Carruthers *et al.,* 1993; Davies, 1994).

At present, dug wells are being sited by local people who divine for water usually near to their homes, while boreholes are generally being sited by the government or aid agency staff who use one or more of the geophysical techniques mentioned. Given the critical importance of siting, the present variability in success

and the ongoing problems of water supply, it can be argued that these approaches, on their own, are inadequate. Clearly, it is important to continue to develop new geophysical well-siting techniques and to ensure that they are practical and can be available, with the appropriate expertise, to future development programmes. It should be noted that the success rates of drilling boreholes that have a reasonable yield can be up to 80% if the expertise is available for carrying out advanced geophysical surveys, such as MER and electro-kinetic sounding, although some of these techniques remain experimental at present (Beamish and Peart, 1998; Beamish, 1999; MacDonald *et al*., 2001).

It is also suggested that increasing use should be made of test or exploratory drilling. If it is used in conjunction with local knowledge, remote sensing and modern geophysics to eliminate negative sites that have hard rock at shallow depth, test drilling with the use of a small portable rig or power auger can directly locate maximum depths of permeable weathering (see **Figure 2**). Test drilling in order to site water points is not a new practice (Clark, 1996), but its use in respect of rural water supply in southern Africa would be a new approach. Thus far its use appears to be limited to the siting of hand-dug wells in Sierra Leone (Akiwumi, 1987) and to collector-well research in Sri Lanka, Malawi and Zimbabwe, where productive water points were sited to support domestic use and irrigated gardens (Wright *et al*., 1989; Lovell, 2000).

The integration of modern geophysics, remote sensing and test drilling into current water supply programmes will be an important research activity. It should be undertaken with comparative economic appraisal of the various costs and benefits.

Choice of appropriate technology Water-point design is therefore a case of 'horses for courses'. It is site-specific and should be decided in real-time and based on the depth and permeability of the saturated weathering found. **Figure 4** shows seven water point designs that could be used to cope with the highly variable ground conditions that are typical of basement aquifers. Only two of these designs (the far left and far right technologies shown) are currently being utilised, namely in pre-designed programmes. The development of a more adaptive approach in water supply programmes is a second important research activity and will be most welcomed by those people who, in the past, have been the recipients of inappropriate water-point designs (**Box 1**).

The relative importance of the regolith and underlying fractured bedrock components of hard rock aquifers depend on the particular basement geology, tectonic history, climate and relief. In Malawi and Uganda, for example, the bedrock rarely forms a significant component and it is the regolith that stores and transmits most groundwater (Chilton and Smith-Carington, 1984; Howard and Karundu, 1992). In Botswana, the regolith only occasionally constitutes an aquifer that is worth developing on its own, but some good yields are obtained from fissured zones in the bedrock (Buckley and Zeil, 1984). In Zimbabwe, both regolith and fractured bedrock can be important, depending on the location. Viable regolith aquifers are most common on younger undifferentiated gneisses and intrusive granites. On older gneiss complexes, the depth of saturated weathering is often too small or the depth to the water table too great. On Karoo basalt, layers of fresh rock in banded weathering make well digging difficult, while regolith aquifers on paragneiss are often saline. In these cases, drilling in the bedrock is necessary.

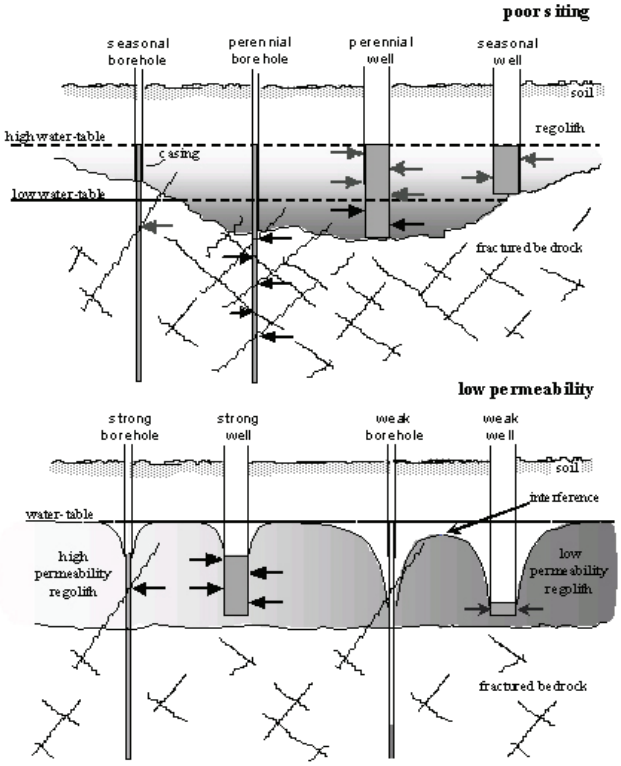

Figure 2: Well and borehole failure mechanisms (redrawn from Lovell, 2000) with (a) poor siting and (b) low permeability.

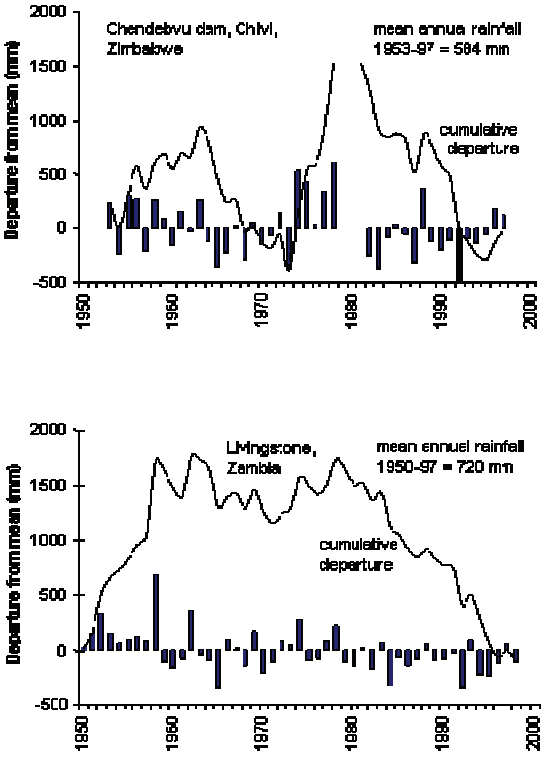

Figure 3: Rainfall cycles in basement areas of Southern Africa (Lovell, 2000).

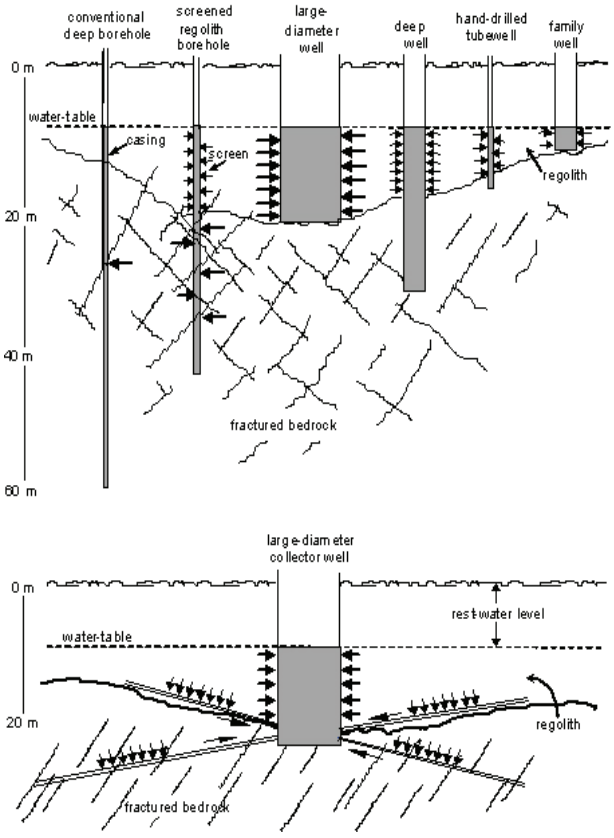

Figure 4: Seven water point designs for basement

Box 1: A review of current practice: Zambia

Groundwater is recognised to be an underutilized resource in Zambia. Massive investment in the national water resources master plan is proposed. Over 1000 boreholes have been drilled in Southern Province alone since 1995. Too many are low-yielding or dry, not because groundwater is particularly scarce, but because the new water points are inadequately sited or of inappropriate design. A review (Lovell and Lombe, 1998) found that 20 per cent are high-yielding, but underutilized, because pump capacity is too low; 27 per cent are low-yielding because of inappropriate design (generally deep boreholes of small diameter in shallow, low-permeability aquifers); 21 per cent are low yielding because of inadequate siting; 32 per cent are satisfactory for domestic supply. Although the driest part of Zambia, it is conservatively estimated that 340 productive water points with small-scale irrigation schemes of a total area 220 ha could immediately be developed to benefit 85,000 people, simply by addressing these inadequacies.

Instead, people at these water points are facing problems on a daily basis by. At Manzambani Village, 50 households have to wait for water to enter their new borehole and they report that pumping the water is very hard. The shallow water table is quickly drawn down due to the low aquifer permeability and soon falls below pump level. In an attempt to overcome the problem, additional pipes were added (at additional cost to the government) to place the pump deeper. This measure did not address the problem of low aquifer permeability. It just made it harder to pump water from an even greater depth. This is a classic example of the inappropriate use of a borehole where a large-diameter well or collector well would be so much better, filling overnight, providing sufficient storage, and easily pumped from a shallow depth. As Headman Manzambani said: “We could see the water, it was shallow, and was coming in from the sides. But the driller went deep. Now the water goes deep because the pipes are deep. Why did he go deep?”.

We can surmise that the driller went deep because programme design predetermined that he should do so. He was not set-up or employed to do otherwise, and he had a vested interest to do so, being paid per metre drilled, irrespective of the outcome.

aquifers (redrawn from Lovell, 2000)

Making more effective use of existing water points

Whilst it is perhaps more attractive to development agencies to site and construct new water points, it is prudent to first look at the performance of existing water points. A major finding of southern African research concerns the number of existing water points that are actually underutilised. This is because they are of inappropriate design or because pump capacity is less than the potential safe yield or because pump maintenance is inadequate. Lovell (2000) outlines a general approach to first identify and upgrade these underutilized water-points, siting and selecting new water points of appropriate design only where it is necessary.

Briefly, an existing well or conventional borehole (cased in the regolith) should potentially be converted to a large-diameter well, collector well or screened-regolith borehole (sited by test drilling) if water-point records show that the yield is low (<0.3 ℓ/s), the rest-water level is shallow (<15 m), drawdown on pumping is rapid and recovery is slow. In contrast, queues of people waiting for their turn to pump water (as opposed to waiting for the water level in the well or borehole to recover) is a good indication that the pump capacity rather than the yield is the constraint. These water points will typically have recorded yields greater than 0.6 l/s where pumping tests have been performed, and will ideally have reasonably shallow groundwater for ease of pumping.

Matching pump capacity to yield at existing reliable water points offers the first and most cost-effective option for improved water supply in many parts of southern Africa. However, this, in itself, is another worthwhile research topic. It again requires consultation and an adaptive approach that is not currently encountered in domestic supply, in respect of which the users are generally not involved in the planning and in which the programme focuses instead on the standardisation of items, such as pumps bought in bulk beforehand and fitted to all water points irrespective of the yield or user preference. The practicalities of moving from this prescriptive arms-length approach to some measure of key investment in social development during scheme implementation is a challenge and will overlap with current policies that are moving towards community rather than state ownership and responsibility for maintenance.

Community-based maintenance

The greatest single challenge that faces rural water supply in southern Africa is the issue of maintenance. Although water points are technically relatively quick to install and upgrade, the short-term, medium-term and long-term problems of maintenance appear to be overwhelming. Government budgets are too small to cover the costs and many water points now remain broken, because local people have not been given the capacity or authority to repair the 'government borehole'. There is also the very real problem of continuous heavy use at the relatively few reliable water points per community, which places extreme pressure on even the most robust of pump designs. The proportion of broken installations is not well documented but estimates vary from 10 to 50 per cent. For example, about 8 000 handpumps on communal water points are estimated to be out of action at any one time in Zimbabwe.

In some countries, water policies now decree that the users themselves are responsible for maintenance, but thus far this concept has achieved limited success. Village-level operation and maintenance (VLOM) costs can be high and ways of collecting sufficient revenue at conventional domestic water points have still to be worked out.

However, initial indications are that where a water point is given an economic value through production, this arrangement can create both the incentive and the means required to make community-based maintenance a reality. At productive water points in Zimbabwe, the multiple pumps fitted to each well (to match safe yield) have been maintained locally from the outset or the users have chosen to pay government pump-minders to carry out repairs (Lovell, 2000). They are choosing to buy spare parts with income derived from the associated gardens and do not rely on external assistance. Although payment regimes have been arbitrary and range from 50 to US$245 per year per scheme, they are significant and in stark contrast to conventional domestic water points where the annual cost to the state is in the order of US$90. This equates to an additional cost of US$1120 amortized over a standard lifetime of 20 years.

Economic appraisal

Economic appraisal is critical to the successful improvement of rural water supply in southern Africa. Throughout the region, water sector politicians and

advisers are being obliged to make choices between vastly contrasting solutions such as traditional or new, simple or complex; private or public; manual or mechanised; and surface or ground water. They need more evidence to make better decisions on the best way to spend the limited funds that are available.

One measure of success that is currently cited, is the number of communities that are given a water point with a handpump yield of 0.3 ℓ/s. With the complexity of basement aquifers and the shortcomings of drought-relief drilling programmes (Calow et al., 1997), this rate can average only some 50-60 per cent at construction (Table 1) and drops further if maintenance arrangements are inadequate. There is therefore the major cost of substantial numbers of failed wells and boreholes, which all governments and development agencies would wish to avoid. Moreover, an average of 50-60 per cent implies a much lower rate in the most difficult areas where the poorest people often live.

Unfortunately, the simplest is not always the best in basement aquifers. A recurring theme is the need to take more care in an adaptive interdisciplinary approach to planning, siting, design and management of water points and to do so in partnership with the user communities. Without doubt, this route takes longer and the initial capital costs are higher, but the benefits accrue over time, not only via lower recurrent costs to the state, but also in the range of extended benefits for the communities and the wider production systems (Waughray et al., 1998; Moriarty and Lovell, 1998b). When evaluating the merits of various options, the temptation is to use a cost basis only, especially if information on the benefit side of the equation is lacking. Therefore more emphasis should be placed on the measurement of these benefits, particularly as demand-assessment (identifying what communities want from their water points and what they are willing to pay) is a key issue that will help underpin future programmes (Waughray et al., 1997).

Box 2 provides an example of technical and social ways in which security of water supply was enhanced at nine productive water points in Zimbabwe (Lovell, 2000). Although the stated methods may represent an extreme, detailed appraisal finds this 'belt and braces' approach to be valid, both socially and economically (**Table 2**) and it reveals the following guiding principles:

- The importance of making money. At the average return of US$2200/ha/year that has been recorded by communities from garden irrigation at these schemes, all water-supply options (apart from new small dams) become economically viable. In other words, the extra costs of taking time and care during the implementation of a scheme (Box 2) are more than outweighed by the subsequent benefits when that reliable water supply is used for production as well as domestic supply. Even test drilling, which is more expensive than conventional geophysical siting, is economically viable due to the reliable yields of water and the associated production that is made possible. Full details of this economic analysis including extensive background notes, construction details and garden performance are provided by Lovell (2000). Briefly, a partial budget is used to take account of domestic water benefits. The capital costs that are shown in Table 2 include all costs that are associated with social development, improved siting (including test drilling), choice of appropriate technology and construction of the irrigation scheme. The recurrent costs include all the costs that are associated with depreciation, repairs and community labour when water is lifted and distributed manually.

- Pump technology has a significant impact on systems cost and performance. Motorised pumps should be investigated in cases in which community labour is valued, groundwater is deep or yields are high. There is also a need to investigate handpumps or footpumps that can be fitted in multiples to existing slim boreholes to make better use of the available yields and, ideally, to lift the water to elevated tanks in order to save labour through gravity-fed irrigation.

- The superiority of the upgrading of existing facilities over creating or purchasing new facilities. Conversion and rehabilitation both make effective use of costs that were incurred previously on the location of water, offer high internal rates of return in their own right and render and higher benefits than a standard domestic borehole.

- The present analysis is weakened by the small sample size and the failure of past programmes to adequately monitor water-point performance, especially during periods of drought. This is especially true of well-meaning 'low-cost' programmes, which even fail to measure the yields of the water achieved at the time of construction.

Generally, it is better to do something properly the first time rather than to have to return to the problem. This is not to say that all future water supply programmes are going to be expensive. Where low-cost solutions are effective and reliable they are the first and logical choice. However, sufficient information should be collected and available to make a rational decision on

the matter. If the rural water supply in southern Africa is to improve, comparative cost-benefit ratios should be undertaken for the various technical and social options, factoring in as many as possible of those hard-to-quantify benefits over a theoretical lifetime of, say, 20 years. It is therefore important, to decide now on the minimum data set and monitoring regime that is required and to ensure that these analyses are undertaken for each contrasting solution so that value for money can be compared directly.

In conjunction with the above, it would also be helpful to develop a number of tenders that call for a more interdisciplinary approach to water supply and that provide relevant training in the appropriate technology chosen, if necessary. The tenders should state that payment will be made for the amount of water reliably delivered rather than per water point completed or per metre drilled. The intention is to move away from (or not allow) inadequate consultation, siting and design and, hopefully, to encourage the formation of effective partnerships between those presently working in different disciplines for the state, non-government organisations and private companies.

Box 2: Improving security of water supply from basement aquifers

- Take time during siting to locate the optimum groundwater location. Use the best combination of local knowledge, remote sensing, modern geophysics and test drilling. This will initially take longer and cost more, but it will be justified in the longer term, both socially and economically.
- Select the design of the water point in real-time, based on the hydrogeological conditions identified. Test drilling helps to decide this matter. Avoid pre-determined programme designs.
- Match pump capacity to the safe yield of water achieved. Determine this relationship by a pumping test and modelling the water table drawdown over an extended dry period.
- Fit multiple pumps to match this safe yield. Multiple pumps also reduces the load placed on single pumps and avoids catastrophe when one pump fails.
- Choose robust user-friendly pump designs, in consultation with the community for which spare parts are readily available and affordable.
- Promote community ownership and responsibility for the maintenance from the outset through participatory planning, social contract, formulation of constitution, appropriate bye-laws, and an official handing-over ceremony.
- In consultation with the community, identify natural leaders who will take the initiative forward.
- Provide community training in operation and maintenance, a gantry over the water-point to aid pump removal, and basic repair tools as part of the water point package.
- Place an economic value on the water point by promoting productive activities that are based upon it.

Putting research into practice

In order to embrace the diversity of challenges that are outlined above, a different kind of research will be needed. The research should redirect objectives towards enhancing adaptive capacity in water-supply programmes by encouraging partnerships; incorporating more participatory approaches; providing training in the use of a variety of tools; addressing key constraints and gaps in knowledge; and by developing policies that move towards payment for benefits delivered. Some suggestions for research in this strategy are provided in **Table 3**.

Integration is the key concept in this new approach. It encompasses integration across components, stakeholders and disciplines. Such integration will require some changes in the culture and organization of research and development agencies that work in the field of rural water supply and some new ways of doing business for both the public and the private sectors. It will undoubtedly take time to benefit many people across large areas as these institutions, roles and responsibilities evolve. However, the justification of the investment lies in the seriousness and widespread nature of the problems that are being faced. The alternative, i.e. to battle on and to face the same or increasing problems in years to come, is not attractive, especially for the people who live in these areas of southern Africa and who already suffer the inadequacies of the current approach.

The need to refocus research towards integration and knowledge sharing is also being faced in other sectors. Integration is central in the current thinking on poverty alleviation. The Sustainable Rural Livelihoods Framework (Carney, 1998) seeks to improve the lives of poor people and to strengthen the sustainability of their livelihoods through a holistic analysis of the five capital assets (natural, manufactured, human, social and financial) upon which individuals and groups draw to support themselves. Likewise, a task force was established recently by the Consultative Group for International Agricultural Research (CGIAR) to examine how its agricultural research could be adapted to provide more emphasis on integrated natural resource management.

The CGIAR supports 16 international research centres that have a combined budget of US$350 million per annum. The papers presented by Campbell and Sayer (2003) constitute a record of the thinking at the time of writing and may be of value when laying the foundations for improved rural water supply in southern Africa.

Table 2: Economic appraisal of water supply options in basement areas (redrawn from Lovell, 2000)

Option	Capital Cost US$	Recurrent Cost US$	IRR (%)	NPV (13%)	US$/m³ of water	US$/ha irrigation	Benefit to Cost Ratio
Rehabilitate existing small dam	18 229	5 047	22	17 888	0.89	6 669	1.3
Upgrade underutilised borehole or well	6 034	2 394	87	13 518	0.95	7 095	1.3
Convert to screened- regolith borehole	7 612	2 158	33	6 580	1.04	7 825	1.1
Convert to large-diameter well	5 921	1 334	69	8 669	0.95	7 093	1.3
Convert to collector well	9 082	1 675	24	5 006	1.02	7 661	1.2
Site and construct new small dam	185 316	13 402	-ve	-297 063	2.65	19 846	0.5
New screened-regolith borehole	9 146	2 235	21	3 688	1.09	8 157	1.1
New large-diameter well	7 456	1 411	32	5 777	1.01	7 575	1.2
New collector well	10 617	1 751	17	2 113	1.08	8 071	1.1
Hydro-fracture existing borehole	6 089	2 028	63	8 773	1.01	7 578	1.2
New conventional deep borehole	7 419	1 416	22	2 389	1.13	8 481	1.1
Deepened family well	1 199	378	∞	7 730	0.93	7 006	1.3
Family well	599	126	∞	6 279	1.18	8 864	1.0
Domestic borehole (no production)	4 719	285	-ve	-9 762	n/a	n/a	n/a

NRRD (1998) notes that the various categories of research and the relevant disciplines needed for comprehensive understanding will require effective co-ordination and management. The integration of relevant strategic knowledge from past and present sector programmes is important, as is the establishment of reliable and enduring partnerships between workers in various disciplines and between institutions that represent various stakeholders. An important task to be undertaken is to test and subsequently transform hypotheses into proven principles that can be applied in practice with confidence. The research effort should therefore be one of learning by doing, bringing the integrated approach into operation within applied water-supply programmes to enable policy makers to synthesize the lessons learned and to promote the new principles across multiple sites. Bringing these policy makers together at this stage to discuss and formulate the research strategy required would be an important first step towards the achievement of this objective.

Table 3: Research to address the challenges of basement aquifers in Southern Africa

Challenge	Research Activity
• Move towards a more interdisciplinary adaptive approach to rural water supply	• Highlight the seriousness of the problem of water supply from basement rocks for people living in southern Africa and the need for reform. Include the shortcomings of present approaches and of drought-relief drilling programmes that emphasise the need for longer-term, pre-drought mitigation measures in order to avoid the need for costly and less effective emergency interventions. • Bring policy makers and donors together to formulate a research strategy. • Promote communication between the relevant disciplines. • Assemble relevant strategic knowledge from past and present sector programmes. • Identify and address training needed to better utilise this knowledge. • Bring the integrated approach into operation within ongoing programmes, e.g. through specific tenders.
• Make more effective use of existing water points	• Establish inventories of water points that are underutilised, of inappropriate design or satisfactory for domestic use, performing pumping tests and modelling of drawdown during drought, where necessary. • Upgrade, convert and rehabilitate as appropriate. • Investigate with local inhabitants and manufacturers the most appropriate pump technologies (manual and motorised) that cover the required range of yields, fit them to existing water points and save labour during irrigation. • Promote production at suitable water points, while developing appropriate social contracts, constitutions and by-laws. • Link with policy development that promotes community ownership and maintenance; and investigate with users the institutional arrangements and payment regimes that best achieve this objective.
• Improve siting and design of new water points	• Continue to develop geophysical well-siting techniques, ensuring that these are practical and can be made available, with appropriate expertise, to future development programmes. • Introduce the private sector, government and non-government agencies to improved siting with the use of a mix of local knowledge, remote sensing, geophysics and test drilling; to the selection and construction of alternative well designs that is based on ground conditions identified; and to investment in social development during scheme implementation. • Quantify with these agencies the most cost-effective mix of local knowledge, remote sensing, geophysics and test drilling. • Reward adequate consultation, siting and design but do not pay per water point completed or per metre drilled but for water made reliably available.
• Better quantify benefits and costs of alternatives	• Agree on the standards required, such as 'water made reliably available' and the ways in which these standards should be determined. A consistent, workable and enforceable set of rules is required. • Introduce these standards into present and future programmes. • Monitor long-term sustainability. The monitoring should include recurring costs to communities in labour and money, which can vary greatly between various technology choices. • Study affordability, willingness to pay and cost recovery and the role for subsidies, financing mechanisms and lease agreements.

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Groundwater management in southern Africa

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Abstract

Aquifers in crystalline basement rocks occur widely in southern Africa and are an important source of water for rural and other communities. These aquifers have poor yields and low productivity, but they are increasingly considered to be a favorable low-cost water supply option for rural communities. Therefore there is a need for more structured management of them. The first part of this paper discusses groundwater management challenges in basement aquifers in southern Africa and the possible management interventions that could be applied to them. In the second part, a case study is presented of the Sand River catchment (South Africa) where some groundwater management approaches have been applied. The conclusion reached from the case study is that single intervention measures for the management of groundwater are not always successful as groundwater management tools. Adaptive management is recommended as an approach for the management of basement aquifers, because it offers the potential for time-variable interventions.

Introduction

Basement aquifers occur widely across the southern Africa region and are used for water supply for domestic, irrigation and livestock use. Their exploitation is increasing due to the spatial and temporal variability and unevenness in the distribution of water resources in the region. Communities are therefore obliged to consider alternative sources of water as drivers of economic development. While the per capita availability of water in the southern Africa region is about 5,000m^3/year, similar to Europe and better than Asia, there are disparities in both spatial and temporal availability (Andrews *et al*., 1999). Together with the hydrological extremes that characterize the region (Andrews *et al*., 1999), the variability adds to the challenge of access to water. Furthermore, many people in the region live in rural areas and do not benefit from water supply systems similar to those in the urban areas. For these people, alternative sources of water fulfil a crucial role in their socio-economic development.

Generally, a large number of rural communities in southern Africa depend on groundwater for water for domestic, irrigation and livestock use. Groundwater is also believed to be the only practical means of meeting community water needs at a relatively low cost (Robins *et al*., 2006). In the driest areas of southern Africa, groundwater is the primary water source for household and livestock use (SADC Water Sector, 2002). The SADC's water sector also estimates that only 23% of the southern Africa population depends on reticulated water from surface water sources. About 37% depends on groundwater sources. The remainder of the population depends on unimproved water sources, either surface water or groundwater. Groundwater also plays the key role of supporting large-scale commercial irrigation in some areas in the region. Countries in the region are increasingly aware of the significance of groundwater and are actively integrating groundwater management into their overall water resource management structures (for example South Africa and Zimbabwe).

There are many reasons for the said dependency on groundwater. These reasons include the widely accepted argument that groundwater is well suited to rural water supply in SSA (see BGS, 2000; Carter, 2003). Groundwater has also been described as a perennial source of water (Calow *et al*., 1997), a resource that can be developed for localized use (Butterworth *et al*., 2001) and as a much-needed buffer during times of drought (Carter, 1988, in Carter, 2003). It is suitable for human consumption because of its good quality (Jha, 1999). Carter (2003), describes groundwater as the ultimate resource for use at local scale as it lends itself to incremental development at relatively low cost and it is more resilient to inter-annual variability than rainwater or surface water.

Unlike river flows that exhibit variations that are similar to the rainfall (Calow *et al*., 1997), groundwater has a delayed response and continues to be a source of water in dry periods. The advantages of groundwater also include its generally good quality, the buffering capacity that it provides against adverse climatic conditions such

as droughts and the relative low cost of developing aquifers (UNEP, 2003).

Because many rural communities rely on groundwater, it is widely acknowledged that effective management of this resource is a key factor in socio-economic development in southern Africa. However, groundwater-based water supply systems are sometimes found to be insufficient and vulnerable to drought due to poor design and insufficient depth of wells that is coupled with the use of inappropriate pumping devices (SADC, 2000). As a result, the communities that are dependent on groundwater are more vulnerable to droughts. According to the SADC's water sector, the main drawbacks of groundwater management include inadequate or inexistent monitoring; lack of protection and poor regulation; lack of awareness of the resource (recharge), which results in unsustainable abstractions, depletion of aquifers and pollution; and inappropriate water supply technology and management.

This paper discusses the management strategies for groundwater with a particular focus on basement aquifers in southern Africa. While it uses a specific case study to illustrate some key issues, it is largely based on general groundwater management principles that are available in global literature. The material presentation is structured as follows: the second section puts groundwater availability and use in southern Africa into perspective. The third section discusses groundwater management problems. In the fourth section groundwater management options are discussed. In the fifth section a case study from South Africa is presented. The final section draws some conclusions and provides recommendations.

Groundwater availability in basement aquifers and use in southern Africa

It is not the purpose of this paper to discuss basement aquifer groundwater occurrence in southern Africa. Only a general summary is given here. Understanding the general distribution of water resources in southern Africa is made difficult by the paucity of data and the lack of reliable statistics. As stated by the FAO (FAO, 2003) with reference to sub-Saharan Africa in general, "The information available is uneven and very poor for some of the African countries". Robins *et al.* (2002) echo this sentiment, citing the poor data availability, discontinuous data collection and poor data management in southern Africa countries. In addition, the distribution of water within Africa is not equal and the continent has the greatest spatial and, perhaps, temporal supply variability of any in the world (Walling, 1996). These descriptions of the situation are equally valid for southern African countries.

Extent of basement aquifer groundwater resources in southern Africa

The African basement complex extends over much of southern Africa (**Figure 1**). Basement complex areas cover most of Zambia, Zimbabwe, Malawi, Tanzania, northern Mozambique, and the northern part of South Africa. The basement complex is characterized by aquifers that have very little or no primary porosity. These aquifers are characterized by poor storage and low yields, typically less than 1 ℓ/s (Field and Collier, 1998; UNEP, 2003). However, despite their low productivity, basement aquifers are regarded as essential for water provision to rural communities, because many poor rural communities are located in areas of basement rocks than in any of the other hydrogeological provinces in southern Africa.

Groundwater use and the importance of its management in southern Africa with reference to basement aquifers

Groundwater in basement aquifers is an important life element for many rural communities in Africa (Chilton and Foster, 1995). Many of these communities are located in areas of basement geology and are without access to alternative water resources or conventional water infrastructure. While coherent data regarding the number of households that rely on basement aquifers for water supply in southern Africa are difficult to come by, a large number of rural communities in southern Africa depend on groundwater because they are not connected to water supplies in the same way that cities and other urban centers are.

Due to its relative geographical availability and ease of access through shallow wells and other low-tech structures, Nicol (2002) estimated that groundwater sources serve about 60% of the urban and rural population in southern Africa. Many rural communities in southern Africa depend on groundwater for all their needs. In South Africa there are in excess of 35,000 boreholes that serve rural communities in the Limpopo Province alone, a province that largely overlays basement aquifers. Similar use is mirrored in Zimbabwe, Zambia and Mozambique. In Zambia, more than 80% of the rural population depends on shallow wells that tap shallow aquifers in wetlands for drinking water (Chiuta,

2002). In one district in Malawi, 104 villages with a population of 70,000 access groundwater from basement rocks for their water supply (Robins *et al*., 2002). In Namibia, the driest country in southern Africa, more than half of the national water supply is based on groundwater (Lange, 1998). In addition to small-scale use of groundwater in rural areas for irrigation and livestock production uses, there is a pronounced use of groundwater in many urban centers. Large cities in southern Africa that are dependent on groundwater include Bulawayo, Lusaka, Maputo, Ndola, Serowe, Walvis Bay and Windhoek (**Figure 2**). In addition, there are smaller urban centers that depend on groundwater. Some of this groundwater is abstracted from basement aquifers as only basement aquifers occur in these areas (**Figure 1**). The importance of basement aquifers for water supply for many communities in southern Africa demands a suitable response for the management of groundwater in thee aquifers

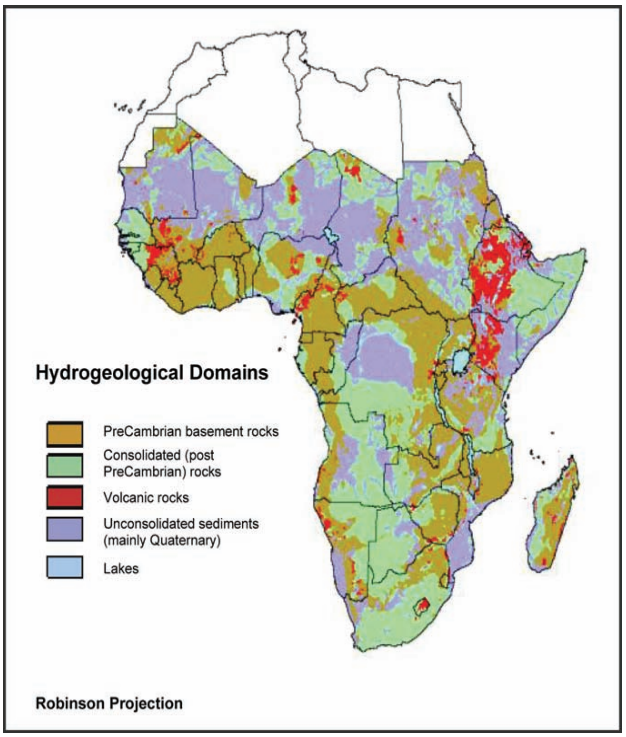

Figure 1: Hydrogeological provinces of southern Africa and sub-Saharan Africa. Source: BGS, 2000.

Figure 2: Groundwater dependent cities in Africa (source: UNEP, 2003).

Groundwater management challenges in basement aquifers in southern Africa

As stated by Smith (2001), in order to understand the challenges facing groundwater managers, it is necessary to understand the groundwater problems that these managers face. While each country or basin in southern Africa, as is the case elsewhere, is different, a number of the groundwater problems are similar in nature. The common problems are related to: (1) overabstraction and the balancing of supply and demand of groundwater over time; (2) operation and management of abstraction and (3) the national policies that (sometimes) create negative environments. The more common problems are described in the following paragraphs.

Awareness of the quantity of the groundwater that is available on an ongoing basis is a critical aspect of managing the resource. Lack of such awareness often creates problems regarding availability of resources over time and regarding the management of the groundwater. The main challenge regarding quantity is the limited nature of the resource due to the geology, with the possible outcome of abstraction far exceeding the supply. This is especially the case in basement aquifers areas in which the aquifers have limited storage

capacity and low yields (Calow *et al.*, 1997). In these areas, even where high yields are initially observed, the yields are not sustained due to the low storage capacity of the aquifers. In such cases, abstraction is usually much greater than the sustainable abstraction. A typical example is Botswana, where the pump operators are simply unable to shut down the pumps at the end of a normal recommended pumping day, because people still need to get water. Abstraction of groundwater from Botswana's aquifers generally exceeds annual recharge (Kgathi, 1999). This causes groundwater decline and possible borehole failure. Ultimately the communities are left without access to water and community members, mainly women and children, walk long distances to fetch water. According to the Department of Water Affairs (Botswana), groundwater levels in some well fields in the country have declined by as much as 2.6 m/year. Overabstraction occurs where the demand is greater than the supply and often where groundwater is the most reliable supply of water. In Namibia, for example, where the quantity of available groundwater is not known, the depletion of groundwater that supplies about half of the country's water needs is a real problem (Lange, 1998). The continued decline of groundwater levels due to overabstraction in the Limpopo water management area in South Africa is a cause for concern for the farmers who depend entirely on groundwater for irrigation (**Figure 3**). The decline rates are in the order of magnitude that is greater than even the highest possible recharge rates in the area and if it is not managed, the water users are faced with the bigger challenge of having no access to water.

Outside of extremely dry areas in which groundwater is the normal supply, groundwater use in southern Africa is, to a large extent, a response to drought. The number of wells that are sunk, increases in drought years as relief agencies help communities to access water. Due to the extended length of some droughts groundwater abstraction often continues without the occurrence of significant recharge. Many of these wells fail as a result of water-table recession that is below well base or abstraction that exceeds storage. In addition, some of the wells are not used after the drought periods due to the failure or restoration of normal water supplies. The climatic variations that lead to time-variable demand and supply present another challenge for water managers who are required to balance groundwater abstraction and supply.

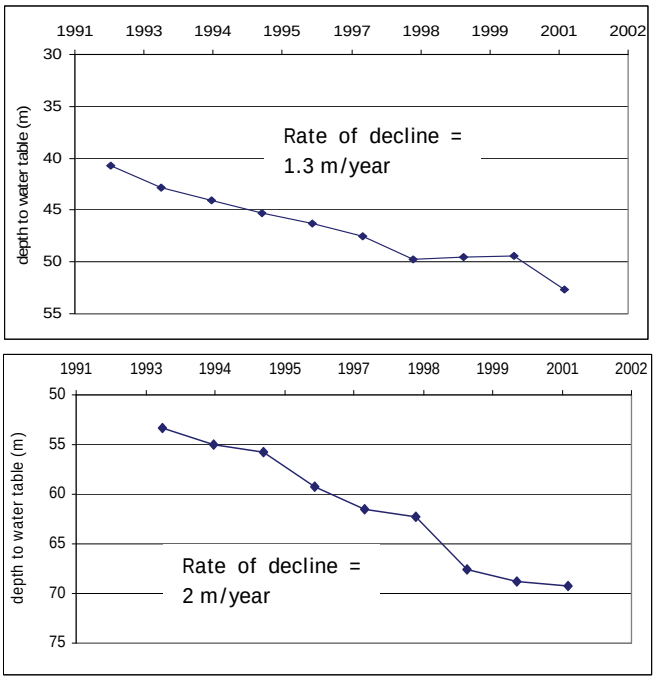

Figure 3: Long-term decline of groundwater levels in the Sand River catchment, Limpopo River basin, South Africa.

Most boreholes in rural areas are installed by donors, NGOs and other well-wishers, usually in response to drought. Such installations usually fail to take into account the capacity required to manage the groundwater supply systems. Often communities do not have the capacity to manage abstraction in order to ensure that the boreholes do not fail due to over abstraction. As a result, boreholes fail and users are left without access to water.

The nature of the challenges described in this section can be addressed by several management approaches. Some of these approaches are presented in the following section as well as in the case study that follows. The case study also illustrates the failure of some management approaches that are applied to basement aquifers.

Options for the management of groundwater

There are numerous groundwater management options that have been applied worldwide. The extent of the success of each option is very much dependent of the context in which it is applied. Literature contains a wealth of examples of groundwater management tools. Some of these tools are given in Table 1. Recommendations for the management of a specific basement aquifer can be deduced from the various

models available. Some of the models have been applied in southern Africa with varying degrees of success, as illustrated in the case study presented in this paper.

Groundwater management approaches can be classified as being either direct or indirect. Direct (also referred to as conventional) approaches are regulatory. They focus on enhancing the resource, depending on the state of the groundwater (Shah, 2004). They are heavily dependent on the presence of data; institutional capacity for regulation; and scientific research (Burke, 2003). Such approaches assume that there is adequate knowledge of the aquifers and that there is capacity to monitor and enforce regulations. Indirect approaches include economic and policy tools; and community management. They are driven by shared concerns, such as threats to livelihoods (Shah, 2005), and collective management. There is a range of management tools that fall into these two categories. A third grouping of groundwater management is considered to be adaptive and comprises time-variable management that uses any of the methods that fall into both the direct and the indirect approaches. The management tools or methods can be grouped into those that relate to the long-term management of groundwater resources and those that relate to the short-term, reactive management of groundwater, such as during drought periods (Calow *et al*., 1997). However, regardless of any of the classifications that might be used, ultimately groundwater management attempts to control abstraction, either by direct abstraction control; relocation of boreholes or abstraction points; or modification of the timing of abstraction (see UNEP, 2003), while giving due consideration to: (1) geographical constraints (2) when and where overdraft is necessary (3) financial constraints and (4) capacity. With this background and also in the context of the issues raised in the previous section, some options for dealing with the groundwater management challenges in basement aquifers in southern Africa are explored in the following sections.

Table 1: Groundwater management types, approaches and tools (typologies created from material in Shah, 2004, Bromley *et al*., 2005; van Steenberg and Shah, 2001)

Type	Management approach	Management tools
Direct	Regulatory measures	• Groundwater abstraction permits • Government controls • Controlling new well installations
Indirect	Collective / community management	• Community movements such as 'recharge movements' (e.g. in India) • Water committees • Water user associations • Groundwater associations • Rules and norms
	Economic and policy tools	• Policies to discourage certain types of crops (e.g. water-intensive crops) • Energy pricing • Water pricing • Subsidies for efficient technologies
Adaptive	Combination of any # of direct and indirect approaches	• Any of the direct and indirect management tools

Direct management

Direct management, also referred to as the conventional approach to groundwater management, takes the hydrological system as a starting point and combines scientific, technical and institutional components to achieve socially defined management objectives (BGS 2004). Such conventional approaches are based on the UNEP (UNEP, 2003) premise that the control of the quantity of groundwater abstracted is the most important option for stabilizing groundwater levels. The management unit for direct approaches is the aquifer and management of the resource is centered on balancing the supply and the demand. Direct approaches include direct regulatory approaches (such as abstraction permits, pumping limits and conjunctive use) that are used in a number of countries, watershed management and recharge activities. For their success, direct approaches are dependent on the availability of scientific data, institutional capacity and political will for reform (Shah, 2005). Conventional approaches continue to be used extensively in South Asia, but without much success (Shah, 2005).

Abstraction control, i.e. the control of the quantity of groundwater abstracted can be achieved in several ways. The recent reforms in the water sector in several countries in southern Africa have introduced permitting in one form or another as a way of controlling abstraction. Groundwater users are legally bound to the volumetric limit stated on the issued permits. Permitting is a globally accepted groundwater management tool. It dates back several decades in the United States, Australia and other countries in which legislation that governs groundwater has long been established. Monitoring is essential in order to effectively institute a permitting system. Following the argument raised by Shah *et al*. (2003) that you cannot manage what you cannot monitor, it could be said that you cannot permit what is not monitored as permits that are issued are usually based on fractions of the available volumes.

Regulatory and policy instruments have been used successfully elsewhere to manage groundwater. For example, through provisions in its water law, Iran enforced a ban on new groundwater abstraction structures in affected areas as a means of conserving water supply (Hekmat, 2002, in Shah *et al*., 2003). Regulation can also be used to impose general pumping limits through permitting that is enforced by government or by catchment or basin authorities. Shah *et al*. (2003) also cite other policy interventions in several countries. However, they argue that the regulation of groundwater abstraction is far more difficult when there are a large number of abstraction points. Regulatory instruments are increasingly being used to support the management of water resources, including groundwater in southern Africa. The extension of regulatory instruments to groundwater management is a recent phenomenon in southern African countries in which groundwater was previously considered to be private water (e.g. South Africa and Zimbabwe).

Conventional approaches appeal to resource managers, because they are resource centered and the principle of balancing demand and supply is widely accepted in the engineering fraternity. However, the implementation of these approaches is hampered by some of the assumptions on which the approaches are centered, namely availability of scientific data, lack of institutional capacity and lack of political will. The Expert Meeting (in Spain 2001) identified some of the limitations to purely regulatory approaches. These limitations include the inability of rigid licensing systems to address situations of stress or change; inability to provide flexibility; the need for adequate enforcement to guarantee compliance; the need for adequate information on the resource; and complete and current water rights or license information. These limitations have an impact on the management of groundwater in basement aquifers in southern Africa, where data collection and management, among other things is poor (Robins *et al*., 2002). Other problems in respect of the direct management of groundwater include the invisible and indivisible nature of aquifers and the lack of incentives for individuals who might act responsibly in the management of groundwater. In some countries, penalties are emposed on users who abstract more than their lawful limit. However, the enforcement of regulations and these penalties are sometimes weak, rendering the systems non-effective. For basement aquifers, it is even more difficult to manage groundwater by abstraction control in the ways described above for two reasons. Firstly, the fractures in which groundwater is found do not constitute continuous aquifers. As such, the extent of the controls required for productive boreholes might differ if they lie on different fractures that are impacted differently by the various pumping regimes. Secondly, because the boreholes in basement aquifers are characterized by low productivity, there are usually many boreholes concentrated in a small area. The monitoring of the abstraction and compliance with regulations can easily become a nightmare. Given these challenges, the success of purely direct approaches to the management of groundwater in basement aquifers in southern Africa remains to be

tested. In addition, the current environment of scarce data and limited capacity remains unfavourable for the successful implementation of groundwater management that uses the direct approaches.Indirect approaches to groundwater management

Economic and policy instruments

Economic and policy instruments are considered to be another way of controlling the abstraction of groundwater. Appropriate power pricing has been said to hold potential for the indirect management of groundwater (Scott and Shah, 2004). It is expected that when the price of power increases farmers reduce pumping. However, this is effective only in areas in which energy costs are not subsidized. In India, where farmers' energy costs are subsidized by the state, economic instruments such as power pricing simply do not work (Shah, 2005). In India, for example, in blocks where recharge is estimated to be higher than abstraction, farmers receive subsidies for installing tube wells, and where abstraction is greater than recharge, subsidies are withdrawn (Shah, 2002). Groundwater use is therefore promoted where groundwater is perceived to be available. In the case of basement aquifers where, by virtue of the unproductive nature of boreholes in these aquifers, there are many scattered abstraction points, the implementation of economic instruments is hampered by the need to meter many boreholes that are run on a small-scale basis. It would be extremely difficult to justify the cost of metering, collecting penalty fees and monitoring all the abstraction points for compliance.

Appealing as they may seem, policy instruments do not guarantee success in the reduction of abstraction or in the curbing of further reduction of groundwater levels. Bromley *et al*. (2001) report such failure in the upper Guadiana basin in Spain where a combination of policy and subsidies did not achieve the intended outcome of reducing the drawdown in the basin. As with other management approaches, the effectiveness of policy instruments as a groundwater management tool is greatly enhanced by using it in combination with other management tools such as those described above.

Community management

Community management, also referred to as self-regulation, is a decentralised collective management by users that can be implemented on its own or as a complement to external regulation (van Steenberg and Shah, 2001). Community management comes in various forms, including informal committees, informal norms, community organisation, water-user associations, and groundwater associations (van Steenberg and Shah, 2001). The common denominators in cases in which self-regulation or community management is practiced include universality and non-discrimination; availability of information (e.g. water balances); [1]rules and norms. Experience elsewhere has shown that in poorer countries, these forms of management are more successful in the management of groundwater than external enforcement mechanisms, because the latter generally do not work well (van Steenberg and Shah, 2001). As with other forms of groundwater management, self-regulation also has its limits. There are cases in which norms and social pressure may not develop adequately (van Steenberg and Shah, 2001).

Adaptive approach

The adaptive approach is a flexible system, given the changing conditions of the groundwater system and of the uses and users. As noted by Burke (2003), the temporal and spatial variable patterns of groundwater use do not present an opportunity for systematic management responses. In addition, there is no correct generic way to manage groundwater. What is good management in one place may be bad management in the same place at a different time or in another place (Smith, 2001). Experience elsewhere has shown that a suite of approaches applied together to manage groundwater is more effective than the application of only one management model. Others have concluded that effective groundwater management will depend largely on the context-specific combination of interventions that are applied for the best possible outcome. For example, while monitoring is important for groundwater management, it does not on its own add value. On the other hand, the implementation of water supply projects and management interventions are best supported by monitoring and the availability of data (Robins *et al*., 2002). Monitoring is likely to work in combination with other management interventions, such as voluntary pumping limits or abstraction control in tandem with feedback given to users and water managers. Experience in the Dendron area in the Sand River catchment in the Limpopo Water Management Area (South Africa) has shown that users tend to become

1 Norms are non-discriminatory do's and dont's, based on universal access. According to van Steenberg and Shah (2001) norms are effective as they are easy to monitor by anyone and any person can, through open contempt or intimidation, withhold another person from breaking the moral code.

despondent and stop their contributions for paying the water-level reader when monitoring appears to be an end in itself [2].

Case study: groundwater management for the Dendron aquifer, Sand River catchment

Background

The Dendron aquifer in the Sand River catchment (Limpopo River basin) in South Africa has traditionally been considered an important source of irrigation water for commercial agricultural activities in the area around the town of Dendron. Continuous expansion of the irrigated area in the Dendron surrounds became a major cause for concern among water users as boreholes dried. The irrigated area more than doubled in a short period. In 1968 the total area irrigated with groundwater was about 1,319 hectares. At that stage, only about 9.3 million cubic meters of groundwater (or 4 % of the rainfall) were abstracted to meet irrigation requirements. By 1986, the irrigated area was about 3,579 hectares, an increase of more than 100% in just under twenty years. Annual water abstraction for irrigation, estimated with the use of crop-water requirements and cropped area, was estimated to be about 21 million cubic meters.

Prior to the South African Water Act (1998), groundwater was considered to be private water. Users did not require a permit to abstract groundwater that occurs beneath their land. This right made it difficult to enforce any regulations on groundwater use. The new water act considers groundwater, together with surface water, holistically and abstractions require permits. Ideally it should provide a better environment for enforcing regulations and monitoring for compliance.

With declining groundwater levels, farmers were faced with the challenge of losing their sole source of irrigation water. Irrigated agriculture would not remain a viable commercial activity in the area if groundwater abstraction persisted at the same levels. There was an urgent need to manage the available groundwater resources sustainably in order for irrigated crop production to remain a viable activity. This case study describes some of the management attempts made by the Dendron aquifer water users in the context of general groundwater management approaches.

Location of case study area

The town of Dendron, the center of the study area and reference point for the Dendron aquifer, is located about 60 km north of Pietersburg in the Limpopo Province of South Africa (**Figure 4**). The aquifer is in the Brakspruit and Hout River catchments, both sub-catchments of the Sand River that drains to the north-east into the Limpopo River. The aerial extent of the aquifer is about 1,600 square kilometers. The area is generally flat and almost featureless and is bound to the north by the Blouberg Mountains and to the north-east by the Soutpansberg. The aquifer is part of the African basement complex and is characterized by fracturing and dolerite dykes. The basin has two interdependent aquifers, a weathered upper aquifer and a lower fractured one (Jolly, 1986). A more detailed description of the aquifers appears in Jolly (1986). The weathered aquifer is unconfined in some areas and semi-confined in others while the fractured lower aquifer is confined. The weathered upper aquifer has a storage coefficient of 0.01 while the lower one has a storage coefficient of 0.0025. The contact between the two aquifers is at 35 – 50 m below ground level. Groundwater yield in the aquifer is extremely variable, ranging from 0.1 to about 45 ℓ/s. A significant proportion of boreholes that are used for irrigation have yields of less than 20 ℓ/s. About 36% of the boreholes surveyed in 1986 yielded between 20 and 45 ℓ/s. In the same year, a survey of boreholes that were used for irrigation ranged from 3 – 35 ℓ/s (Jolly, 1986). Recharge to the aquifer has been estimated to be between 2% and 5% of annual rainfall when rainfall is at least 400mm per annum (DWAF, 1990).

2 See details of case study.

Figure 4: Location of study area

The Sand River catchment is characterized by summer rainfall that typically starts in November and lasts until March or April. The average annual rainfall is about
400 mm. Potential evapotranspiration is always much greater than precipitation and during average rainfall years there is always a water deficit in the basin. Long-term trends of average rainfall and potential evaporation are shown in **Figure 5**. With limited surface flows in this catchment, the communities around Dendron depend on groundwater for most of their water requirements.

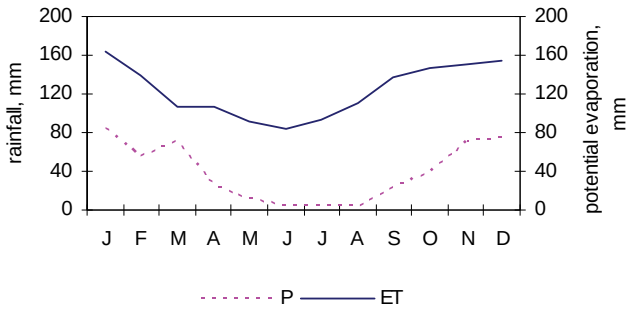

Figure 5: Long-term average rainfall and potential evaporation

The Dendron groundwater problem

In the past two decades there has been growing concern over the sustainability of the rates of groundwater abstraction from the aquifer. These concerns arose from the expansion of the irrigated area that led to increased abstraction and a lowering of the groundwater levels by 5 to 35 m. Irrigated area increased by more than 170% (from 1,319 to 3,578 hectares) between 1968 and 1986 (Northern Transvaal Cooperative, NTC, 1989), with a corresponding increase in annual abstraction from about 9.3 to 21 MCM (**Table 2**). The increased demands for irrigation resulted in the overabstraction of groundwater. Over abstraction was also evidenced in the unreliability of the supply that ensued. As groundwater levels declined, boreholes dried and deeper ones were sunk in order to mitigate the problems of water shortages.

While some of the groundwater fulfilled livestock and domestic water demands, irrigation was the largest user in the area. More than two hundred farms were reported in the area, of which fifty had irrigation activities. The remainder of the farms utilized groundwater for livestock watering purposes. The crops that were irrigated include potatoes, wheat, maize, cotton, oats, pumpkins and vegetables (tomatoes, onions, etc). Of the 335 boreholes surveyed in the area in 1986, 69 % were used for irrigation, 27 % for domestic purposes and 4 % for livestock watering (Jolly, 1986). In terms of volume, irrigation accounted for 95 % of all abstractions Jolly, 1986).

1986, the Department of Water Affairs and Forestry (DWAF) issued a warning to the water users that the aquifer could reliably supply water for a further 13 years only under the water-use conditions that prevailed. A number of interventions that were aimed at reducing abstraction from the aquifer were initiated. However, in early 2001, the water levels in the aquifer were reported to be still low. Yet the aquifer still supported a substantial extent of irrigation. Some of the farmers were of the opinion that the state of the aquifer had improved and that the water table had been rising in recent years. It was not apparent that any of the measures that had deliberately been taken to reduce abstraction had achieved the intended objectives.

Direct management of the Dendron aquifer

A study by the water authority established that the area that could be sustainably irrigated with the use of available groundwater resources was equivalent to 3 % of the total farm area. In line with the recommendation to limit the irrigated area, the farmers' union agreed to implement what was referred to as the 3 % rule. Following this rule, only 30 hectares could be irrigated for every 1 000 hectares of farmland.

Table 2: Abstraction and irrigated area trends in the Dendron area.

Year of study	Area irrigated (ha)	Estimated abstraction 10^6 m^3	Depth to groundwater (m)
1968	1 319	9.3	12 – 21
1974	1 474	8.5	15 – 35
1986	3 579	21.0	40 – 50
2000	–	–	50 – 100

A key point of this management approach was that the rule was enforced for new irrigated areas that were commissioned after the rule had been established. It did not apply to land that was under irrigation prior to the establishment of the regulation.

As a parallel measure and at the initiative of the local farmers' union, the water authority and other stakeholders initiated a study to develop a groundwater management system for the aquifer. The objective for the groundwater management system was to predict the availability of groundwater for irrigation on an ongoing and regular basis. Such a management system would enable water abstraction rates to be continuously and accurately monitored and new compliance measures to be set in order to prevent further overexploitation of the aquifer. As part of the study, groundwater-level monitoring was initiated in the early 1990s with the earliest water-level records dating from 1991. A water-level meter reader was appointed to record water levels on a regular basis. The farmers made contributions towards the remuneration of the water-level reader. There were no continuous monthly or annual groundwater-level measurements. The data available indicates an unevenness in the data collected and there are several discontinuities, with no data for many periods. The groundwater-level data is also only representative of specific periods. The water-level records were kept at the farmers union's office in Pietersburg. In 2001, water-level records were available from the union's offices in their original format without ever having been analyzed. Furthermore, no feedback on the results of the monitoring had been given to the farmers who paid for the monitoring exercise. Water-level recording was discontinued after 2000 due to many reasons, one of which was the discontinuation of financial contributions by some farmers.

Indirect approaches to managing the Dendron aquifer

In addition to the restriction of the irrigated area, a number of interventions were implemented by individual farmers. They included: (1) a change from the irrigation of maize that has high irrigation-water requirements and lower returns to high-value crops that have less consumptive use, but increased returns and (2) change of irrigation methods to more efficient methods as well as technological changes that improved water application efficiency. These interventions are considered to be community management as they were self-imposed by the farmers who use groundwater for irrigation.

Self-regulation of crop choices

The second community management approach, namely switching to crops that have less consumptive water use, resulted in a shift from the irrigation of maize, a low-value crop that has a high consumptive use of water, to high-value crops such as potatoes. The water use by crop per unit area ranged from about 3 000 to over 10 000 m^3/ha per season (Jolly, 1986). The largest water user in the Dendron area has traditionally been maize. Potatoes, the more commonly grown crop in recent years, have crop water requirements that are about three quarters that of maize. During the time that the interventions were being implemented, cropping patterns changed with most farmers switching from growing maize to growing potatoes, vegetables and other crops that have lower water requirements. Although this shift in cropping patterns may have been driven directly by producer price, it has had the potential to impact directly on production costs, if the cost of pumping is included. For example, the shift from maize to potatoes theoretically resulted in a saving of over 2,000 m^3 of water per hectare per season in pumping costs and it reduced abstraction for irrigation. As abstraction records were not kept, groundwater abstraction could only be estimated from the cropping patterns and it is not possible to conclude that groundwater abstraction was effectively reduced through this intervention.

Self-regulation by changing irrigation management

Irrigation water management has changed over time with a shift from furrow irrigation to manually movable sprinkler systems and eventually center

pivots that are currently being used on most farms (Cotzee, 2001: personal communication). With furrow irrigation, the irrigation efficiency was considerably lower. As such, more water was abstracted in order to meet crop water demands adequately. Farmers switched to different formats of sprinkler systems. Even with the center pivot irrigation systems, presumably the most efficient irrigation methodology, some farmers made yet another technological shift from high pressure to low pressure systems in order to save even more water (Cotzee, 2001). With the use of on-farm mini weather stations to compute evapotranspiration and crop-water requirements more accurately, some of the farmers in the area now follow accurate irrigation scheduling. On some farms (e.g. Cotzee), tensiometers are used for mapping out soil moisture profiles to schedule the timing of irrigation. All these measures targeted the reduction of irrigation water requirements and abstraction rates.

Results of water level monitoring

In 2001, farmers indicated that the recovery of groundwater levels began in the 1990's, indicating the effectiveness of the several management interventions that had been implemented. The average depth of boreholes, an indicator of the general depth to groundwater, is shown in **Figure 6**. This figure shows the average depth at three time periods, namely 1969, 1974, and 1986. Generally over time the farmers had to drill deeper to access groundwater. This indicated the receding groundwater levels.

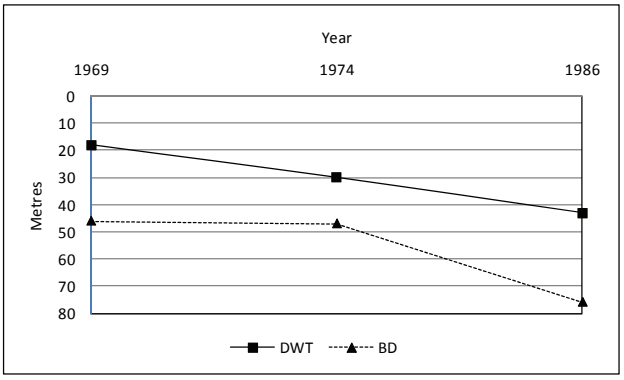

Figure 6: Average depth to water table (DWT) and average borehole depth (DB) (Source: Jolly, 1986).

Selective results of water-level monitoring on two farms are shown in **Figure 7**. These two farms have groundwater level data that date back to 1976, the longest recorded period available for the Dendron area. These data indicate the continuous increase of the depth to groundwater with an increased rate of decline of groundwater levels in the latter part of the observation period.

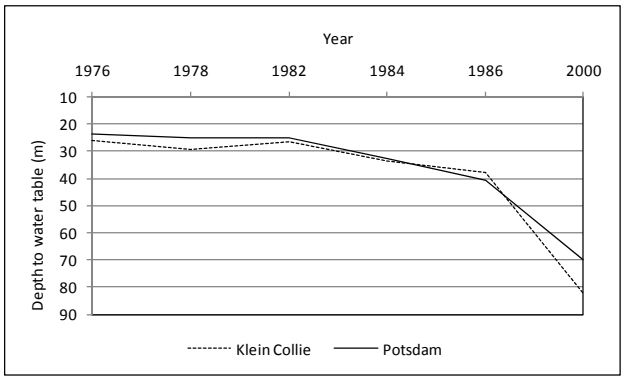

Figure 7: Changes in depth to water table (1976 – 2000) at Klein Collie and Potsdam farms (Source: Jolly, 1986 and DWAF 2001, unpublished data).

These two indicators show that there was no groundwater-level response to the management interventions implemented. In fact, the rate of decline of the groundwater levels increased much faster from the mid-eighties to the nineties (**Table 3**).

Table 3: Rate of decline of groundwater levels

Period	Rate of groundwater level decline, m/year	
	Klein Collie	Potsdam
1976 - 1982	0.14	0.28
1982 - 1984	1.79	2.00
1984 - 1986	1.04	1.97
1986 - 2000	3.16	7.24

Summary

The continued decline of groundwater levels in the Dendron aquifer suggest that the management interventions were not effective in controlling abstraction.

The management interventions may have failed for several reasons. There are three apparent reasons. Firstly, the direct management approach of limiting the cropping area assumes that groundwater abstraction for irrigation is directly proportional to cropped area, regardless of the crop as well as the intensity of cropping. Irrigation water use is a function of crop type and the area under the crop and not of the area alone. Therefore the restriction of the irrigated area to only 3 % of the total farm area would not necessarily reduce abstraction. Secondly, the farmers who had been irrigating more that 3% of their land continued to do so as they were not affected by the new rule. Thirdly, recharge to the aquifer has

been estimated to be about 5% of annual rainfall when rainfall is greater than 400 mm per annum. As a result of the rainfall pattern, the area is prone to lengthy periods of little or no recharge (**Table 4**). As such, to control abstraction only would not have been effective in reducing groundwater abstraction as abstraction took place even in years of low or no recharge.

Table 4: Estimated recharge (based on the DWAF model) to the Dendron aquifer as a percentage of rainfall (Source of rainfall data: The Agricultural Research Council's Institute of Soil Climate and Water).

Period	Recharge as % of rainfall
1969 – 1970	5.5
1970 – 1971	4.3
1984 – 1985	3.0
1999 – 2000	< 2

Groundwater management in the Dendron aquifer was being implemented in an environment in which groundwater was treated as being private water. The implementation of any of the management interventions was dependent on how each user perceived the problem and how it would impact on him. Cropping and technological changes, while they made sense, were implemented by individuals who thought that such changes made (economic) sense. There was no monitoring of the usage of groundwater and it was therefore not possible to determine whether or not groundwater abstraction had reduced.

Even the 3% rule was not enforceable as there was no monitoring for compliance; neither was there a fine for non-compliance.

Finally, there was no mechanism in place to monitor the compliance of the various groundwater users.

A positive behaviour that emerged from the groundwater-level problems at Dendron was the monitoring of groundwater levels. However, the groundwater-level data was not analysed and the monitoring appeared to be an end in itself. Had this data been analyzed, it would have been apparent much earlier that despite the interventions being put in place, groundwater levels were continuing to decrease.

To conclude, the attempts to manage groundwater in the Dendron area were a series of ad hoc direct and indirect management approaches to control abstraction. Furthermore, these management tools were not systematically implemented. As a result, there was no real benefit in implementing any of the interventions. This aquifer is perhaps a classic case of demand that exceeds the supply and that requires the direct control of abstraction in combination with other management interventions in order to effectively manage the groundwater. With the implementation of the 1998 Water Act, the control of abstraction in the aquifer will benefit from the regulatory tools that are part and parcel of the new water management approach in South Africa.

Conclusions

Several models for the management of groundwater resources are available in groundwater management literature. As different situations call for different approaches, models are applicable both individually and in combination. Because of the nature of basement aquifers and their importance in southern Africa, a combination framework for the management of groundwater in these aquifers is recommended. The models discussed in this paper, and that lend themselves suitable for the management of groundwater in basement aquifers, are abstraction control through permitting and voluntary pumping limits; monitoring; use of policy instruments; and adaptive approaches. The extent to which any of these methods achieves the desired outcomes, when implemented individually or in combination with other methods, depends entirely on the local situation.

Considering the scarcity of data, lack of capacity and the dispersed nature of groundwater users, many of the groundwater management tools discussed in this paper can be applied to the management of basement aquifers in southern Africa. The low-yielding nature of the aquifers and lack of data make it difficult to manage abstraction by balancing abstraction and supply in the classical sense. To ease the burden of groundwater management, there is a need for more research in the following areas: (1) further development of knowledge on groundwater availability and benefits of its use in southern Africa (2) enhancing groundwater monitoring schemes to harness adequate and reliable data for water resources planning (3) development of groundwater management models that can be integrated within existing water resources management frameworks and (4) use of regional experiences to design adaptable groundwater management models that sufficiently address the complexities that are associated with groundwater in basement aquifers and thus better integrate groundwater within the overall water-resources management models.

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Aspects of groundwater management that is pertinent to basement aquifers in the southern African development community (SADC)

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Abstract

Groundwater management issues that are pertinent to basement aquifers in southern Africa are identified. The resource management issues include resource constraints, pollution of resources, health issues and institutional arrangements for proper resource management. The complexity of these issues requires innovative mechanisms for groundwater management.

A decision-making framework for groundwater management in the basement aquifers of Namaqualand was developed. It was done through the adoption of a multiple-criteria decision analysis (MCDA) approach to the formulation of a synthesis, within a coherent framework, of the complexity of the decisions to be taken on groundwater management problems that allows the decision maker to identify critical alternatives and pathways or activities. A value-function method was selected, which provides decision support by interval SMART/SWING. The method provides an interactive technique to interrogate various alternative decisions that are based on prior knowledge of the decision-maker.

Introduction

In sub-Saharan Africa, crystalline metamorphic and igneous rocks (collectively termed basement rocks) occupy 40% of the land area and 220 million people live in rural areas that are underlain by such rocks (MacDonald *et al*., 2002). Fortunately, much of the crystalline basement in Africa is weathered and has a mantle, which is commonly 10-30 m thick, of more permeable material known as the basement aquifer (Calow *et al*., 2002). These types of aquifers are considered to be minor in hydrogeological terms (**Figure 1**), but they nevertheless provide water for millions of people in the rural areas of sub-Saharan Africa.

Hydrogeologist have used the concept of safe yield, which is defined as follows:

> *"Safe yield is the amount of naturally occurring groundwater that can be withdrawn from an aquifer on a sustained basis, economically and legally, without impairing the native groundwater quality or creating an undesirable effect such as environmental damage" (Fetter 1994). The sustainable development debate has broadened this definition to: "Sustainable groundwater use is defined as the level of development of groundwater that meets the needs of the present generation without compromising the ability of future generation to meet their needs" (Morris et al., 2003).*

This means that, in order to achieve sustainable groundwater use, the management of groundwater resources should balance economic, environmental and social considerations. Consequently, methodologies are required that facilitate a more holistic approach to sustainability in which coping strategies as well as technical measures form part of the groundwater problem-solving process (Morris *et al*., 2003; FAO 2003). This quest is supported by research, which suggests that strategies that build on existing trends within society or that help populations to adapt may be effective as strategies that attempt to manage the groundwater resource base directly (FAO, 2003). Furthermore, research that has been undertaken to clarify existing coping mechanisms and to identify or test the viability of adaptive strategies could present a major starting point for an initiative to rethink groundwater management (FAO, 2003).

However, it is acknowledged that groundwater management is among the most important, least recognised and highly complex of natural resource challenges that face society (Foster 2000). This paper

presents the pertinent issues for groundwater management of basement aquifers in southern Africa. Basement aquifer types are found throughout southern Africa and occur in Angola, Mozambique, Namibia, Swaziland, South Africa, Malawi, Botswana, Zambia, Tanzania and Zimbabwe (**Figure 1**). The management issues concerned are identified as being the following (MacDonald and Davies, 2000; Pietersen, 2004):

- Sustainability of groundwater drawn 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 that causes problems in respect of the quality and quantity of groundwater.
- The poor natural water quality of basement aquifers that is 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 sound resource management.
- The relative performance and operational costs of boreholes, wells, family wells and collector wells.

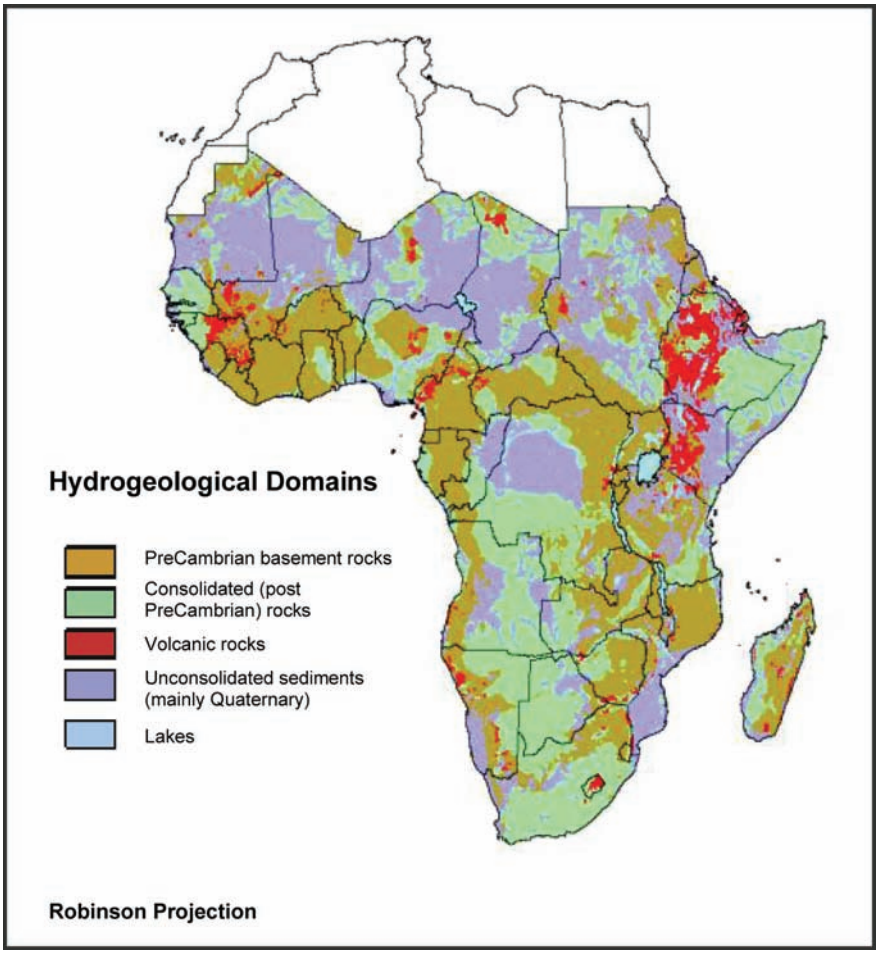

Figure 1: Hydrogeological domains of sub-Saharan Africa (MacDonald and Davies 2000).

Governance of transboundary basement aquifers in southern Africa

Transboundary co-operation in water matters in southern Africa takes place within the framework of the Protocol on Shared Watercourses in the Southern African Development Community. The protocol seeks to (Burchi and Mechlem, 2005):

1. Promote and facilitate the establishment of shared watercourse agreements and shared watercourse institutions for the management of shared watercourses.
2. Advance the sustainable, equitable and reasonable utilisation of shared watercourses.
3. Promote a co-ordinated and integrated environmentally sound development and management of shared watercourses.
4. Promote the harmonisation and monitoring of legislation and policies for planning, development, conservation and protection of shared watercourses and allocation of the resources thereof.
5. Promote research and technology development, information exchange, capacity building and the application of appropriate technologies in shared watercourse management.

Good progress has been made in respect of reforms in the water sector with the adoption of integrated water resource management (IWRM) principles (to deal with surface water, groundwater, socio-economic and other issues in an integrated manner). Most countries have adopted the river catchment as the basic unit for integrated planning and management of water resources and the legal establishment of catchment management institutions that have specified powers and responsibilities (Beekman and Pietersen, 2005). A number of river basin commissions have been established in southern Africa, which include the:

- Zambezi Watercourse Commission (ZAMCOM).
- Orange-Senqu River Commission (ORASECOM).
- Okavango River Basin Water Commission (OKACOM.
- Limpopo Watercourse Commission (LIMCOM).

Unfortunately, these commissions are structured in accordance with surface water needs and do not take into account the management of groundwater resources. To date, no groundwater commission for transboundary aquifers have been established. The underdevelopment of international law that encompasses transboundary groundwater management further complicates governance systems for sustainable groundwater utilisation. The current legal regime that incorporates transboundary groundwater is attributed to six significant contributions, namely the Helsinki Rules, Seoul Rules on International Groundwaters, Bellagio Draft Treaty, Draft Articles on International Watercourses, with its respective Resolution on Confined Transboundary Groundwater and the Convention on the Law of Non-navigational Uses of International Watercourses (Rankin, 2004). Neither the Helsinki Rules, Seoul Rules or Resolution on Confined Transboundary Groundwater are binding as they are frameworks that are based loosely on recommendation. In addition, the Bellagio Treaty merely serves as a template for groundwater management (Burchi and Mechlem, 2005). The UN watercourse convention excluded confined aquifers from the definition of a watercourse. **Table 1** is a summary of the various international rules and resolutions pertaining to groundwater. There is a deal of uncertainty regarding what legal rules should govern the exploitation of groundwater (Turton: personal communication).

The transboundary implications for groundwater management present a number of institutional challenges. In South Africa, for example, a legal framework has been established to manage water resources in accordance with water management areas (WMA). The established WMA boundaries normally do not take into account the groundwater boundaries and, for reasons of sovereignty cannot extend beyond international boundaries. As such the Revised Protocol on Shared Watercourses becomes an important instrument. It requires the development of regional institutions that focus on transboundary groundwater basins. This is particularly relevant for the identification of the Incomati, Kunene, Limpopo, Okavango, Orange-Senqu and Zambezi as basins that are at risk of becoming areas of potential dispute (Wolf *et al.*, 2003).

Table 1: Summary of international law that relates to groundwater (Matsumotu, 2002)

Rules/Treaties/Conventions	Summary
Helsinki Rules (1966)	Defines a body of underground water, except confined groundwater, as part of an international drainage basin
Seoul Rules (1986)	Defines an *international drainage basin* as "An aquifer intersected by the boundary between two or more States that does not contribute water to, or receive water from, surface waters of an international drainage basin for the purpose of the Helsinki Rules"
Bellagio Draft Treaty (1989)	Hydrologic interdependence between surface water and groundwater Transboundary aquifer is an *international basin*
Agenda 21 (1992) Chapter 18	Suggests a comprehensive action plan for environmental management Recognizes groundwater as freshwater bodies, and gives parallel status to surface water Recommends holistic freshwater management Neglects transboundary aspect of freshwater management
The Draft of the Law of the Non-Navigational Use of International Watercourses (1994)	Uses an International Watercourse approach Does not include confined aquifer
Convention on the Law of the Non-Navigational Use of International Watercourses (1994)	Uses the same definitions of watercourses as in the draft (1994)
The Resolution of the Law of the Non-Navigational Use of International Watercourses (1994)	Recognizes that a confined aquifer, that is groundwater not related to an international watercourse, is also substantial The rules regarding water management that are presented in the draft of the Law may be applicable to transboundary aquifers

Resources management issues that are related to basement aquifers

Sustainability of groundwater resources in basement aquifers (with special emphasis on drought episodes)

With the exception of southwest Africa and some southern African coastal areas, austral summer (i.e. October–March) is the main rainfall season over much of southern Africa (Richard *et al.*, 2001). Southern Africa also has extensive drought periods and episodic flood events that are normally associated with El Niño and La Niña ocean circulation events.

Groundwater resources in most cases have a buffering effect to drought periods. However, while, in most hydrogeological environments, drought security is not a significant concern, in certain situations the storage capacity is more limited and some wells may dry up altogether, resulting in "*groundwater drought*" (Foster *et al.*, 2000). The time-lag and severity of the impact of drought on groundwater depend on (according to Foster *et al.*, 2000):

- The duration of the drought episode.
- The type, design and siting of groundwater supplies (shallow dug wells are likely to be more sensitive).
- The demand on the sources.
- The characteristics of the aquifer, in particular its storage capacity (the crystalline basement and volcanic aquifers are likely to be more sensitive than large alluvial formations).

In Malawi, when, by the end of the 1991-92 drought, the normally reliable groundwater sources began to fail and left some three million mainly rural people without adequate water supplies (Calow *et al.*, 2002). One consequence thereof was the use of unprotected sources for drinking as a result of which outbreaks of diarrhoea, cholera and dysentery claimed many lives (Calow *et al.*, 2002).

Groundwater flow and recharge (influences on quantity and quality)

The combined evidence from lithological, hydrological and hydrochemical data suggests that the basement aquifer in the savannah regions of sub-Saharan Africa consists of a composite flow system that has three main interacting components, namely one near-surface component and two with deeper circulation, either through preferential pathways or (slower) matrix flow (Wright,1992). Basement aquifers are considered to have limited storage capacity and groundwater is generally rapidly depleted. Economic quantities of groundwater are normally associated with the weathered overburden. The most productive zone for groundwater in basement aquifers is considered to be the lowest zone of the weathered profile and the top of the fractured bedrock. Viable yields are found where the weathering profile extends below the piezometric surface.

Groundwater development is reliant on the best estimate of groundwater sustainability, which is dependent, among other factors, on reliable recharge estimates, dominant recharge mechanisms and its spatiotemporal characteristics (Adams *et al*., 2004). In, especially, arid zones, recharge of groundwater in basement aquifers depends on above-normal rainfall events. **Figure 2** is a conceptual model for recharge pathways and flow for basement aquifers in the central Namaqualand region of South Africa. Adams *et al*. (2004) found that geomorphic features play an important role in the recharge process. The alluvium (or soil cover) and weathered zones are important in that they store infiltrating water and may, under favourable conditions, transmit the stored water to the fractured aquifer (Adams *et al*., 2004). Groundwater recharge rates to the basement aquifers were estimated to be within 0.1 and 10 mm/yr, with the higher rates mainly applicable to the composite/weathered aquifers and the lower limits to the fractured rock aquifers (Adams *et al*., 2004).

The groundwater quality in basement aquifers can vary over short distances as a result of complex groundwater flow patterns and weathering processes. With increasing aridity, the TDS content increases and the anion composition of the groundwater changes to sulphate or even chloride that has varying cation content (Titus *et al*., 2002). In most regions of sub-Saharan Africa, groundwater in basement aquifers is generally young and has low solute concentrations (MacDonald and Davies, 2000).

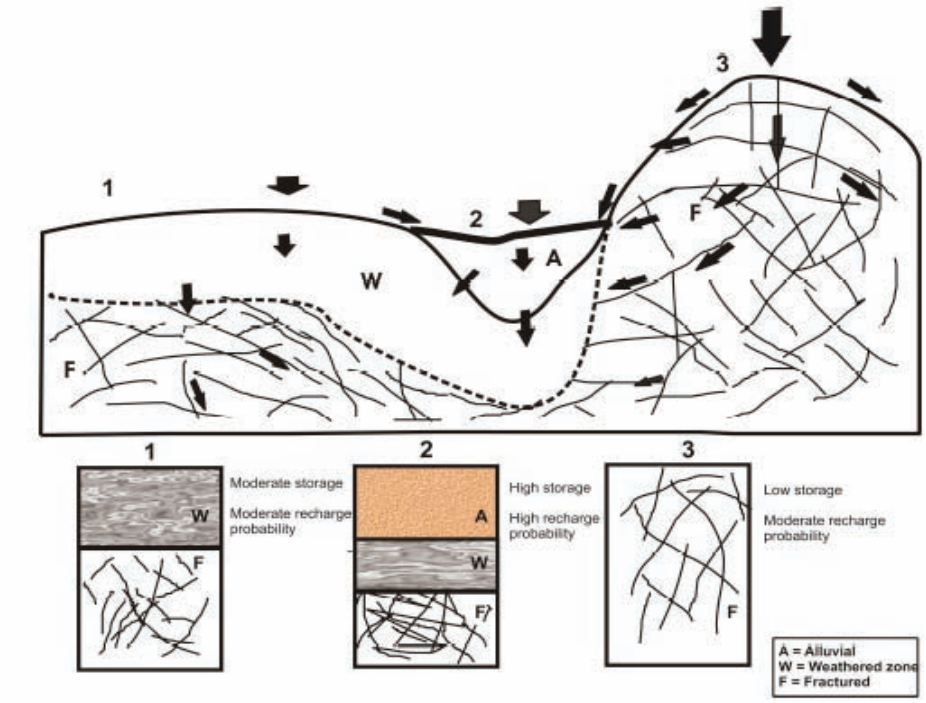

Figure 2: A conceptual model for recharge pathways and flow in the central Namaqualand region of South Africa (Adams *et al*., 2004)

Water quality and health implications for affected communities

Groundwater has excellent natural microbiological quality and generally adequate chemical quality for most uses (MacDonald and Davies, 2000). However, human health can be affected by long-term exposure to either an excess or a deficiency of certain chemicals in groundwater.

High fluoride concentration tends to occur where fluorine-bearing minerals (particularly fluorite, apatite and micas) are abundant in aquifer rocks (MacDonald *et al*., 2002). According to MacDonald *et al*. (2002) the main areas of southern Africa in which high fluoride groundwater is a particular problem are parts of South Africa and the East African Rift area (parts of Kenya, Tanzania, Ethiopia and Malawi). The most common consequence of exposure to excess fluoride is dental fluorosis ("mottled enamel"), a condition that involves interaction of fluoride with tooth enamel and that causes staining or blackening, weakening and possible loss of teeth (Smedley *et al.,* 2002). With more extreme exposure to fluoride, skeletal fluorosis can result (Smedley *et al*., 2002).

High arsenic concentration in groundwater can occur naturally or can be exacerbated by local mining activities (MacDonald *et al*., 2002). Arsenic is a toxin and a carcinogen (cancer-causing). Long-term arsenic intake has been linked with skin disorders and more serious health problems such as skin cancers, diabetes and cardiovascular, neurological and respiratory diseases (MacDonald *et al*., 2002). No widespread naturally occurring arsenic has been detected in groundwater to date, although in South Africa, arsenic contamination of groundwater that results from mining has been observed. Other trace elements of concern in groundwater are Ag, Hg, Se, Cd, Cr, Pb, Al, Y, Mn, Fe, Zn and F. Diseases caused by some of the elements include (Selinus, 2004):

- Iron (haemochromatosis).
- Copper (chronic copper poisoning; Wilson- Bedlington disease).
- Zinc (metallic fever, diarrhoea).
- Cobalt (heart failure, polycythaemia).
- Magnesium (ataxia).
- Chromium (nephritis).
- Selenium (alkali disease, blind staggers).

Pollution

Water-borne diseases results from infection as a result of the consumption of water that is contaminated with pathogens. There are four broad types of water-borne pathogens that commonly occur in groundwater, namely viruses (enteric viruses), bacteria (*Vibrio cholerae, Shigella dysenteriae, Escherichia coli, Campylobacter* spp*., Salmonella paratyphi, Salmonella typhi and Arcobacter butzleri*), protozoans (*Cryptosporidium parvum, Giardia* spp.) and helminths (Murray *et al*., 2004). The infections frequently result in diarrhoeal diseases.

The main inputs of nitrate into groundwater are derived from anthropogenic activities such as fertilizer application to land, sewage sludge application to soil, wastewater irrigation, on-site sanitation, deforestation and the mineralization and mobilization of natural soil nitrogen by the tilling of the soil (after Tredoux, 2004). Infants are particularly prone to serious health concerns as a result of elevated nitrate (when reduced to nitrite) concentrations. The health threat is related to the reduction of nitrate to nitrite in the digestive tract and the subsequent formation of methaemoglobin, a relatively stable compound that prevents the blood from conveying oxygen to the cells in the body (Tredoux, 2004). The relevant health concerns include (Tredoux, 2004):

- Spontaneous abortion or still-birth.
- Gastric and other cancers.
- Hypertension.

The vulnerability of basement aquifers to pollution is strikingly illustrated in the city of Kampala in Uganda. In Kampala (population about 1 million), the hilly topography has produced differential weathering with thin mantles of weathered material on high ground discharging to springs that have formed at geological boundaries on the lower slopes (Morris *et al*., 2003). The aquifer that supplies the protected springs therefore lacks a deeply weathered zone and is characterised by shallow flow through fractured rock (Morris *et al*., 2003). There are more than 300 springs in the city and many residents who are without a domestic tap connection use these springs for part or all of their domestic water needs, including drinking and cooking (Morris *et al*., 2003). The aquifer is extremely vulnerable and tests have shown that contamination by faecal bacteria was widespread even for protected springs (Morris *et al*., 2003). This scenario extends to other regions in Africa where the weathered layer is thin or absent and fractures extend close to the ground surface.

Institutional arrangements

Inadequate analyses of the consequences of groundwater exploitation, or a lack of technical understanding and inadequate institutional frameworks, often lead to management decisions that cause the irreversible loss of stored groundwater, the quality of groundwater or even the aquifer storage capacity. For example, the efficient use of groundwater resources located in the basement rocks of north-western South Africa is influenced by the following (according to Titus *et al.*, 2002):

- Appropriate technology. Communities are unable to operate and maintain the level of technology (e.g. diesel-operated borehole systems) for the existing water supply.
- Centralisation. The local government that is responsible for maintenance in most rural setups is relatively inaccessible.
- Cost recovery. The costs of the services that policies prescribes in terms of water supply and sanitation cannot be met by the communities.
- Sense of ownership. As a result of the lack of ownership, it is not sustainable for local government to service stock watering points. Many of these points are not operational.
- Representation. No community is homogeneous and structures are frequently dominated by the "privileged" sectors of the community.
- The needs of different sectors of the community may differ and cause conflict, e.g. water used for agricultural purposes rather than for basic needs.
- Capacity (scale of project and viability). The capacity does not exist for communities to manage schemes at the desired level.

Institutional development programmes are required to build the capacity of the communities (at various scales, namely, community, local government and regional) to manage groundwater resources in order to achieve the following:

- Sustainability.
- Effective use.
- Replicability.

Operation and maintenance

The current exploitation of groundwater in basement aquifers is mostly done by means of shallow hand-dug wells and deeper boreholes but the yields of water are often low and many of these water points fail during drought periods (Lovell in press). For example, in Zimbabwe, forty per cent of wells and boreholes in similar hydrogeological domains failed in the 1991/92 drought. Forty-seven per cent of new boreholes that were drilled in a subsequent World Bank drought-relief programme were either dry or could not support a hand-pump yield of 0.3 ℓ/s (Lovell in press).

Despite the above-mentioned resource challenges, a significant number of these boreholes fail as a result of equipment failure rather than resource failure. The reasons for these failures are frequently:

- The high population pressure per borehole.
- Misuse of pumps for multi-use purposes other than the intended use.
- Drop in groundwater level during dry periods.
- Poor payment for services.
- Many of the pumps are located in remote and scattered places, which in turn complicates access. Maintenance therefore takes place on an irregular basis.
- Maintenance and costs differ from place to place, depending on the availability of spare parts and technicians.

An approach to the development of ground-water management options

The translation of sustainability principles into practice to support the implementation of groundwater management is highly complex (Pietersen, 2005). The transboundary nature of many basement aquifer systems adds a further level of complexity. The water resource manager is often confronted with a set of overwhelming issues when faced with having to decide on how best to use limited resources in the implemention of water services programmes. A set of approaches are required that synthesise this information in a coherent framework that allows the water resource manager to identify critical pathways or activities in dealing with a complex decision problem (Pietersen, 2004). The management approach has the following elements:

- Structuring the problem through the use of technical and socio-economic studies, i.e. identification of the problem.

- Formulation of coping strategies to address the identified problem (normally done in consultation with the relevant stakeholders).
- Generating and identifying the alternative decisions and attributes by the decision-makers.
- Decomposing and modelling the problem.

Pietersen (2004) applied the above management approach to the basement aquifers located in Namaqualand in the north-western region of South Africa

Structuring the problem

The arid nature and groundwater characteristics of the region mean that communities are confronted with issues of water quantity and quality. In Pietersen (2004), the following livelihood challenges (as they relate to water) were identified:

- A dependency paradigm that is created through the adoption of inappropriate technologies (a scenario that is typical in developing communities).
- The burden placed on women to perform the daily chores and tasks in order to provide subsistence to households.
- Health risks (microbiological and chemical) that are associated with poor quality groundwater (natural and anthropogenic) and inadequate sanitation systems.
- Centralised decision-making, which often does not take community dynamics and processes into account.
- The challenge to produce sufficient food in an environment of extreme variability in respect of climate and water resources (mostly drought conditions).
- The degradation of the natural environment that results in flood problems in periods of high rainfall.
- Policies that focus on basic needs rather than on production (livelihood) requirements (supply approach rather than a demand driven approach).
- The low population densities that make reticulated water systems excessively costly.

The following definition is provided for sustainable rural livelihoods (DFID, 2000) – A livelihood comprises the capabilities, assets (including both material and social resources) and activities that are required for a means of living. A livelihood is sustainable when it can cope with and recover from stresses and shocks and maintain or enhance its capabilities and assets both now and in the future without undermining the natural resource base.

In order to deliver sustainable groundwater services and thereby contribute to rural livelihoods in meaningful manner, the groundwater manager should address the following issues (Pietersen, 2004):

- Security of water supply and improved water facilities for productive use rather than for subsistence purposes only.
- Community involvement and ownership of productive water facilities and processes should be agreed upon in order to ensure the sustainable use of the resource.
- The role of groundwater in maintaining the natural and economic resource base in the community.
- The sensitivity of the groundwater system to stresses (e.g. over-pumping) and its variability over a range of spatial and temporal scales.

In the absence of surface water, the only water supply options that communities have, are groundwater, which is predominantly located in crystalline metamorphic and igneous rocks. To address the issues mentioned above will require an integrated decision-making framework that incorporates technical and social considerations.

The development of an understanding of the issues involved in groundwater management issues in the region has required detailed investigations. For this study, the investigations included the following (Pietersen, 2004):

- Field investigations to collect data in order to understand the physical conditions of the groundwater system. The case study consisted of detailed investigations (hydrological, hydro(geological) and hydrochemical data collection, interpretation and analysis).
- Pilot studies and workshops in affected communities to consult with them and to gain an understanding of the issues related to water services. The methods that were used in the case study consisted of questionnaires and field data that was collected with the use of participative techniques, semi-structured interviews and in-depth focus discussions with various communities in the region.
- Consultations with decision makers, implementing agents and water resource managers at the local, provincial and national levels. This was done in the case study through the use of interviews and interactions at various forums.

Formulation of coping strategies to address the identified issues

Based on the conditions that prevailed in the region, an exhaustive list of potentially beneficial groundwater-related management interventions were drawn up. Coping strategies were developed for the following issues (Titus *et al.*, 2002):

- To overcome adverse climatic conditions.
- To overcome climatic variability.
- Sound aquifer system assessment.
- Management of the aquifer systems in a sustainable manner.
- Cost recovery.
- Development of an adequate operational and maintenance (O&M) skills base.
- Sectorial water demand allocations.
- Community participation and education.

Table 2 gives an example of the coping strategies identified to address adverse climatic conditions. The region has low rainfall and high potential evaporation rates. Climatic variability, on both the temporal and the spatial basis, plays a central role in determining the livelihoods of the majority of the people who live in sub-Saharan countries (Seeley, 1999). The implications for water resources are that recharge only occurs during exceptional rainfall events and only when the soil moisture deficit has been exceeded. Due to the high potential evaporation to precipitation ratio, highly soluble salts accumulate on the surface and as well as in the near-surface environment. These salts are periodically flushed into the saturated zone and affect the water quality. The average annual rainfall varies both spatially and temporally and is influenced by orographic effects. This means that available groundwater resources vary spatially in terms of both quantity and quality. Recharge cycles are also influenced by both spatial and temporal climatic variability. The region is affected by hydrological drought conditions as a result of low and infrequent rainfall and the high potential evaporation.

Generating and identifying the alternative decisions and attributes by decision-makers

A number of alternative decisions are developed, preferably through stakeholder consultation prior to the commencement of the decision-making process. For example, for the issues related to adverse climatic conditions, the following alternative decisions were formulated (the list in **Table 2** was categorised and shortened):

- Implement water enhancement strategies such as artificial recharge, water harvesting and fog harvesting.
- Reduce water loss and leakage through measures such as the maintenance of water distribution systems.
- Practise water-level and water-quality monitoring in order to characterize the response of the aquifer system with regard to adverse climatic conditions and to adapt water supply in accordance with such conditions.

The result was a comprehensive list of potentially beneficial alternative groundwater-related management decisions that deals with the coping strategies that were identified (**Table 3**). A selection of key options from the list should be effective in moving from the current situation to a preferred sustainable livelihood-based development scenario. The current situation focuses on increased coverage of services rather than on sustainability. The driving forces for implementation are not the customers, but the providers. In this scenario, water service needs are provided for, but with limited support mechanisms. This situation results in a disenfranchised community with resultant disempowerment, especially of the vulnerable sections of the communities. The resources are used in an unsustainable manner and the maintenance of services is neglected. This scenario results in the breakdown of the intended benefits from the provision of services. Ecological demise will be followed by social demise. The preferred situation is that of communities that are empowered through local government support (i.e. political and financial) and are able to implement the sophisticated legislative requirements This situation results in sustainable resource use with the intended benefits of providing clean and safe water. It will ensure the improvement of the quality of life for the present generation and future generations.

Table 2: Subset of objectives and associated measures for sustainable rural livelihoods (Titus *et al*., 2002)

Issues	Objectives and associated measures
Adverse climatic condition	• Implement artificial recharge schemes to supplement poorly naturally recharged groundwater systems when surface water resources are in excess. • Continue conjunctive use of groundwater and surface water resources. • Implement water harvesting by storing roof runoff in rainfall tanks and the construction of structures to channel the overland flow to reservoirs. • Consider fog harvesting in coastal and mountainous regions. • Implement water harvesting during exceptional rainfall events through retention walls in streams to enhance infiltration. • Undertake proper maintenance of reservoir systems/pipelines to reduce leakage and evaporation. Closed tanks, instead of open dams, located in the proximity of the boreholes may also reduce evaporation. • Manage the resource soundly through water-level and water quality monitoring to characterise the response of the aquifer system with regard to adverse climatic conditions.

Table 3: Alternative decisions for groundwater management in Namaqualand (Pietersen 2004).

Issues	Alternatives decisions
Cost recovery	*Involve communities in the selection of technology and development of the cost-recovery system* *Facilitate technology selection and tariff setting at the local government level*
Aquifer management	*Conduct water demand assessments; develop community participation and management systems* Undertake technical assessments of the aquifer systems and institute aquifer monitoring systems.
Aquifer protection	Develop protection zones around identified environmental assets. Compile an inventory of contamination sources Determine groundwater contribution to base flow *Develop borehole protection zones from contamination sources*
Aquifer assessment	Undertake a detailed geological and geomorphologic review of the region (including geodynamics and structural geology). *Characterise aquifers at the regional scale (regional groundwater flow model).* Characterise aquifers at the local scale (e.g. sound pump-testing analysis).
Coping with climate variability and change	*Use the outputs of a suitable predictive model that is available to inform decision makers about spatial and temporal climate variability and change.* *Undertake a water demand analysis to indicate trends and resource availability*
Adverse climatic conditions	*Implement water enhancement strategies such as artificial recharge, water harvesting and fog harvesting*. Reduce water loss and leakage through measures such as the maintenance of water distribution systems. Practice water-level and water-quality monitoring in order to characterise the response of the aquifer system with regard to adverse climatic conditions and to adapt water supply in accordance with such conditions.
Ensuring operation and maintenance skills base	*Ensure the training and retention of the necessary skills (including gender considerations) for the operation and maintenance of the water services system at the community level*, Facilitate the operation and maintenance of water services by local authorities.
Facilitating community participation and education	*Ensure the implementation of effective community participation in and education regarding all water services schemes* Ensure that training is targeted at the local government level (e.g. water-care operators)
Underlined and italics: Preferred alternatives	

Decomposing and modelling the problem

Pietersen (2004) concludes that a multiple-criteria decision analysis (MCDA) approach would be the most appropriate approach with which to address the multiple management objectives within the context of a decision support framework for groundwater management. The intention of this paper is not to describe the theoretical framework for MCDA, but rather to illustrate an alternative approach to support the management of groundwater in basement aquifers. The reader is referred to Belton and Stewart (2002) for detailed conceptual and theoretical considerations of MCDA. A value-function method that uses interval assessments was chosen for this study (Pietersen, 2004). The problem was structured visually with the computer software known as *Workbench for Interactive Preference Programming* (WINPRE). The method and theory for the description of the process of value-tree construction and analyses are described in Pietersen (2004; 2006). The value tree (**Figure 3**) was based on the objectives and alternative decisions that are identified in **Table 2** and **Table 3**. These attributes were weighted and used to obtain insight into the relative desirability of the alternatives (**Figure 4**). Several preferred alternatives were elicited (Pietersen, 2004). These alternatives are underlined and shown in italics in **Table 3**.

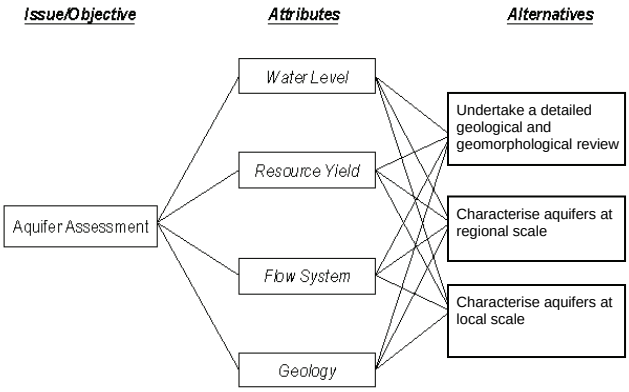

Figure 3: An example to illustrate the value tree for construction (Pietersen 2004)

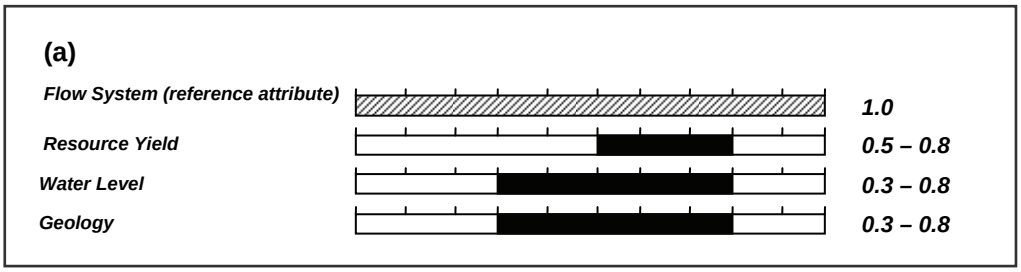

Figure 4: Interval SMART/SWING weighting in the decision-making procedure - comparison of attributes (Pietersen 2004)

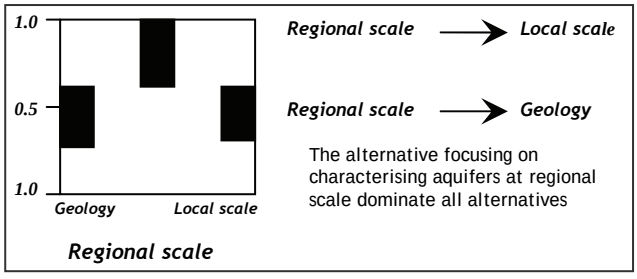

Figure 5: An example to illustrate overall value intervals and dominance relations (Pietersen 2004).

The combination of the relationships (**Figure 4**) resulted in the overall value intervals and the dominance relations that are shown in **Figure 5**.

The routing, as described, of the objectives and alternatives that were identified by Pietersen (2004) by means of the value-tree framework enabled the resulting attributes to be compared and evaluated and the alternatives to be prioritised in terms of the achievement of the most desirable scenario that is linked to sustainable rural livelihoods. The application of this method enabled Pietersen (2004) to define a critical path for the addressing of groundwater management issues. The critical path focuses on the most crucial steps in the development of a rural groundwater supply strategy that is selected from the wide range of objectives and measures and the corresponding alternatives identified by Titus *et al*. (2002) and Pietersen (2004).

Discussion

Adopting an approach that is based on local knowledge and supported by a MCDA approach has enabled a more affordable and implementable critical path to be established for groundwater management in arid zones. This means that the decision maker is able to focus on water resource management options that are identified as being the most important. MCDA support should in future be extended by involving stakeholders in the MCDA processes, thereby ensuring that the importance of the issues identified are fully acknowledged by stakeholders. It is recognised that this process should be iterative rather than once off.

The application of MCDA has been demonstrated to be an innovative planning and information technology tool that assists the decision-making process towards sustainable groundwater resource management (Pietersen, 2006). The application of the tool in a participatory environment requires further refinement and adaptation (including further work regarding sensitivity analysis). However, MCDA is a tool and should be viewed as such by water resource managers. This means that the methodology should be used circumspectly by decision makers who have the necessary experience base. A "black box" approach should be cautioned against.

Conclusion

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

- Determine the sustainable yield of the aquifer systems and to develop policy and strategies for groundwater management at the community and catchment scale.
- Protect the aquifer from possible pollution risks such as the improper location of pit latrines and indiscriminate disposal of waste.
- Protect communities from poor quality groundwater.
- Establish mechanisms by means of which communities can participate in a meaningful way. They need to be well informed regarding 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.

In basement aquifers, the infiltration and flow of water is controlled by the prevailing complex fracture networks, which vary in space and time. Such observations relate to structurally controlled flow systems and varying water chemistry amongst closely spaced fracture systems. The complexity of groundwater development is further complicated by the lack of governance of groundwater at the local, regional and international scale.

The application of a MCDA methodology enabled the development of coping measures and a problem-solving approach to groundwater management. In an example, the technical, economic, social, legal, political and environmental options that affect the management of groundwater in the arid zones of South Africa were analysed. The objectives and appropriate measures to overcome the barriers for sustainable development were also presented. This was necessary to structure the problem regarding the decision to be taken and to generate and identify the alternative decisions. Therefore alternative decisions were formulated for the various elements of the objectives in order to achieve preferred scenarios. The analyses resulted in a value-based model for groundwater management in arid zones. The application of MCDA has been demonstrated to be an innovative planning and information technology tool that can assist the decision-making process towards sustainable groundwater resource management. The application of the tool in a participatory environment requires further refinement and adaptation.

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